MICSSA

MICSSA 2023 - Digital Transformation in Achieving Defence Information Excellence in the Journey to Greatness

PROCEEDINGS

20 to 25 August 2023

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Proceedings

of the 9th Military Information and Communication Symposium of South Africa

20 to 25 August 2023
CSIR International Convention Centre, Pretoria, South Africa

ISBN: 978-0-7961-2498-2

Editor:
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Contents available on the conference website: www.micssa.co.za
Published by Military Information and Communication Symposium of South Africa (MICSSA)
www.micssa.co.za

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INTRODUCTION

The Command and Management Information Systems (CMIS) Division strives towards Information Excellence through information advantage, information and communication technologies (ICT) security and ensuring digital sovereignty in the Department of Defence (DOD).

The goal above is achieved through the reliance on universities and research institutes for discovering and developing the latest knowledge, methods and techniques, and the ICT industry to provide effective and economical ICT goods and services to the DOD. This support will enable the CMIS Division to optimise the current ICT systems and modernise the new ICT systems for DOD, by maximising the output with limited resources using the Pareto Principle. This can only be achieved through the cooperation between the CMIS Division, academia, research institutes and the ICT industry to contribute to the overall achievement of Information Excellence, i.e., the right information, to the right user, in the right format, at the right time and at the right place.

ICT is the nerve system of any organisation. In the current Fourth Industrial Revolution (4IR), the CMIS Division cannot deliver an effective ICT capability to the DOD without the relationship and support of universities, research institutes and industry. MICSSA is an opportunity to explore and enhance these relationships.

The CMIS Division hosted the ninth Military Information and Communications Symposium of South Africa (MICSSA) on behalf of the DOD with the conference over the period 22 to 24 August 2023.

OPENING SPEECH C SANDF

The Chiefs of Service and Divisions;
Generals and Admirals; Officers, Senior Warrant Officers and NCO's;
International Military Officers and Attache's;
Honored guests;
Our hosts and esteemed Partners from Armscor, BCX, CSIR and SITA;
Our various speakers;
Distinguished Delegates and Guests from the Public and Private Sectors;
Captains of industry;
To all of our patrons and sponsors;
Ladies and Gentlemen;

Good afternoon and a warm welcome to this cocktail function being the start of all the important activities and proceedings of MICSSA 2023. Allow me to extend my gratitude to each and every one for being here today. Your presence makes this event all the more special and it is a pleasure to have you all here with us.

Although the actual opening of the symposium will be tomorrow morning, this occasion is important as it offers an opportunity to generate excitement and anticipation for the symposium and set a positive and enthusiastic tone for what lies ahead for the week. I am sure today will set the tone, create a relaxed atmosphere, and encourage networking and social interaction.

As a soldier and one who understands the importance of Military Applications and Effectiveness, including the very important enabling capability of Information Communication Technology, it is a pleasure for me to form part of this prestigious event called the Military Information and Communications Symposium of South Africa.

If I look around me and see the great interest of current and former soldiers, both local and international, as well as the ICT related industry, I can see that MICSSA 2023 is going to be a huge success. In this regard the aim of bringing together the Information and Communications related Defence community - government and industry - local and international – to discuss ideas, strategies, requirements and potential ICT solutions can be shared and discussed will be achieved.

It is pleasing to know that MICSSA is continuing to be hosted biennually because this event contributes to highlighting the importance of ICT in the

SANDF. The theme of MICSSA 2023 emphasises the fact that in today's world, information is power, and this is especially true for the Defense Force. Defense Information Excellence is about ensuring that the right information is available at the right time and to the right people. It is about using information to make better decisions, improve operational effectiveness, and ultimately, ensure National Security.

So I would like to wish the Chief CMIS Div, Maj Gen Shashape, and the MICSSA partners – Armscor, BCX, CSIR and SITA, all of the best with MICSSA 2023 and we look forward to benefitting from all the papers, presentations and informal opportunities that this symposium is going to provide.

Please make use of tonight to start off these interactions and I trust everyone will enjoy the festivities tonight and be up and awake tomorrow morning ready for the formal opening of MICSSA 2023. In this regard it is then my privilege to open the exhibition today and encourage everyone to use this opportunity to visit the respective stands provided by the ICT supporting Industry.

Please enjoy the rest of the afternoon and Good Night.

Gen R Maphwanya
C SANDF

CLOSING SPEECH CHIEF CMIS

It is with the greatest honour that I give this closing speech for MICSSA 2023. Reflecting on the past eight MICSSA conferences the 9th MICSSA was definitely a success.

The theme - “Digital Transformation in Achieving Defence Information Excellence in the Journey to Greatness”.

Brought through the importance of ICT in all aspects of business from private to government – giving a wide view on technology, applications, security and learning.

The military adoption of ICT over the years has allowed for militaries to be more effective in fulfilling its role and this has enabled militaries to strive for digital transformation especially with the drive of the 4th industrial revolution.

The ICT position of the DOD is no different in trying to satisfy the demand for a more intelligent and effective way to implement ICT solutions on different levels in the DOD namely strategic, operational and tactical and is of vital importance to the RSA national defensive posture.

Post Covert 19 epidemic the new normal was often referred to. Adaptive and Agile approached to implementing quick win ICT solutions were called upon to provide accurate information on demand.

Considering ICT research and development this is vital for the survivability of any organisation and nation in that this allows for foresight and insight into new technologies and ICT directions. Coupled to this is the importance of learning and the approaches to learning, investing in our youth to enhance a better and more technologically advanced future for the RSA and Africa. Skills retention is crucial and achieving continuity in developing a sound ICT capacity to take on these new innovations within the ICT world, thus becomes a non-negotiable.

Artificial Intelligence has revolutionised the worlds ICT environment. The techniques and methods that have been implemented in certain areas in commerce’s, education and health sectors have assisted in decision making and paving the way forward. With this comes the standpoint that autonomy in using AI and the ethical view is a heated debate which has to be considered and appreciated.

Cyber Security has been a discussion for a number of years and dually noted. The 5th domain of war the Cyber Space has been witnessed in various wars and conflicts over the past 15 years. The adoption of the 5th Domain of warfare has its challenges and the DOD ICT environment is to stand vigilant in its approach to combat threats to the national and DOD mission critical networks.

Challenges that the DOD ICT environment is facing - focuses on the declining defence budget and the ability to retain and acquire ICT skills that are based on industry competitive packages. Furthermore, the Intellectual property drain due to the defence industry challenges, leads to a drive to try to use what is available to ensure that ICT can ensure and support the DOD business. However; DOD ICT strategies and implementation plans have been developed to address scenarios to arrest the decline of ICT with the drive to enabling a digital strategy looking to the future.

The wins within the DOD towards striving to a more virtual environment. The development of initiatives to bridge the gap of using business intelligence platforms by utilising big data techniques. The adoption of limited digitalised Command and Control platforms and DOD unique networks are pushing the drive towards the “Journey to Greatness”.

In closing I would like to Thank you as the;

- Organisers,
- The CSIR ICC,
- Industry representatives,
- Partners,
- Authors,
- The support staff,
- and most importantly the delegates

Hope to see you at MICSSA 2025

Maj Gen M P Shashape
C CMIS

MILITARY INFORMATION AND COMMUNICATIONS SYMPOSIUM OF SOUTH AFRICA (MICSSA)

The 9th Military Information and Communications Symposium of South Africa (MICSSA) 2023 was held at the Council for Scientific and Industrial Research (CSIR) International Convention Centre (ICC) Pretoria, over the period 20-25 August 2023.

Aim of the Symposium

- To create an opportunity to promote Information and Communications Technology related development between the Defence community, Government and Industry, locally and internationally.
- To provide the platform where ideas, strategies, requirements and potential solutions can be shared and discussed.

Theme of the Symposium

"Digital Transformation in Achieving Defence Information Excellence in the Journey to Greatness"

Target Audience

- Military ICT related Academia and Technology Developers.
- The South African National Defence Force (SANDF).
- MICSSA Partners (ARMSCOR, CSIR, SITA and Telkom).
- Defence Forces of Africa and other developing countries.
- National and International Defence related industries.
- Academic and Research Institutions.
- Government departments that could benefit from ICT in the execution of their functions.
- South African Development Community (SADC) and Brazil, India, China and South Africa (BRICS) countries.
- ICT Military related Opinion Formers.
- Military personnel active in Communication and Information Systems.
- Persons responsible for the acquisition of Information and Communication Technologies (ICT) systems for the military.

Logo Representation

- The traditional Postal Runner with its origins as a postal service in Namibia established in 1814 between the missionary stations.
- The runner is in motion, symbolizing the "Transfer of Information", which is communication.
- The MICSSA runner embodies Information and Communication in an African context.
- The logo was initially designed during MICSSA 2003 and has been used ever since with a few adaptations.
- 2023 is the ninth occasion that MICSSA will be presented and the colours represent the 9th Anniversary Gemstone Lapis Lazuli in blue, black and gold. Lapis Lazuli's benefits consist of a powerful intense stone used to open minds and providing enlightenment.
- The lightning bolt resembles the provision of Telecommunications. It is a symbol of Power, Strength and Speed and used to represent Communications and Transmissions.
- The Radio Waves point to Wireless and Digital Communication.

Previous MICSSA Themes

- MICSSA 2018: "ICT as a Military Capability"
- MICSSA 2016: "Gaining the Edge through ICT Modernisation"
- MICSSA 2014: "Military Information and Communications Technology within a Rapidly Evolving Cyber World"
- MICSSA 2011: "Matching World Class Solutions to shrinking Budgets"
- MICSSA 2009: "Interoperability - Big Words or an Achievable goal?"
- MICSSA 2007: "The African Battle Space: Are the ICT Solutions required really Unique?"
- MICSSA 2005: "Information and Communications Technology: The Key to Military Information Superiority in Africa"
- MICSSA 2003: "In pursuit of affordable Strategic Solutions"

MICSSA 2023 Theme

Five initial themes with a description were developed as a baseline for inputs, namely:

- ICT risks for Military Effectiveness: A Strategic Dilemma.
- African Inspired Military ICT Solution for the evolving African Battle Space.
- Next Generation of ICT in the African Battle Space.
- Military in the 4th Industrial Revolution.
- The "New Normal" for Militaries Enablement of ICT.

Approach to Development MICSSA 2023 Themes

- Word cloud generated from inputs given from external and internal sources.
- Inputs received were then translated into a word cloud.
- Inputs were requested from stakeholders including members in CMIS Division, CSIR and Defence Decision Support Industry (Armscor).
- Word cloud was combined with both inputs.

From the Word Cloud the focus was on dominant, secondary and subset words:

- Dominant words: New Normal, African Battle space, Data Science, Military ICT Solutions, ICT strategy.
- Secondary words: Military effectiveness, Common operating perspective, Joint Force Employment, Military mission readiness, big data, strategic dilemma, Business drivers, end state advantage, decisive edge, mitigating risk.
- Subset words: Solutions new C4, Military silicon valley, Automation, 4IR, Artificial Intelligence methods, SMART ICT.

From the dominant, secondary and subset words the following proposed or sub-themes were determined as a new baseline:

- Utilising Data Science to achieve a Common Operating Perspective in the African Battle space.
- Effective Military ICT Solutions to achieve the Military End State Advantage inspired by African ICT Solutions.
- ICT Business drivers to attain the Decisive Edge in the "New Military Normal" to adapt and adopt ICT trends.

Combination of Themes Outcome:

- An integrative approach was followed to determine an overall theme that addresses all three themes in which the initial three themes can be track themes for the symposium.
- Proposed Overarching Theme MICSSA 2023.

Relevant Fields for paper, with the focus on utilisation in the Military - included but not limited to:

- Computer Games, Computer Graphics and Virtual Reality
- Applications of Artificial Intelligence and Machine Learning
- Energy efficient computing and communications
- Ubiquitous and distributed computing
- Visualization
- Software Defined Storage
- RF and Satellite communication
- Tactical Data Links
- Network enables communication
- Web and social media technologies
- Digital signal processing
- Interoperability
- Sensory technologies
- Bandwidth compression and optimisation
- Adaptive computing
- Quantum computing
- Management of ICT systems
- Cloud computing and services
- ICT for health and smart-grid
- Open Source development
- Big Data
- Data Mining and Information Retrieval
- Bioinformatics and Biomedical Engineering
- Data de-identification
- Natural Language Processing
- Pattern Recognition
- Robotics and Automation
- Computer Networks
- Security in Information and Telecommunication Systems
- AI Security and Cryptography
- Data security/protection
- Database and Information Systems
- Digital Signal and Image Processing
- Digital System, Logic Design and Embedded Systems
- Distributed and Parallel Processing
- E-commerce and E-governance
- Forensic Data Analysis
- Human Computer Interaction
- Internet and Web Applications
- Multimedia Tools and Applications
- Social Networking
- Software Engineering
- Ubiquitous and Mobile Applications
- Wireless Communication and Mobile Computing
- Internet of Things
- Internet of Things
- 3D printing and Automated Industrialisation
- ICT for Education
- Emulation, simulation, and holographic

Final Theme for MICSSA 2023

"Digital Transformation in Achieving Defence Information Excellence in the Journey to Greatness"

SUBMISSION AND REVIEW PROCESS

For MICSSA 2023, speakers were invited to submit full papers or presentations only.

Authors submitted abstracts for full papers and it was screened for suitability by a panel of reviewers of the Command and Information Management Systems (CMIS) Division. Successful authors were invited to submit a full paper. All submitted papers were reviewed by Defence Intelligence (DI) and then sent for a double blinded peer review by an expert panel of reviewers, all invited through an open invitation and expert in the field of information and communication technology. All review comments were recorded using a standardized review form to record comments and decisions. All papers have been assigned at least two peer reviewers. Only papers that passed the peer review process are published in the proceedings.

Thank you to everyone who made a submission to MICSSA 2023 and congratulations to the authors whose papers are accepted for publication. A total of 32 submissions were received for MICSSA 2023. A total of 13 peer reviewed papers were accepted for publication in the MICSSA 2023 proceedings. All the authors gave written permission to MICSSA to publish their papers.

Thank you very much to the Technical Review Committee and the Peer Review Panel for all their outstanding work.

PEER REVIEW PANEL

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Modernisation and Optimisation of Defence Networks Through Optic Fibre for Metro Ethernet

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***Abstract*—The SANDF doesn't have a fiber optic backbone for the ICT networks. This research is aimed in finding solutions that will be cost effective. A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication systems use high carrier frequencies (~ 100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called lightwave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (~ 1 GHz). Fiber-optic communication systems are lightwave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and have revolutionized the field of telecommunications. Indeed, lightwave technology, together with microelectronics, led to the advent of the "information age" during the 1990s. Now in the 2000 Millennium this transmission medium introduced Metro Ethernet.**

Ethernet is a technology that has had major success in the LAN, displacing other once-promising technologies such as Token Ring, FDDI, and ATM. Ethernet's simplicity and price/performance advantages have made it the ultimate winner, extending from the enterprise workgroup closet all the way to the enterprise backbone and data centers. The metro is the last portion of the network standing between subscribers or businesses and the vast amount of information that is available on the Internet. The metro is entrenched with legacy time-division multiplexing (TDM) and SONET/SDH technology that is designed for traditional voice and leased-line services. These legacy technologies are inadequate for handling the bandwidth demands of emerging data applications.

Ethernet in the metro can be deployed as an access interface to replace traditional T1/E1 TDM interfaces. Many data services are being deployed in the metro, including point-to-point Ethernet Line Services and multipoint-to-multipoint Ethernet LAN services or Virtual Private LAN services (VPLS) that extend the enterprise campus across geographically dispersed backbones. Ethernet can run over many metro transport technologies, including SONET/SDH, next-generation SONET/SDH, Resilient Packet Ring (RPR), and wavelength-division multiplexing (WDM), as well as over pure Ethernet transport. Ethernet, however, was not designed for metro applications and lacks the scalability and reliability required for mass deployments.

The SANDF is currently using TDM and this research will give guidance on how Metro Ethernet can be adopted in ICT networks.

I. Introduction

Optic fiber development and rollout thereof has made an excellent progress since optical communication started. From the progress made since the 1990's to the current progress made in the 2020's bandwidth and data traveling speed has improved drastically. The global layout of fiber optic cables has now covered a large footprint. South Africa is now increasing the fiber optic cabling to reach residential areas. Digital medium transmission has improved through optical fiber.

The data interface termination development has improved in terms of multiplexers. We started with Frequency Division Multiplex (FDM) then Time Division Multiplex (TDM). Now with the progress made with fibre optic we can effectively use Wavelength Division Multiplex (WDM). Metro Ethernet (ME) is the quick and effective data interface termination method that allows more services and applications at the same instance..

II. OPTIC FIBRE COMMUNICATION

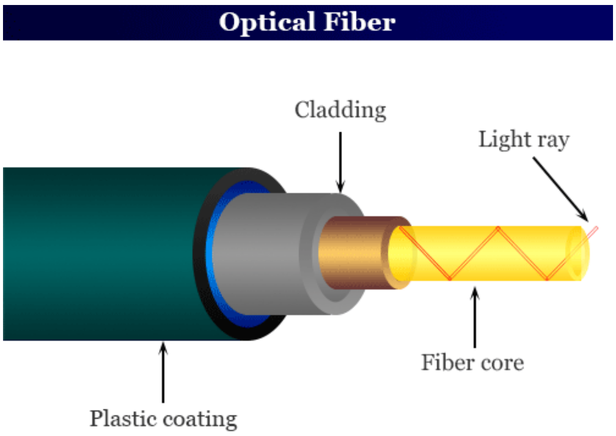

Fig 1.1 Basic Optic fiber

A. *Optic fiber development*

Optical communication systems differ in principle from microwave systems only in the frequency range of the carrier wave used to carry the information. The optical carrier frequencies are typically ~ 200 THz, in contrast with the microwave carrier frequencies (~ 1 GHz). An increase in the information capacity of optical communication systems by a factor of up to 10,000 is expected simply because of such high carrier frequencies used for lightwave systems. This increase can be understood by noting that the bandwidth of the modulated carrier can be up to a few percent of the carrier frequency. Taking, for illustration, 1% as the limiting value, optical communication systems have the potential of carrying information at bit rates ~ 1 Tb/s. It is this enormous potential bandwidth of optical communication systems that is the driving force behind the worldwide development and deployment of lightwave systems. Current state-of-the-art systems operate at bit rates ~ 10 Gb/s, indicating that there is considerable room for improvement.

B. Optic fiber transmition medium

The role of a communication channel is to transport the optical signal from transmitter to receiver without distorting it. Most lightwave systems use optical fibers as the communication channel because silica fibers can transmit light with losses as small as 0.2 dB/km. Even then, optical power reduces to only 1% after 100 km. For this reason, fiber losses remain an important design issue and determines the repeater or amplifier spacing of a long-haul lightwave system. Another important design issue is fiber dispersion, which leads to broadening of individual optical pulses with propagation. If optical pulses spread significantly outside their allocated bit slot, the transmitted signal is severely degraded. Eventually, it becomes impossible to recover the original signal with high accuracy. The problem is most severe in the case of multimode fibers, since pulses spread rapidly (typically at a rate of ~ 10 ns/km) because of different speeds associated with different fiber modes. It is for this reason that most optical communication systems use single-mode fibers. Material dispersion (related to the frequency dependence of the refractive index) still leads to pulse broadening (typically < 0.1 ns/km), but it is small enough to be acceptable for most applications and can be reduced further by controlling the spectral width of the optical source

C. WDM Lightwave Systems

WDM corresponds to the scheme in which multiple optical carriers at different wavelengths are modulated by using independent electrical bit streams (which may themselves use TDM and FDM techniques in the electrical domain) and are then transmitted over the same fiber. The optical signal reaching the receiver is then demultiplexed into separate channels by using a suitable optical device. The WDM technique allows us to exploit the large bandwidth offered by optical fibers. For example, hundreds of 40 Gb/s channels can be transmitted over the same fiber when channel spacing is reduced to near 100 GHz. Figure 6.1 shows the low-loss transmission windows of standard fibers centered near 1.3 and 1.55 /im. If the OH peak is eliminated using the so-called "dry" fibers, the total capacity of a WDM system may exceed 50 Tb/s.

III. METRO ETHERNET

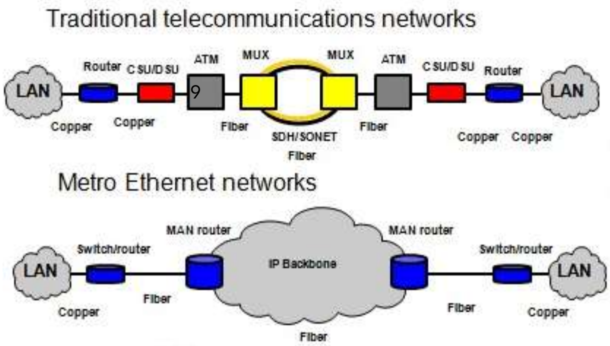

Figure 1.2

A. Difference between TDM and ME model

Figure 1-1 shows the difference between the TDM model and Ethernet model for delivering Internet connectivity. In the TDM model, the metro carrier, such as an ILEC or RBOC, offers the point-to-point T1 circuit, while the ISP manages the delivery of Internet services, which includes managing the customer IP addresses and the router connectivity in the point of presence (POP). This normally has been the preferred model for ILECs who do not want to get involved in the IP addressing and in routing the IP traffic. In some cases, the ILECs can outsource the service or manage the whole IP connection if they want to. However, this model keeps a demarcation line between the delivery of IP services and the delivery of connectivity services..

B. Ethernet interface

In the Ethernet model, both network interfaces on the customer side and the ISP side are Ethernet interfaces. The ILEC manages the Layer 2 (L2) connection, while the ISP manages the IP services. From an operational perspective, this arrangement keeps the ILEC in a model similar to the T1 private-line service; however, it opens up the opportunity for the ILEC to up-sell additional service on top of the same Ethernet connection without any changes to the CPE and

C. Metro Ethernet communication

Ethernet technology has so far been widely accepted in enterprise deployments, and millions of Ethernet ports have already been deployed. The simplicity of this technology enables you to scale the Ethernet interface to high bandwidth while remaining cost effective. The cost of a 100Mbps interface for enterprise workgroup L2 LAN switches will be less than R500 in the next few years

These costs and performance metrics and Ethernet's ease of use are motivating carrier networks to use Ethernet as an access technology. In this new model, the customer is given an Ethernet interface rather than a TDM interface

D. Bandwidth scalability

The low cost of an Ethernet access interface on both the CPE device and the carrier access equipment favours the installation of a higher-speed Ethernet interface that can last the life of the customer connection. Just compare the cost of having a single installation of a 100-Mbps Ethernet interface versus the installation of a T1 interface for 1.5-Mbps service, a T3 for 45-Mbps service, and an OC3 (155 Mbps) for 100-Mbps service. A TDM interface offering results in many CPE interface changes, many truck rolls deployed to the customer premises, and equipment that only gets more expensive with the speed of the interface.

E. Bandwidth granularity

An Ethernet interface can be provisioned to deliver tiered bandwidth that scales to the maximum interface speed. By comparison, a rigid TDM hierarchy changes in big step functions. It is important to note that bandwidth granularity is not a function specific to Ethernet but rather is specific to any packet interface. Early deployments of metro Ethernet struggled with this function because many enterprise-class Ethernet switches did not have the capability to police the traffic and enforce SLAs.

IV. ME TECHNOLOGY SHIFT

A major shift in how data services are offered to businesses and residential customers. The metro has always been a challenging environment for delivering data services because it has been built to handle the stringent reliability and availability needs for voice. Carriers will have to go through fundamental shifts to equip the metro for next-generation data services demanded by enterprise customers and consumers. This is not only a technology shift, but also a shift in the operational and business model that will allow the incumbent carriers to transform the metro to offer enhanced data service.

A. ME Services

The metro services vary depending on the target market commercial or residential and whether it is a retail service or a wholesale service. The following list gives a summary of some of the metro services that are promoted

1) *Internet connectivity*.
2) *Transparent LAN service (point-to-point LAN to LAN)*
3) L2VPN (point-to-point or multipoint-to-multipoint LAN to LAN)
4) LAN to network resources (remote data center)
5) Extranet
6) LAN to Frame Relay/ATM VPN
7) Storage area networks (SANs)
8) Metro transport (backhaul)
9) VoIP.

B. Resilient Packet Ring

RPR also plays an important role in the development of data services in the metro. RPR is a new Media Access Control (MAC) protocol that is designed to optimize bandwidth management and to facilitate the deployment of data services over a ring network. The roots of RPR go back to the point at which Cisco Systems adopted a proprietary Data Packet Transport (DPT) technology to optimize packet rings for resiliency and bandwidth management. DPT found its way into the IEEE 802.17 workgroup, which led to the creation of an RPR standard that differs from the initial DPT approach.

RPR has so far been a very attractive approach to multiple service operators (MSOs), such as cable operators that are aggregating traffic from cable modem termination systems (CMTSs) in the metro. It remains to been seen whether RPR will be deployed by the incumbent carriers, such as the RBOCs and ILECs, that so far haven't been widely attracted to the RPR concept. The primary reason why they lack interest is that they view RPR deployments as new deployments, compared to EOS deployments, which leverage existing infrastructure and are therefore more evolutionary. RPR is a new packet-ring technology that is deployed over dark fiber or wavelength division multiplexing (WDM) instead of the traditional SONET/SDH rings. RPR could be deployed as an overlay over existing SONET/SDH infrastructure; however, the complexity of overlaying logical RPR rings over physical SONET/SDH rings will probably not be too attractive to many operators. Although RPR and EOS solve different issues in the metro (EOS solves Ethernet service deployment, and RPR solves bandwidth efficiency on packet rings), both technologies will compete for the metro provider's mind share..

C. Label Switching in a Nonpacket World

MPLS networks consist of LSRs connected via circuits called label switched paths (LSPs). To establish an LSP, a signaling protocol is required. Between two adjacent LSRs, an LSP is locally identified by a short, fixed-length identifier called a label, which is only significant between these two LSRs. When a packet enters an MPLS-based packet network, it is classified according to its forwarding equivalency class and, possibly, additional rules, which together determine the LSP along which the packet must be sent. For this purpose, the ingress LSR attaches an appropriate label to the packet and forwards the packet to the next hop. The label itself is a shim layer header, a virtual path identifier/virtual channel identifier (VPI/VCI) for ATM, or a data-link connection identifier (DLCI) for Frame Relay. When a packet reaches a core packet LSR, that LSR uses the label as an index into a forwarding table to determine the next hop, and the corresponding outgoing label. The LSR then writes the new label into the packet and forwards the packet to the next hop. When the packet reaches the egress LSR (or the one node before the egress LSR for penultimate hop popping), the label is removed and the packet is forwarded using appropriate forwarding, such as normal IP forwarding.

In TDM networks, the concept of label switching happens at the circuit level or segment level. Switching can happen, for example, at the time-slot level where an input OC3 time slot is crossconnected to an output OC3 time slot.

For WDM-capable nodes, switching happens at the wavelength level, where an input wavelength is cross-connected to an output wavelength. As such, SONET/SDH add/drop multiplexers (ADMs) and OXCs become equivalent to MPLS LSRs, time-slot LSPs and lambda LSPs become equivalent to packet-based LSPs, and the selection of time slots and wavelength becomes equivalent to the selection of packet labels. Also, nonpacket LSPs are bidirectional in nature, in contrast to packet LSPs, which are unidirectional.

The concepts of label switching in both TDM and WDM networks are similar in the sense that with TDM networks

GMPLS controls circuits and WDM GMPLS controls wavelengths..

Problem Statement

The SANDF doesn’t have a fiber optic ICT infrastructure backbone. The units in the country are using fiber optic connection but the is no topology nor ICT architecture in place to link or interlink the whole network. Microwave is the current the only reliable medium of connectivity.

Findings

The SANDF is capable of building the ICT fiber optic backbone without contracting vendors or outsourcing the work required. If Log Div, CMIS Div, Defence Works Div, SA Army Signal formation to mention a few can plan and execute cost effectively.

Acknowledgment

I wish to acknowledge, with appreciation and self-effacement, everyone who has expressively or Unsuspectingly, directly or indirectly, prejudiced my life in a positive way. I also wish to thank everyone who has made it possible for me to complete this research: My Creator, Allah Subhana wa Taala who constantly watches over me, my mentor, Col M.D Smit, for his insights and guidance in completion this paper. I would also like to thank Mr Simon Ditshego whose support throughout this research has provided me with the inspiration and motivation to deliver on expectations. However, any errors of fact or interpretation that may be contained in this reesearch, are entirely my own.

Abbreviations and Acronyms

add/drop multiplexers (ADMs)

AF Adaptation Function

BR-FP Branch-Root Flow Point

cable modem termination systems (CMTSs)

CEN Carrier Ethernet Network

Data Packet Transport (DPT)

data-link connection identifier (DLCI)

E-Access Ethernet Access (service)

EI External Interface

EVC Ethernet Virtual Connection

Frequency Division Multiplexer

INNI Internal Network-Network-Interface

LAN Local Area Network

LLC Logical Link Control

MAC Media Access Control

Metro Ethernet (ME)

multiple service operators (MSOs)

label switched paths (LSPs)

NID Network Interface Device

PDU Protocol Data Unit

Data Packet Transport (DPT)

RMI Remote Management Interface

RPR Resilient Packet Ring

Time Division Multiplexer

UNI User-Network Interface

VLAN Virtual LAN

WAN Wide Area Network

WEN Wide Area Ethernet Network

Virtual Private LAN services (VPLS)

virtual path identifier/virtual channel identifier (VPI/VCI)

Wavelength Division Multiplexer

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Application of Machine Learning Algorithms to Tuberculosis Detection

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***Abstract*—Tuberculosis (TB) is an infectious disease caused by a bacterium called Mycobacterium tuberculosis. TB affects primarily the lungs, but can also spread to other parts of the body, such as the kidneys, bones, and lymph nodes. TB claims the lives of many people throughout the world and its timely diagnosis and treatment is the key to maximizing the chances of full recovery. Machine learning-based disease detection offers many advantages over traditional approaches (with human involvement), which can enable it to play a key role in the medical diagnostic process. These advantages include higher precision, rapid diagnosis, higher scalability, cost effectiveness, and higher consistency. In this work, machine learning algorithms, i.e., a convolutional neural network (CNN), a support vector machine (SVM) and decision tree algorithms, are applied to the classification of tuberculosis in chest X-ray images into healthy and TB-infected. Herein, the SVM, CNN and decision tree achieved an accuracy of 99.58%, 99.50% and 98.75%, respectively, in classifying the images. The performance of these algorithms is optimized by employing hyperparameter optimization techniques. These methods could serve as a complement to traditional disease detection methods used in the medical profession, including applicability to point-of-care settings.**

***Index Terms*—Convolutional neural network, Support vector machine, Machine learning, Hyperparameter optimization, Image classification, Decision tree.**

I. Introduction

A number of diseases are categorized as life-threatening; these are diseases that have the potential of leading to the deaths of patients. Diseases are divided into various levels, and those with high possibilities of danger falls within the higher level [1, 2]. The risk factors of the diseases are evaluated based on their impact on human lives [3, 4]. Some of the diseases at the higher level are caused by various types of viruses, bacteria, parasites or fungi; and they affect one of the major systems of the human body, the respiratory system. Humans use the respiratory system to exchange oxygen and carbon dioxide through inhalation and exhalation [1]. During this process, the lungs play important role in the respiratory system by allowing gas exchange. Many diseases at high-risk interfere with the functions of the respiratory system [5, 6]. Tuberculosis (TB) is one of the diseases classified as high-risk [1-4].

TB is an infectious disease caused by a bacterium called Mycobacterium tuberculosis (Mtb) [5-10]. Mycobacterium tuberculosis is an intracellular pathogen that is extremely adapted to humans and has developed mechanisms to avoid the human immune response, allowing it to persist indefinitely in the host [11, 12]. In the cases when the bacterium replicates, infected people can spread the infection [1]. The bacterium invades human lungs and reduces the efficiency of lung functionality [1]. Although TB primarily affects the lungs, it can also spread to other parts of the body, such as the kidneys, bones, lymph nodes, spine and brain [13, 14]. Tuberculosis can be active and latent, but the TB bacterium is present in both cases which associates patients with risk factors such as human immunodeficiency virus (HIV) co-infection and diabetes mellitus [1, 15, 16]. The risk factors are associated with active TB, while latent TB does not cause symptoms or spread the disease. Tuberculosis is considered life-threatening by the World Health Organization (WHO) which makes it a significant public health problem [1, 4]. According to the 2019 WHO report, there were 10 million people who tested positive for TB worldwide, with 88% being older people [17, 18].

Timely diagnosis of TB is the key to maximizing the chances of full recovery, as this can lead to early treatment and a short period of infectiousness [1]. Considering the nature of diagnostics, computer technology, particularly machine learning (ML), plays a key role in modern, dynamic healthcare systems by improving the diagnostic process while maintaining quality and safety [6]. Machine learning technology is an integration of statistical concepts and scientific knowledge of computers that enables computers to automatically read and interpret data [19, 20]. It is a subset of artificial intelligence (AI) that is associated with algorithms that permits computer processors to automatically process and classify new input data based on previously processed data and information using mathematical models [10]. This allows computers to predict data and infer based on training data (sample data) without comprehensive programming [10]. As such, machine learning-based disease detection offers many advantages over traditional approaches (with human involvement). Some of the advantages include higher accuracy, rapid diagnosis, higher scalability, cost-effectiveness, and higher consistency [6].

In this work machine learning algorithms, i.e., a convolutional neural network, a support vector machine and decision tree algorithms are applied to the classification of tuberculosis in chest X-ray images into healthy and TB-infected under supervised learning. The performance of these algorithms is optimized by employing hyperparameter optimization techniques coupled with dimensionality reduction techniques (principal component analysis) to achieve more accurate results.

The research methodology, dataset specifics, machine learning algorithm details, and the formulae used to assess the effectiveness of the algorithms are all included in Section II of this work. In section III, the performance of the algorithms is also described and evaluated against similar studies. Section IV provides a conclusion to the paper.

II. Materials and Methods

This work follows supervised learning where the algorithms (a convolutional neural network, a support vector machine and a decision tree) are provided with labeled sample data for training to predict outputs. The algorithms are optimized by employing hyperparameter optimization techniques. The techniques were implemented using Python programming language on Google Colab [21, 22]. The aim of the work is to develop an optimized automatic TB detection system to classify chest X-ray images into healthy and TB infected. The research methodology follows these steps: dataset preparation, hyperparameter optimization, convenient model, comparison of the optimized models and comparisons of the models under study with different lightweight deep learning systems using different performance metrics. The process of classifying chest X-ray images is shown in Fig. 1. The input chest X-ray images were adopted from publicly available Kaggle datasets [23, 24]. The input images are enhanced with image processing techniques (image reshaping, flattening and normalization) to minimize error rates and improve detection performance. The output of the preprocessing stage are updated image inputs [1]. Thereafter optimized models perform the classification of the images into healthy or tuberculosis, for which their accuracy is evaluated.

A. Datasets and Description

The chest X-ray images used in the work were acquired from the publicly available TB-dataset on Kaggle datasets [12]. The sample images are shown in Fig. 2. This specific work first divides the image samples into health and TB, then resized all images in 200×200 pixels to enable the models to train faster. The images were then converted to grid of values that contain information about the raw dataset (NumPy arrays).

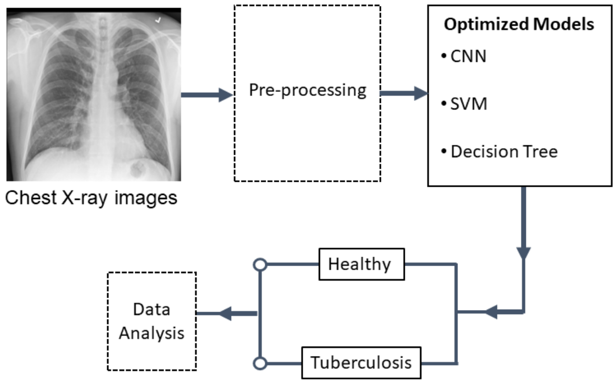

Fig. 1. A schematic representation of the approach followed in the research.

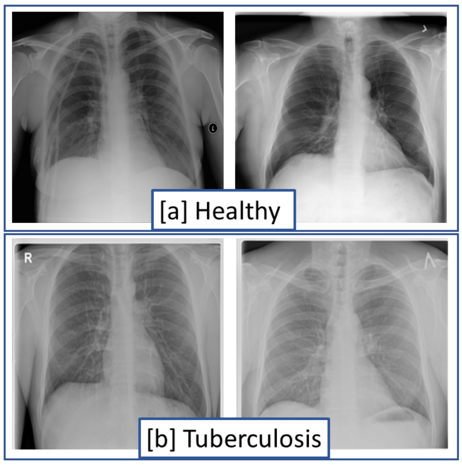

Fig. 2. The chest X-ray images of [a] healthy patients and [b] tuberculosis (TB) infected patients downloaded from Kaggle TB-dataset [12].

The arrays were then converted into two-dimensional arrays with a shape of 40000 through the process of flattening. The data split into training and testing was performed on a ratio of 8 : 2 from 1206 input images. All features were brought to the same scale by feature scaling (division by 255), with maximum and minimum values of 1 and 0 respectively. The features were then selected from a principal component analysis (PCA) to detect sensitive information while minimizing information loss (dimensionality reduction). Lastly, models were trained on the dataset and evaluated on new data.

B. Support Vector Machine (SVM) Algorithm

The SVM is a supervised learning algorithm that works by finding a hyperplane that optimally separates data into different classes [10]. The SVM was employed with the aim of generating the best decision boundary (hyperplane) to separate two-dimensional space into two classes. In this work, the linear-type SVM was employed to separate the two classes by a straight line.

C. Decision Tree Algorithm

The decision tree is a nonparametric supervised learning algorithm that divides the tree structure into sub-trees in solving classification problems [19]. The decision tree algorithm in this work used an information gain/entropy function to measure the quality of splitting the samples. The function takes a product of the class probability and the log_2 of the class probability as shown in (1):

$$Entropy = \sum_{i=2}^{C} -p_i \times log_2(p_i) \tag{1}$$

where, C is the number of classes and p is the probability of samples in a class. The algorithm used 8 minimum number of chest X-ray images to split an internal node, with a maximum tree depth of 17. The selected parameters provided good precision during the grid search.

D. Convolutional Neural Network Algorithm (CNN)

The CNN model in this work was instantiated as Sequential with densely connected layers. The only hidden layer had 64 nodes, with input data shape of 40000 dimensions and rectified linear activation function. The hidden layer is followed by batch normalization. The output layer of the model consisted of 1 node with a logistic activation function (sigmoid). The model had 2560358 total parameters, 2560257 trainable parameters and 128 non-trainable parameters. The model was optimized by Adam optimizer with a learning rate of 0.19 to two decimal places and a loss function of categorical crossentropy. During training, 100 chest X-ray images were packed into a patch of the model for 80 cycles.

E. Confusion Metrics

In TB image classification, quantitative indicators such as accuracy, precision, F1 score, positive and negative predictive value, sensitivity/recall and specificity are used to evaluate the performance of classification algorithms (optimized models) where, TP: True Positives, TN: True Negatives, FP: False Positives and FN: False Negatives.

- **Accuracy :** The accuracy is used to measure the classification performance of each algorithm by evaluating the ability of each model to correctly predict all the sample images [1]. Accuracy is calculated as [25]:

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \tag{2}$$

  The measure of accuracy herein does not consider a state of positivity or negativity of the predicted samples. It denotes a total of correctly identified instances amongst all instances.
- **Sensitivity:** The sensitivity is used to measure how accurately the optimized models were able to distinguish image features. Moreover, it analyses the correct proportion of the true positive samples [1, 13]. The measure of sensitivity/recall was determined from [25]:

$$Sensitivity = \frac{TP}{FN + TP} \tag{3}$$

  In this paper, the sensitivity measure considers total instances and denotes only true positive measures.
- **Precision:** The precision measure is used to analyze the positively predicted samples. It is the ratio between correctly predicted positive samples and all predicted samples [1, 25, 26]. It is calculated as follows [25]:

$$Sensitivity/recall = \frac{TP}{TP + FP} \tag{4}$$

- **Specificity:** The specificity measure is used to identify a number of true negatives that are correctly identified in the samples. It is a representation of the abilities of the optimized model to correctly predict negative samples from all negative samples in the input data set [1, 25]. It is formulated as follows [25]:

$$Specificity = \frac{TN}{FP + TN} \tag{5}$$

- **F1-Measure (F1-score):** In this work, F1-score is used as the performance metric due to its capability of being robust against imbalances in the dataset. The F1 score assesses the balance between precision and sensitivity/recall [1, 25]. In a harmonic manner, the F1 score is the mean of accuracy and sensitivity/recall. It is formulated as follows [25]:

$$F1Score = \frac{2 \times TP}{2 \times TP + FN + FP} \tag{6}$$

  where true positive (TP), true negative (TN), false positive (FP) and false negative (FN) represents the number of TB chest X-ray images that are predicted as TB, number of healthy chest X-ray images that are predicted as healthy, number of healthy chest X-ray images that are predicted as TB and number of TB chest X-ray images that are predicted as healthy, respectively.

III. Results and Discussion

A. Performance Metrics

The performance of classification models was evaluated using confusion metrics as shown in Fig. 3. Out of 1200 chest X-ray images, 400 were for healthy patients and 800 were for TB patients. Convolutional Neural Network correctly classified 398 images as healthy and incorrectly classified 2 images as healthy while they were TB-infected. The model further correctly classified 796 images as TB-infected and failed on 4 images. Conversely, the SVM correctly classified 399 images as healthy and failed on only one image. For TB-infected images, the SVM correctly classified 796 images and failed on 4 images.

Lastly, the decision tree classifier correctly classified 386 healthy images and failed on 14 images. For the images infected with TB, the classifier correctly classified 794 images and failed on 4 images. Hence, the SVM algorithm performed better than both CNN and the decision tree algorithms. Although SVM and CNN perform the same on classifying TB-infected images, CNN lacks in classifying healthy images by one image to the SVM in 400 images.

TABLE I
COMPARISON OF CLINICAL INDICATORS OF OPTIMIZED MODELS ON THE TUBERCULOSIS CHEST X-RAYS TEST DATASET.

Model	Accuracy	Sensitivity	Precision	F1 Score	Specificity	Time (ms)
CNN	0.9950	0.9975	0.9950	0.9962	0.9900	93.4447
SVM	0.9958	0.9987	0.9950	0.9969	0.9900	35.7917
Decision Tree	0.9833	0.9827	0.9925	0.9875	0.9846	11.5445

TABLE II
COMPARISON OF LIGHTWEIGHT NETWORKS ON TUBERCULOSIS X-RAY IMAGES.

CNN	Accuracy (%)	Sensitivity (%)	Specificity (%)	Precision (%)	F1 Score (%)
EfficientNetB3 [1]	98.7	98.3	99.0	98.3	98.3
InceptionRenNetV2 [1]	98.1	98.7	97.7	96.1	97.1
This Work	99.5	99.8	99.0	99.55	99.6

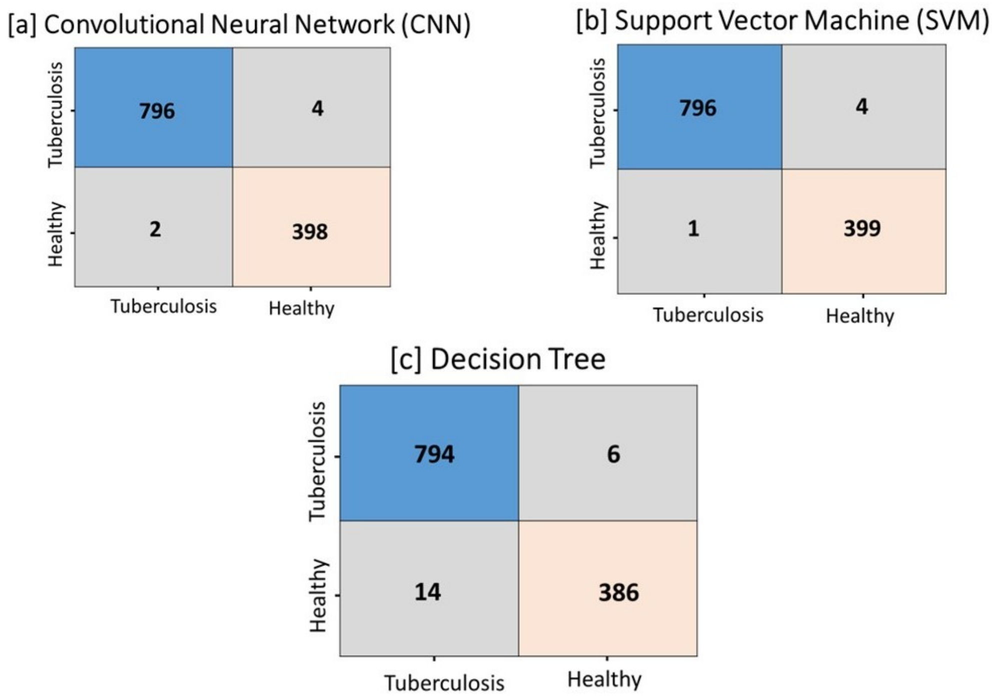

Fig. 3. Graphical representation of confusion matrices on the optimized model on the testing set: [a] Convolutional Neural Network (CNN), [b] Support Vector Machine and [c] Decision tree.

Table I illustrates the performance of the optimized models in the testing dataset. The results are calculated using equations (2) - (6) from the confusion metrics in Fig. 3. The SVM achieves a maximum accuracy of 99.58% in 35.79 ms. The model can recognize healthy chest X-rays images by 99% and TB-infected chest X-rays images by 99.87%. The F1 score of the mode is close to 1 to indicate perfect precision and recall. Since the dataset has only two features, the hyperplane in the algorithm was one-dimensional offering maximum margins. The CNN model archives an accuracy of 99.50% in 93.44 ms. The model recognizes normal chest X-rays images by 99% and TB-infected images by 99.75%. The accuracy of the model is related to the quality of the input dataset [25]. The model has a lower learning rate of 0.91 to two digits, which indicated the rate at which the optimal weights were calculated. The learning rate controls a change in the model in response to the estimated error each time the model weights are updated. Although the model had a lower learning rate, it had a longer computation time as seen in Table I. The CNN model proposed in this work is a lightweight model with a faster learning rate and faster reasoning process. This is due to a reasonably low number of iterations and an early stopping, which increased the generalization ability of the model on the test data to avoid overfitting. Lastly, the decision tree classifier archives an accuracy of 98.33% in classifying chest X-ray images. The model can recognize normal chest X-ray images by 98.46% and TB-infected chest X-rays images by 99.50%. The SVM in comparison to CNN and decision tree models in this work offer a reduced number of missed classification by 59% with 99.5% of being accurate.

B. Comparisons of Models

Table II shows the performance comparisons of two lightweight networks on the testing dataset of chest X-ray images [25]. The CNN model of the present work shows an improvement in accuracy. The model offers more ability to recognize normal X-ray images and improvement to recognize TB X-ray images. Therefore, this work offers a comparative advantage in working with point-of-care devices due to its reduced number of missed diagnoses. This improvement was brought about by the ability of principal component analysis (PCA) feature selection to detect sensitive information while minimizing information loss from the input dataset. This perfect performance is reflected by an F1 score that is close to the probability of unity, suggesting perfect precision and recall.

IV. Conlusions

This work presents a comparative study of lightweight optimized CNN, SVM, and a decision tree algorithm to classify chest X-ray images of healthy patients and TB-infected patients. A PCA showed a great impact in detecting sensitive information from the images while minimizing information loss. This enabled the achievement in the accuracy of 99.58%, 99.50% and 98.75% from SVM, CNN and decision tree, respectively. The linear nature of the data distribution offered a one-dimensional decision boundary with maximum margins in both lasses. As such a linear kernel of the SVM produced the maximum distance between the classes (best hyperplane) which classified normal chest X-ray images by 99% and TB-infected chest X-ray images by 99.87% precision. The model was better than both the CNN with rectified linear activation function and decision tree algorithm. The average accuracy performance of the models to classify chest X-ray images into healthy and TB-infected is at 99.14%, offering improvement from comparative models with 98.4% [1]. The use of the models in the classification and prediction of diseases in the medical field can provide a second opinion to doctors' decisions in diagnosing patients. Owing to hyperparameter optimization, the models in this work perform better with reduced computational complexity. This aligns well with the intentions of network design and the deployment of devices with a lower level of hardware. Hence, the models can be operated on basic machine using small portions of the memory.

Acknowledgment

We acknowledge the Department of Science and Innovation (DSI) for funding this research.

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Application of quantum computers to the simulation of phase-based quantum biosensing experiments

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***Abstract*—As quantum computing continues to develop, there is a great need to develop useful applications of this technology. Quantum technologies, revered for their expansive application potential, have been making significant strides in the realm of biological sciences. They're not only enhancing the performance of microscopes and biosensors but also elevating the sophistication of molecular process simulations. Furthermore, they're paving the way for innovative methods to manipulate biomolecular behavior and chemical reactions. In this work, the authors will look at how quantum computers could potentially be used to simulate quantum biosensing experiments such as phase-based surface plasmon resonance experiments. These phase-based biosensing setups can be modelled as interferometers which are relatively simple to model on a quantum computer. An example simulation of a Mach-Zender interferometer will be performed on an IBM quantum computer in this work and we will show how this can be useful for phase-based biosensing applications. Phase-based biosensing experiments have been identified as a promising target for quantum simulation because of the convenience of implementing phase simulations on a quantum computer. Phase-based quantum biosensors can be modeled as interferometers, where a phase shift would correspond to the binding activity on the surface of the biosensor. The authors will use quantum circuit models to directly simulate quantum interference and entanglement used in phase-based quantum biosensing experiments. The quantum circuits that model the phase-based biosensing experiment will be implemented on IBM quantum processors. The authors will illustrate two interferometer experiments in this work, one with a single qubit and one with two entangled qubits. The authors will also discuss parameters critical to biosensing experiments such as limit of detection and discuss how these can be extracted from simulations. This work sets up for possible future simulations including other quantum states such as squeezed states. Simulations are useful for illustrating the role quantum mechanics can play in setting new records for precision measurements on biosensing platforms, which can be applied at point-of-care settings.**

***Index Terms*—Quantum sensing, biosensing, entanglement, mach-zender.**

I. Introduction

Quantum sensing, quantum computing, and quantum information involve the use of quantum mechanical systems to process information and perform computing tasks [1], [2]. Quantum mechanics is described as a physical and mathematical framework for understanding the behavior of particles on a very small scale, such as photons and atoms. Quantum mechanics became important in the early twentieth century as classical physics began to predict absurdities, and it is now a critical part of science and engineering [3]. In 1982, physicist Richard Feynman suggested building computers based on the principles of quantum mechanics to avoid difficulties in simulating quantum mechanical systems on classical computers. David Deutsch then devised the first quantum algorithm, the "Deutsch algorithm" [4], and researchers began investigating quantum algorithms in the early 1990s. In 1994, mathematician Peter Shor demonstrated "Shor's algorithm" [5], which could solve two important problems that are intractable on classical computers. In 1995, computer scientist Lov Grover introduced "Grover's search algorithm" [6], which can speed up searching through unstructured databases on a quantum computer. These breakthroughs demonstrate the potential of quantum computers over probabilistic Turing machines due to their exponential speed-up.

Applications of quantum mechanics are at the forefront of modern research. This is the result of researchers increasingly utilizing quantum resources, such as entanglement and superposition, for quantum metrology, quantum sensing, quantum simulation, and quantum computation [7]–[9]. Quantum computers employ entanglement to achieve processing capacities beyond those of classical computers, allowing for the development of algorithms such as Grover's algorithm, which allows for a quadratic speedup in structured database searching, and the quantum Fourier search algorithm, which allows for an exponential speedup in performance over the classical alternative [10]. A key application of quantum mechanics has been in biosensing, where a lot of work has shown that the use of quantum states of light can improve the precision of biosensors [11].

In biosensing experiments a critical parameter of interest is the limit of detection (LoD) of our biosensors; the limit of detection depends on the parameter of interest in the biosensing experiment [12]. For example, in phase-based experiments the limit of detection refers to the lowest measurable unit of phase change that is detectable by our experiments, hence in simulating our experiments it is critical that we can calculate the limit of detection. For a signal, the LoD of an optical

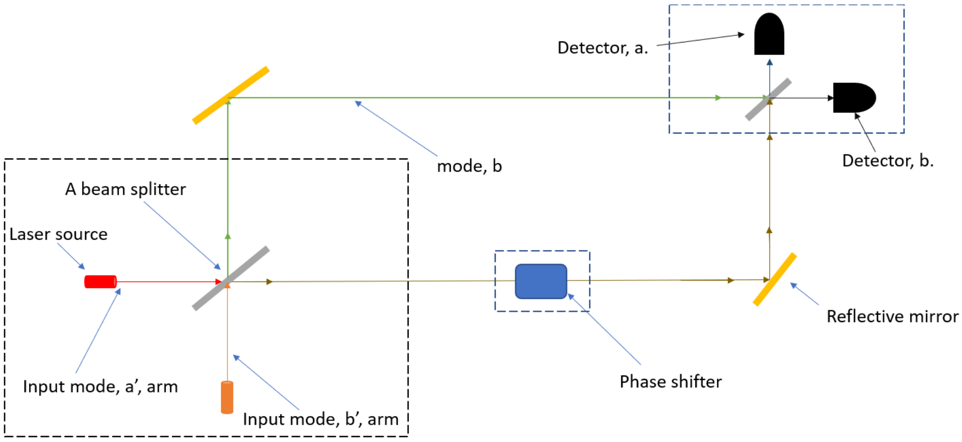

Fig. 1: Mach-Zehnder setup illustrating the implementation of a two-mode phase sensing system. By measuring the intensity difference between detectors A and B, phase sensing can be performed. The dotted box surrounding the lasers designates the input preparation region, while the one encircling the phase shifter indicates the intermediate process region. The dotted box around the detectors represents the measurement region. Taken with permission from [1].

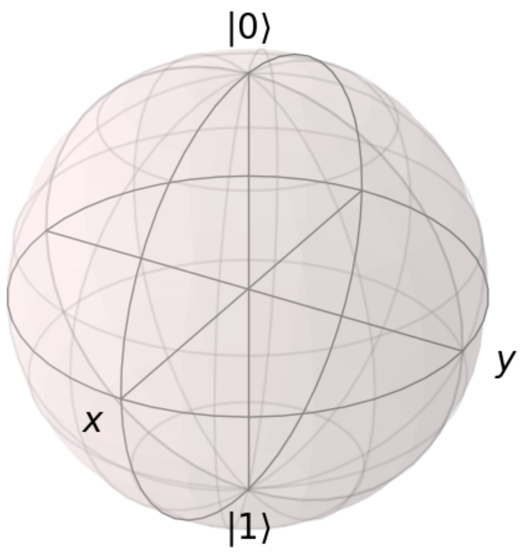

Fig. 2: A 3D representation of a Bloch sphere, which is used to visualize the state of a qubit in quantum computing. Taken from [2].

biosensor for example depends on the noise in the signal [13]. The LoD is expressed as,

$$\text{LoD} = \frac{\text{signal} - \text{noise}}{\text{biosensor} - \text{sensitivity}}. \tag{1}$$

The LoD can be enhanced by either augmenting the sensitivity or diminishing the noise level. While numerous modifications can be made to boost the sensitivity of optical biosensors, the fundamental constraint lies in the intrinsic statistical properties of the classical light employed as input for the setup. Researchers have demonstrated that by utilizing quantum states of light, noise reduction can be achieved, thereby improving the LoD of optical biosensors and surpassing the shot-noise limit [14]–[16].

The sensitivity of the biosensor is defined as

$$\text{sensitivity} = \left| \frac{\text{response} - \text{in} - \text{signal}}{\text{change} - \text{in} - \text{signal} - \text{parameter}} \right|. \tag{2}$$

In biosensing sensitivity can be a change in the intensity of the signal in response to changing binding activity.

The IBM Quantum Experience is an online quantum computing platform that provides the opportunity to simulate quantum algorithms on real quantum hardware. In other work, IBM Quantum Experience has been used for a wide range of applications, such as teaching students about quantum metrology, which is the science of measurement and is one of the first areas of quantum science where entanglement has found practical applications [11]. In this work, the authors will show how phase-based quantum biosensing experiments can be simulated on a quantum computer, and we show an example of how results can be useful for analyzing biosensing experiments [11]. Using a IBM machines the authors simulate an interferometer and perform analysis on the output and highlight how this analysis can be useful for further analysis.

II. Fundamentals of Quantum Computing

The most fundamental structure in understanding the evolution of a quantum state is the Bloch sphere (see Fig. 2). The Bloch sphere is a geometric representation of the state of a two-level quantum system, also known as a qubit, in quantum computing. The sphere is named after Felix Bloch, a Swiss physicist who introduced the concept in 1946 [17]. The Bloch sphere is a unit sphere, with the north pole representing the state $|0\rangle$ and the south pole representing the state $|1\rangle$. The equator of the sphere represents the states that are a superposition of $|0\rangle$ and $|1\rangle$, that is, the states of the form $\alpha|0\rangle + \beta|1\rangle$, where α and β are complex numbers satisfying $|\alpha|^2+|\beta|^2 = 1$. The equator is also known as the "computation basis" of the qubit.

In classical computing the fundamental unit of information is the bit, i.e., 0 or 1 whereas in quantum computing the fundamental unit of information is the qubit, i.e., $|0\rangle$ or $|1\rangle$. In order to perform computational tasks, these bits in the classical picture and or qubits in the quantum picture need to be manipulated somehow. The manipulation of qubits requires gates that perform these operations. Examples of these gates include the X gate, Y gate, Z gate, and CNOT gate. The X-gate is a single qubit gate that performs a bit flip operation, that is, it converts $|0\rangle$ to $|1\rangle$ and vice versa. It can be represented as,

$$\mathrm{X} = |0\rangle\langle 1| + |1\rangle\langle 0|, \tag{3}$$

which performs the equivalent of a π rotation about the x-axis of the Bloch sphere. The Y-gate is a single qubit gate which can be represented in braket notation as,

$$\mathrm{Y} = -i|0\rangle\langle 1| + i|1\rangle\langle 0|, \tag{4}$$

which performs the equivalent of a π rotation about the y-axis of the Bloch sphere. The Z-gate is a single qubit gate which can be represented in braket notation as

$$\mathrm{Z} = |0\rangle\langle 0| - |1\rangle\langle 1|, \tag{5}$$

which performs the equivalent of a π rotation about the z-axis of the Bloch sphere. The Hadamard gate, H creates a superposition of the $|0\rangle$ and $|1\rangle$ states. When applied to the $|0\rangle$, it results in,

$$\mathrm{H}|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \tag{6}$$

and

$$\mathrm{H}|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle). \tag{7}$$

Another quantum gate is the phase gate known as the P-gate defined as,

$$\mathrm{P} = |0\rangle\langle 0| + \mathrm{e}^{\mathrm{i}\psi}|1\rangle\langle 1|. \tag{8}$$

The P-gate completes a rotation of ψ around the Z-axis of the Bloch sphere. Outside of the single-qubit gates we also have the multi-qubit gates such as the C-NOT gate. The C-NOT operates in the following manner,

$$\mathrm{CNOT}|0\rangle|x\rangle = |0\rangle|0 \oplus \mathrm{x}\rangle, \tag{9}$$

and

$$\mathrm{CNOT}|1\rangle|x\rangle = |1\rangle|1 \oplus \mathrm{x}\rangle, \tag{10}$$

where x is binary digit.

These qubits and quantum gates can be integrated into complex systems to implement complex tasks such as optimization, machine learning, searching tasks, and factorization tasks. The simplest algorithm which can be implemented using a quantum computer is the Deustch algorithm and we will briefly discuss this algorithm here.

III. Phase-based biosensing

Phase-based biosensing experiments can be modeled using a Mach-Zehnder interferometer (Fig. 1). In this setup, the phase shifter component can represent various types of biosensors that rely on different sensing mechanisms. Examples of such biosensors include surface plasmon resonance (SPR)-based plasmonic biosensors (see Fig. 5), localized surface plasmon (LSPR)-based biosensors, and photonic crystal-based biosensors. These sensing technologies enable highly sensitive and selective detection of biological molecules, such as proteins, nucleic acids, and small molecules, by monitoring changes in the optical properties of the sensor surface.

In this work, we will show as an example how an SPR-based biosensor, which operates on the principle of monitoring changes in the refractive index near a metal-dielectric interface, can be modeled within a Mach-Zehnder interferometer. This approach allows for the investigation of the sensor's performance under various conditions, such as changes in the incident light wavelength, angle of incidence, and polarization. Moreover, the Mach-Zehnder interferometer model can be used to explore how different quantum states can further enhance the sensitivity and selectivity of the SPR-based biosensor in detecting target analytes.

IV. Calculations for models implemented on quantum computer

In this section we look at analytical calculations for the implementation of the Mach-Zender interferometer. The calculations considered here do not account for any losses in the setup. Because in implementing algorithms with a real quantum computer there will in fact be losses, it is critical to understand the impact of losses in our work. Unfortunately, this is beyond the scope of this work.

A. Single qubit implementation

In this section the quantum circuit is implemented on single qubits. The circuit that implements this algorithm is shown in Fig. 3. The first step for the single qubit is to implement the Hadamard

$$|0\rangle \xrightarrow{\mathbf{H}} \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \tag{11}$$

The next step is to apply the phase shift using, $\mathbf{R_z}(\phi)$, which rotates $\frac{\phi}{2}$ radians anti-clockwise about the z-axis of the Bloch sphere.

$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \xrightarrow{\mathbf{R_z}(\frac{\phi}{2})} \frac{1}{\sqrt{2}}(\mathrm{e}^{-\mathrm{i}\frac{\phi}{2}}|0\rangle + \mathrm{e}^{\mathrm{i}\frac{\phi}{2}}|1\rangle) \tag{12}$$

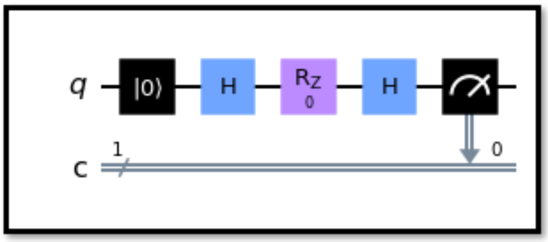

Fig. 3: Quantum circuit representation of a Mach-Zehnder interferometer using a single qubit. The circuit employs quantum gates to simulate the interferometer's behavior, allowing for the study of quantum interference and phase manipulation in a compact and intuitive manner.

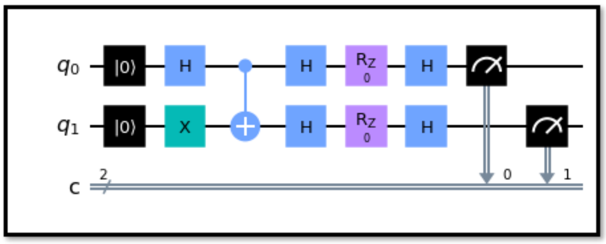

Fig. 4: Quantum circuit representation of a Mach-Zehnder interferometer implemented on a quantum computer, using entangled qubits. This circuit uses the unique properties of entanglement to simulate the behavior of the interferometer, enabling the exploration of quantum interference, phase manipulation, and enhanced sensitivity in the context of quantum computing.

The next step is to apply another Hadamard gate results in the following expression

$$\frac{1}{\sqrt{2}}(e^{\frac{-\phi}{2}}|0\rangle+\mathrm{e}^{\mathrm{i}\frac{\phi}{2}}|1\rangle) \xrightarrow{\mathbf{H}} \frac{1}{2}[(\mathrm{e}^{-\mathrm{i}\frac{\phi}{2}}+\mathrm{e}^{\mathrm{i}\frac{\phi}{2}})|0\rangle+(\mathrm{e}^{-\mathrm{i}\frac{\phi}{2}}-\mathrm{e}^{\mathrm{i}\frac{\phi}{2}})|1\rangle] \tag{13}$$

This reduces to the final state, $\langle\psi|$, where

$$|\psi\rangle = \cos\frac{\phi}{2}|0\rangle - \mathrm{i}\sin\frac{\phi}{2}|1\rangle \tag{14}$$

Taking a measurement using the measurement operator $\hat{\mathrm{M}} = \frac{1}{2}(|1\rangle\langle 1| - |0\rangle\langle 0|)$, we get

$$\langle\hat{\mathrm{M}}\rangle = \langle\psi|\hat{\mathrm{M}}|\psi\rangle = -\cos\phi \tag{15}$$

Next we calculate, $\langle\Delta\hat{\mathrm{M}}\rangle$,

$$\langle\Delta\hat{\mathrm{M}}\rangle = \sqrt{\langle\hat{\mathrm{M}}^2\rangle - \langle\hat{\mathrm{M}}\rangle^2} \tag{16}$$

In order to calculate $\langle\hat{\mathrm{M}}^2\rangle$ we use the operator $\hat{\mathrm{M}}^2 = \frac{1}{2}(|1\rangle\langle 1| + |0\rangle\langle 0|)$. Hence it follows that we can calculate the LoD, $\Delta\phi$, as

$$\Delta\phi = \langle\Delta\hat{\mathrm{M}}\rangle|\frac{\partial\mathrm{M}}{\partial\phi}|^{-1} \tag{17}$$

For this single qubit case we find that,

$$\Delta\phi = (\sin\phi)/(\sin\phi) = 1. \tag{18}$$

The SQL formula for the phase, which gives the LoD in the classical case is given by (see calculation/derivation in Appendix A of [1])

$$\Delta\phi_{\mathrm{SQL}} = \frac{1}{\sqrt{N}}, \tag{19}$$

where N is the number of qubits, hence in this case the single qubit gives an accuracy at the SQL when loss is not considered in the phase estimation.

B. Entangled qubit implementation

In this section, the quantum circuit is implemented on entangled qubits. The circuit that implements this algorithm is shown in Fig. 4. Here the first step is to create an entangled state and to do this we begin by applying the Hadamard and X gate on a pair of vacuum state qubits as shown,

$$|0\rangle_1|0\rangle_2 \xrightarrow{\mathrm{H}\otimes\mathrm{X}} \frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 + |1\rangle_1|1\rangle_2) \tag{20}$$

The next step in generating the entangled state is to apply the CNOT gate which gives,

$$\frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 + |1\rangle_1|1\rangle_2) \xrightarrow{\mathrm{CNOT}} \frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 + |1\rangle_1|0\rangle_2) \tag{21}$$

After preparing the entangled state, the authors can model the state inside the Mach-Zender interferometer. To do this we apply a pair of Hadamard gates on the individual modes of tehe system.

$$\frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 + |1\rangle_1|0\rangle_2) \xrightarrow{\mathrm{H}_1\otimes\mathrm{H}_2} \frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2) \tag{22}$$

The phase shift can be modelled by applying the, $\mathrm{R}_Z(\phi)$, gates on both modes, this results in the following,

$$\begin{gathered}\frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2) \xrightarrow{\mathrm{R}_Z(\phi)\otimes\mathrm{R}_Z(\phi)} \\ \frac{1}{\sqrt{2}}(\mathrm{e}^{-\mathrm{i}\phi}|0\rangle_1|0\rangle_2 - \mathrm{e}^{\mathrm{i}\phi}|1\rangle_1|1\rangle_2)\end{gathered} \tag{23}$$

This is followed by a pair of Hadamard gates which represents

$$\begin{gathered}\frac{1}{\sqrt{2}}(\mathrm{e}^{-\mathrm{i}\phi}|0\rangle_1|0\rangle_2 - \mathrm{e}^{\mathrm{i}\phi}|1\rangle_1|1\rangle_2) \xrightarrow{\mathrm{H}_1\otimes\mathrm{H}_2} \\ \frac{-\mathrm{e}^{\mathrm{i}\phi}}{2\sqrt{2}}(|0\rangle_1|0\rangle_2 + |0\rangle_1|1\rangle_2 + |1\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2) \\ +\frac{\mathrm{e}^{-\mathrm{i}\phi}}{2\sqrt{2}}(|0\rangle_1|0\rangle_2 + |0\rangle_1|1\rangle_2 + |1\rangle_1|0\rangle_2 + |1\rangle_1|1\rangle_2)\end{gathered} \tag{24}$$

This simplifies to the final state before measurement, $|\psi\rangle$,

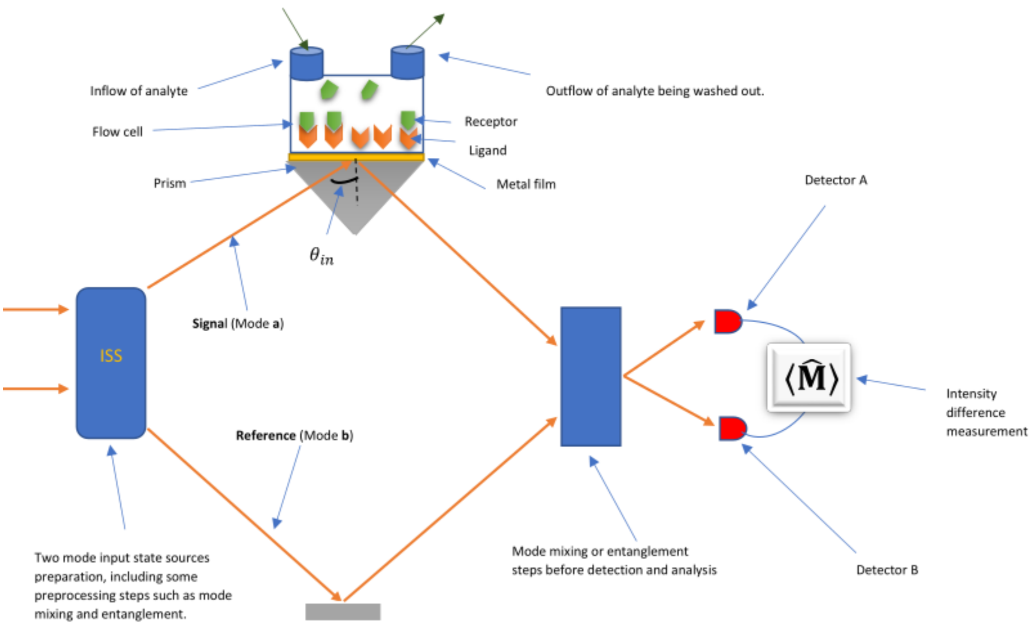

Fig. 5: This figure shows the phase-based plasmonic biosensing setup with Krestchmann configuration integrated Mach-Zehnder interferometer for phase-based detection.

$$|\psi\rangle = \frac{\cos\phi}{\sqrt{2}}(|0\rangle_1|1\rangle_2+|1\rangle_1|0\rangle_2)-\frac{i\sin\phi}{\sqrt{2}}(|0\rangle_1|0\rangle_2+|1\rangle_1|1\rangle_2) \quad (25)$$

Taking a measurement $\langle\hat{A}\rangle$, defined as $\langle\hat{A}\rangle = (|0\rangle\langle 0| + |1\rangle\langle 1|) - (|0\rangle\langle 1| + |1\rangle\langle 0|)$, we get

$$\langle\hat{A}\rangle = \langle\psi|\hat{M}|\psi\rangle = -\cos 2\phi \quad (26)$$

Next, the authors calculate, $\langle\Delta\hat{A}\rangle$,

$$\langle\Delta\hat{A}\rangle = \sqrt{\langle\hat{A}^2\rangle - \langle\hat{A}\rangle^2} \quad (27)$$

Here, $\langle\hat{A}^2\rangle = |0\rangle\langle 0| + |1\rangle\langle 1| + |0\rangle\langle 1| + |1\rangle\langle 0|$, hence,

$$\langle\Delta\hat{A}\rangle = \sqrt{1-\cos^2 2\phi} = \sin 2\phi. \quad (28)$$

Hence,

$$\Delta\phi = \frac{1}{2}. \quad (29)$$

The Heisenberg limit is given by

$$\Delta\phi_{\mathrm{HL}} = \frac{1}{N}. \quad (30)$$

Where N is the number of qubits. It follows that $\Delta\phi = \frac{1}{2}$. The entangled state gives better precision beyond the shot noise limit. We know that the shot noise limit bount is given by, $\frac{1}{\sqrt{N}}$, where N is the photon number. So at the shot noise limit a 2 photon system would have a precision of, $\Delta\phi = \frac{1}{\sqrt{2}}$.

V. Implementing Mach-Zender Interferometer on an IBM Quantum Computer

IBM Quantum Computers can be utilized to simulate a Phase Sensing Biosensing Experiment, a process that detects and measures changes in the refractive index of a medium using an optical sensor. Quantum computing can be employed in this type of experiment to speed up computations and improve accuracy. This can be achieved by using quantum circuits to simulate the behavior of the sensor under different conditions and predict the outcome of the experiment. IBM Quantum Computers are particularly suitable for this task due to their advanced quantum hardware and software capabilities. They provide access to qubits that can be used to build quantum circuits that are capable of performing complex computations, such as quantum Fourier transforms, which are essential in phase sensing experiments. Additionally, IBM Quantum Computers offer a variety of software tools, such as Qiskit and Aqua, that facilitate the creation and execution of quantum circuits. Using IBM Quantum Computers in phase sensing biosensing experiments can result in faster and more accurate results, leading to improved detection of changes in the refractive index of a medium.

In Fig. 6 we see a plot of the polarization when we run the circuit on a simulator versus when we run it on a real quantum computer. The real quantum computer has actual inefficiences and losses; hence why we see a drop in the polarization height. Looking at Fig. 7 we can see the increased sensitivity in the entangled system input. As expected, the ibmq-belem machine

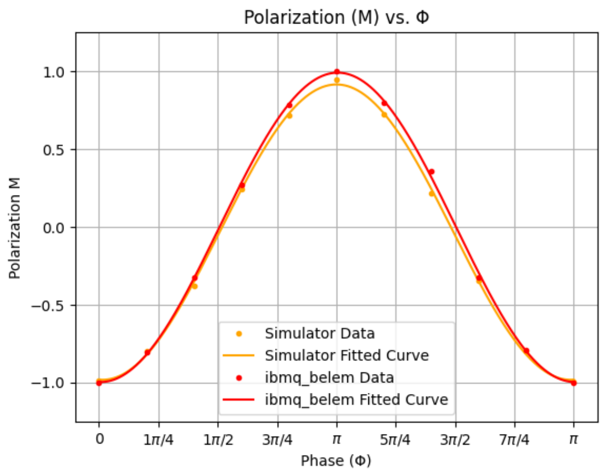

Fig. 6: The polarization measurement, represented by M, was determined by analyzing data collected from both the quantum computer (represented by the blue curve) and the simulator (represented by the orange curve). Thirteen different angles ranging from 0 to 2π were tested, and the resulting data was used to create best-fit curves. The error bars were too small to be visible and the curves were fitted to the data using free parameters for amplitude and offset. The quantum device used was the ibmq-belem. Python code was written to interact with the quantum computer and to generate these plots.

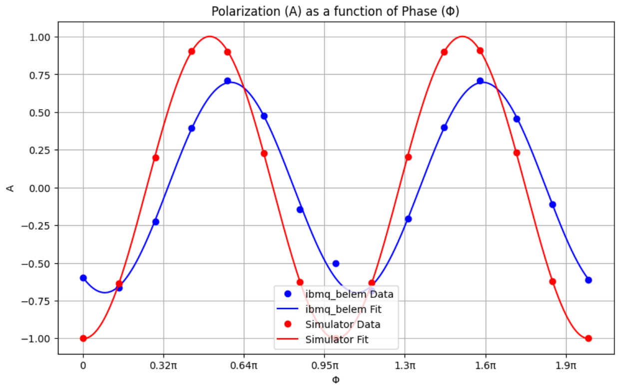

Fig. 7: The function A, which measures parity, was plotted as a function of ϕ. The data collected from the two-qubit interferometer on the quantum computer ibmq-belem at 15 different angles between 0 and 2π are shown as purple circles, while the data collected from the simulator ibmq-qasm simulator at the same angles are shown as green squares. The standard deviation of 5 trials is represented by error bars. The curves were fitted to the data using amplitude and offset as free parameters. Python code was written to interact with the quantum computer and to generate these plots.

will have a lower sensitivity compared with the simulator; this is because of the losses in the quantum computer measurements. In principle we could follow Eq. to calculate the LoD in both the plots. We will leave this for future work. At this point we have demonstrated the implementation of the Mach-Zender interferometer on a quantum computer.

VI. Example application with a surface plasmon resonance biosensor

Plasmonic surface biosensors can be integrated with the Mach-Zender interferometer as shown in Fig. 5. Such a setup can be used to model or simulate biosensing experiments which are applied to diesease detection. By using a quantum computer, we can simulate the phase measurement when different input states are used; these could be single-photon states, entangled multiphoton states, or squeezed states. In this example, the Krestchman configuration setup is integrated into a phase sensing setup. When the phase, ϕ, is measured such that $\phi = 0$, there is no binding reaction and therefore this would be a false or negative result in the context of disease detection; however, if the phase has a numerical value ($\phi \neq 0$) this would correspond to a binding reaction occurring on the surface of the biosensor implying that the analyte of interest is in fact detected and the sample would give a positive result in the context of detection of dieseases.

A. Phase based biosensor as a quantum circuit

In the interferometer, a photon is initially emitted from a monochromatic laser source, traveling towards the beam splitter. The starting direction of the photon corresponds to the quantum state $|0\rangle$. Upon reaching the beam splitter, the photon has a 50% chance of reflection, resulting in an equal superposition of the photon continuing along its initial direction (quantum state $|0\rangle$) and being reflected perpendicularly (quantum state $|1\rangle$). This process is equivalent to the action of a Hadamard gate on a single qubit. Following the beam splitter, each state acquires a phase proportional to the distance covered in the corresponding arm. Within a biosensing context, variations in the length of the two arms can be attributed to changes in the refractive index on the sensor surface. This altered refractive index, typically caused by target analytes binding to the sensor surface, leads to a phase difference ϕ between the two states, similar to the effect of an $R_Z(\phi)$ gate.

Once the photon is retro-reflected at the end of each arm, it passes through the beam splitter again, which is represented by another Hadamard gate. Subsequently, photons in the state $|1\rangle$ are detected, which means a computational measurement, Z. By examining this measurement, insights can be gathered into the changing refractive index and the presence of target analytes on the sensor surface.

In the SPR setup shown in Fig. 5, the measured phase can be used to study other parameters such as the intensity, refractive index, and angle of incidence. The relationship between the phase and reflectivity is given by the equation

$$\phi = i\ln(\frac{\mathrm{r}}{|\mathrm{r}|}) \tag{31}$$

where r, the reflectivity is a function of the refractive index on the surface of the biosensor and the incident angle of light to the biosensor surface. This work can also be extended to calculate the limit of detection of the setup.

VII. Generation of Entangled states with the Mach-Zender Inteferometer

It is worth mentioning that these particular experiments implemented on the IBM quantum computer with the single qubit and the entangled qubit system can be implemented on an optical setup. In this section we will discuss how a single photon source can be used to implement the same experiment and generate similar results. In optics these entangled states can be generated by coupling a single photon sources with a Mach-Zender interferometer. To generate an entangled state using a single-photon source and a Mach-Zehnder interferometer, you can follow these steps: Single-photon source: Start by preparing a single-photon source, which can be achieved using methods such as spontaneous parametric down-conversion (SPDC), where a non-linear crystal converts a single photon from a pump laser into a pair of lower-energy entangled photons. Mach-Zehnder interferometer: Set up a Mach-Zehnder interferometer, which consists of two beam splitters (BS1 and BS2) and two mirrors (M1 and M2). The interferometer has two input ports (A and B) and two output ports (C and D). Injecting the single photon: Inject one of the entangled photons from the single-photon source into input port A of the interferometer, and leave input port B empty.

First beam splitter (BS1): At the first beam splitter, the incoming photon will be split into a superposition of two paths, one going towards mirror M1 and the other towards mirror M2. This superposition of paths will create a single-photon state that is in a superposition of being in both arms of the interferometer. Mirrors (M1 and M2): The mirrors M1 and M2 will reflect the photons in each arm of the interferometer towards the second beam splitter (BS2). Second beam splitter (BS2): At the second beam splitter, the two superposed paths will interfere with each other, creating a new superposition of the photon in output ports C and D. The probability of detecting the photon in either output port C or D depends on the relative phase difference acquired in each arm of the interferometer. Entangled state: The other entangled photon from the single-photon source can be used as a reference to create an entangled state between the two photons. The entangled state will exhibit correlations between the two photons that cannot be explained by classical physics alone. When measuring both photons, you will observe correlations in their properties (such as polarization) that indicate entanglement. It is important to note that this method generates entanglement between two photons, not between two qubits within a single photon. The entangled state generated can be used for various quantum information processing tasks, such as quantum communication and quantum sensing.

VIII. Conclusion

In this work the authors show that phase-based biosensing experiments can be implemented in a Mach-Zender interferometer which can be simulated on a quantum computer. Simulating these experiments on a quantum computer allows researchers to study how a range of quantum states can be used to simulate the phase measured in a biosensing experiment and how this measured phase can be used to analyze the precision as a result of the different states. The IBM experience quantum computer is extremely useful in the simulation of biosensing experiments such as the quantum surface plasmon resonance experiment. In this work we see that using entangled states can generate better precision of the measured phase of our setup. Future work will look at the implementation of squeezing operations and how these can improve the sensitivity of our biosensors.

IX. Acknowledgment

We acknowledge the Council for Scientific and Industrial Research (CSIR) for funding this research.

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Towards a Digitally Transformed Criminal Justice System: A South African case study

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***Abstract*—The criminal justice system is a critical component of the South African government and its developmental and operational activities must be seamless to ensure timely delivery of justice to those who committed crimes. This study provides a glimpse into the current initiatives by the South African government towards a digitally transformed criminal justice system and conducts a gap analysis on these implementations, as well as highlights improvement opportunities. The study also proposes some of the technological paradigms (such as blockchain, 3D printing, digital twins, artificial intelligence and 5G) which demonstrate great potential to transform the South African criminal justice system. Last but not least, Estonia's digital transformation initiatives to improve the criminal justice system are presented to benchmark the South African justice maturity level. From our analysis, it was discovered that South Africa has made significant strides towards modernizing its justice system. However, there is still room to modernize the justice system further by leveraging emerging technologies. Notably, these modernization efforts may require lengthy legislative processes, which is likely to delay utilization of the digital solutions by the justice cluster.**

Keywords— Criminal justice system, South Africa, Justice and Protection Services, JPS, Artificial Intelligence, Blockchain, 3D printing, Digital Twins

I. INTRODUCTION

Over the last decade, South Africa's crime rate has steadily increased, with a slight dip of 8.5% observed in 2020 during major national lockdowns which were put in place in response to the COVID-19 pandemic [1]. Even though a slight decline was observed during lockdowns, the rate of homicide increased by 8.7% [1]. The increase in crime levels means that the criminal justice system (which constitutes court systems, law enforcement agencies, prosecutors, legal representatives and corrections) is overburdened by an influx of criminal cases which must be processed. Thus, it is critical to integrate smart digital technologies into the criminal justice system to enhance operational efficiency, ease of administration, and seamless coordination between different functions. Moreover, technology integration into the criminal justice system means better prospects of successful investigations and prosecutions and minimizes wrongful convictions.

This paper unpacks some of the major initiatives by the South African criminal justice system, locally known as the Justice and Protection Services (JPS), towards the digital transformation of the justice system. The current gaps and improvement opportunities are also presented including the specific transformative technologies, namely blockchain, 3D printing, digital twins and artificial intelligence, that JPS can consider in its quest for a modernized justice system. The paper also briefly highlights some of the major initiatives by Estonia (which ranks among the most digitally transformed countries) towards digitally transforming its criminal justice system. To the best of our knowledge, there is a lack of publications in the literature that review current digital transformation initiatives and maturity levels of the South African justice cluster, and this study aims to close this gap.

The paper is organized as follows: Section 2 gives an overview of the structure of the South African criminal justice system and chain of events, Section 3 highlights South Africa's initiatives towards a digitally transformed justice system and some shortcomings, Section 4 presents Estonia's digitalization efforts of its justice system, Section 5 presents new digital trends that can be used to enhance the criminal justice system, and lastly, Section 6 concludes the paper and highlights future work.

II. SOUTH AFRICA'S CRIMINAL JUSTICE SYSTEM

A. *Structure of South Africa's Criminal Justice System*

At the cabinet level, South Africa's criminal justice system is organized into one of five government clusters called the Justice and Protection Services (JPS), formerly known as the Justice, Crime Prevention and Security cluster (before cluster reconfigurations). The JPS cluster constitutes a total of 7 core ministries, namely the Police Ministry (locally known as South African Police Services (SAPS)), State and Security Agency, Home Affairs, Justice and Constitutional Development, Office of the Chief Justice, Defence Ministry (which is the Department of Defence), and Correctional Services [33]. JPS ministries work in an integrated pattern to deliver on the cluster's mandate of reducing crime, improving the efficiency of the criminal justice system, fighting corruption, improving border integrity, managing the population registration system and fighting against and preventing cyber-crimes.

At its core, JPS is about strengthening coordination between different ministries under its jurisdiction to streamline communication between said ministries to build safe, just, inclusive and resilient communities.

B. Criminal Justice Case flow

The criminal justice system constitutes four main events namely, (1) Initial entry into the system, (2) Prosecution and pretrial services, (3) Adjudication, (4) Sentencing and sanctions, and (5) Corrections. In South Africa, seven government departments, namely, Legal Aid South Africa, Department of Correctional Services (DCS), Department of Social Development (DSD), Department of Justice and Constitutional Development (DoJ&CD), Office of Chief Justice, National Prosecuting Authority (NPA), and SAPS, are involved in prosecution, adjudication, and sentencing, except for SAPS and DCS, who are involved during initial entry in the system and corrections, respectively. Fig. 1 gives a simplified view of the case flow through the criminal justice system.

1) Entry into the system: The trigger point of the criminal justice system is the reporting of a criminal offense by dialling 10111 or going to the nearest police station to report the crime. After a crime is reported, the police open a docket and an investigation into the crime commences, evidence is secured, and the accused is apprehended.

2) Prosecution and pretrial services: The docket is then submitted to the prosecution office which (in consultation with the grand jury) decides whether or not to prosecute the accused. If the verdict is to file a charge, the accused is taken before the judge for an initial appearance, who decides whether or not there is probable cause to detain the accused. At this stage, the accused is either detained or released on bail, own recognizance or supervision, while waiting for trial. In many jurisdictions, an initial appearance is followed by a preliminary hearing to determine if there is reasonable ground to believe that the accused has committed the crime they are accused of. If the judge does not find probable cause, the charge is dismissed. However, if the prosecution case is strong and sufficient evidence is presented, the case is bound over to a grand jury, which determines if there is probable cause for the charges. If enough evidence is presented, the grand jury submits an indictment to the court which schedules an arraignment for the accused. At the arraignment, the accused is asked to enter a plea to the charges.

3) Adjudication: If the accused pleads guilty, the case does not proceed to trial and the accused is sentenced during the arraignment proceedings or at a later date determined by the judge. If the accused pleads not guilty or guilty by reason of insanity, the case is scheduled for a trial. At the trial, the lawyers (both prosecutors and defense) present their case and all their evidence to the court.

4) Sentencing and sanctions: If the trial is decided by a judge, the judge decides if the accused is guilty or innocent. The guilty verdict must be given beyond reasonable doubt. The verdict can be decided by the judge independently or by a jury for capital offenses. If the accused is found guilty, the judge can order probation officers to conduct a presentencing investigation which is used to determine if there are extenuating circumstances which should influence the severity or leniency of a criminal sentence. After a conviction and presentencing investigation, the sentence is imposed and the accused is incarcerated. Other sentencing choices are available to the judge, such as the death penalty, probation, restitution, community service or boot camps.

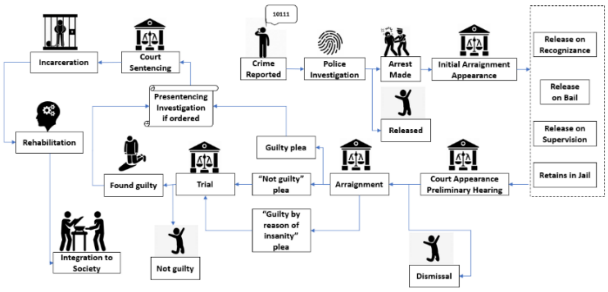

Fig. 1: Criminal justice chain of events

5) Corrections: Offenders sentenced to incarceration serve their sentence at either a local jail or a maximum-security prison. A prisoner may be eligible for parole after serving some of his/her sentence. If released by parole, the releasee will be under supervision by a parole officer for the remainder of their sentence. For successful integration into society, prisoners are encouraged to attend social reintegration programs, in-prison education, and vocational training.

III. Current Initiatives by the South African Justice System

A. The Integrated Criminal Justice System

The Integrated Criminal Justice System (ICJS) is an initiative by the JPS cluster designed to modernize and digitise the criminal justice system to enhance the operational efficiency and effectiveness of the justice system. This section presents some of the major initiatives under the ICJS and highlights some of the strengths and shortcomings of these initiatives.

1) Person Integration: The person integration project [2] constitutes initiatives for robust and secure identification, verification, authentication, and tracking of persons in the criminal justice system. Person tracking across the criminal justice system provides all authorised stakeholders of the justice cluster with up-to-date information regarding the location (in rehabilitation, incarcerated, released on bail and awaiting trial, acquitted, in parole, etc.), case status (investigation, pre-trial, trial, sentencing, etc.), case history, case handlers and criminal records of persons of interest.

JPS is also currently developing a Person Identification and Verification Application (PIVA) for secure identification of individuals by retrofitting multi-modal automated biometric identification and registration systems to their platforms, which use a combination of person identifying characteristics such a fingerprint, palmprint, facial and iris scanning, voice recognition, handwriting, and ear height. The use of multi-modal biometrics increases the scope and variety of input of identifying characteristics which minimises identity fraud and enhances identification accuracy. With PIVA, individuals are verified against the Department of Home Affairs National Identification System (HANIS) [2], which constitutes the identity and status information of all individuals within the borders of South Africa. PIVA has been successfully implemented by SAPS to verify the identity of detainees during the admission process and to provide verification services for SAPS operations at several airports. Another beneficiary of PIVA is the South African Social Security Agency (SASSA), which has integrated PIVA into its enrolment systems to combat identity fraud, which is quite prevalent in this vertical. PIVA is chiefly enabled by artificial intelligence (AI) technologies, such as natural language processing (NLP) [3], deep learning, and machine learning. An important requirement during biometric identification and verification is the high reliability of the AI algorithm as well as the security and reliability of the telecommunication link to the data centre(s) used to host the Home Affairs databases.

2) Integrated Case Docket Management System: JPS has made significant strides towards modernizing its case management by integrating an electronic docket (e-docket) management system to ensure seamless case information exchange between SAPS, NPA and DoJ&CD. The e-docket management system currently has a footprint in about 509 courts and 982 of 1146 police stations in South Africa. The system was designed to improve operational efficiency and to prevent dockets from being stolen, destroyed or manipulated [4]. Although widely deployed, the uptake of the e-docket management system, particularly by police stations, is rather slow [5]. To further enhance the security of the e-docket management system, JPS should consider integrating emerging technological trends such as blockchain [6] to fully tamper-proof the e-docket system. Blockchain is the technology behind Bitcoins and other crypto currents. It is a distributed network of servers, where information is securely replicated on all participating computers using cryptography. The main advantage of this technology is that it does not have central management authority, meaning that changes to the blockchain can only be consensually implemented by blockchain participants, making this technology tamper-proof.

3) Audio-Visual Remand (AVR): JPS has made significant investments towards courtroom modernization by integrating audio-visual technologies into their courtrooms and correctional facilities, which enable court proceedings, including witness testifying and language interpreting to be conducted virtually [7]. Using Audio Visual Remand (AVR), detainees at correctional facilities are tried virtually via a live video conference link to the corresponding courts handling their cases. This revolutionary system is both time-efficient and cost-efficient as it eliminates the logistics involved in transporting detainees to court. Additionally, the system also minimizes the possibility of escapes which typically occurs during transit from the correctional centre to the courthouse and vice versa. AVR has been very effective in curbing the spread of COVID-19 and in making sure that all court hearings and trials occur as scheduled, especially during major national lockdowns which restricted movement and physical meetings [8].

The main beneficiaries of this system are magistrates, prosecutors, attorneys, and lawyers, who can communicate with the inmates from the correctional services centres. Unfortunately, the AVR platform has only been rolled out at a few court complexes and correctional facilities. To date, there are only 46 AVR sites operational across the country [9]. An important requirement towards an effective AVR system is a robust telecommunication infrastructure optimised to provide very high bandwidth and ultra-low latency, to ensure ultra-high-definition live video conferencing during virtual court proceedings. Video quality and real-time audio and video transmissions are critical during court proceedings to capture the accurate witness' and defendant's accounts, and to detect deception and sincerity.

A common major challenge reported by most courts (especially those located in rural areas) is poor network connectivity [8], which causes audio stuttering and video buffering. 5G promises to cost-effectively offer capabilities such as ultra-low latency and high-bandwidth communications, capitalizing on advanced technologies which include, but are not limited to, massive MIMO (multiple-input multiple-output) communications [10], New Radio Frequencies [11], and Mobile Edge Computing [12], for the last-mile infrastructure, and Software Defined Wide Area Networks (SDWAN) [13] and Network Function Virtualization (NFV) [14], for the core networks and data centre networks. It would thus be prudent for the government to start exploring optimal ways to integrate these new technologies into the telecommunication infrastructure to cost-effectively support bandwidth-hungry applications such as AVR.

4) The Paperless Estates Administration System (PEAS): DoJ&CD has made significant progress towards the implementation of its paperless working environment initiative by successfully rolling out the Paperless Estates Administration System (PEAS) at about 15 Master Offices [15] and 280 magistrates' service points across South Africa. The service points are linked to the master offices, which oversee the appointment process to ensure that all South Africans receive the same quality of master's services, without travelling long distances to the 15 Master's Offices [16].

PEAS is used by the Master's Office to capture the deceased's estate information and to manage case workflows. The main objective behind the development of PEAS is to improve service delivery and time management by the Master's Office as well as to strengthen document security and retention and generate an automatic audit trail of all actions performed on the system [17]. The main drawback of PEAS is that the original documents are received by the Estate Controller as hard copies from the applicants and forwarded to what is called a "Scanner Clerk" who scans the documents to generate electronic copies. As a result, the system is not as environmentally friendly and calls for further digitization efforts. Moreover, there are stringent confidentiality and security requirements as it pertains to estate documents. Blockchain is a promising solution which could be leveraged to create distributed ledgers of tamper-proof estate documents.

5) The Court Recording Technology (CRT): JPS has successfully implemented and operationalized a digital audio recording technology in over 1900 courts in the country. This technology is used to record court proceedings (such as trial, or pre-trial hearings) for review and playback during court sessions and to address future transcription needs [2]. The court recordings are automatically sent via a secure link to local and national servers for safekeeping. The drawback of CRT is that it still requires manual transcription efforts, which is a time-consuming exercise. Moreover, the lack of automatic transcription capabilities makes CRT very costly in terms of internet bandwidth. This is because to access transcripts, the attorney, litigant, journalist or member of the public, has to apply to the clerk of the court for a copy of the transcript for a specific trial or court hearing. The clerk of the court then has to locate the recording and send the downloaded files to transcribers for speech-to-text conversion. As a result, the processing times of the transcripts are very extensive, depending on the length of the recordings and the backlog of applications for transcripts. According to transcribers, the processing time ranges between six weeks to two months for an average transcription, excluding the time it takes to courier the transcripts back to the court [18].

The transcripts delivery format is still paper-based requiring the applicant to physically collect the transcripts from the court which is both time-consuming and costs money. There is an opportunity to integrate automatic transcription capabilities into CRT leveraging AI and NLP. Such technologies have already been tried and tested in various court settings and have demonstrated great accuracy and efficiency. For instance, the CourtSide [19] software application can create verbatim transcripts in just a matter of seconds for audio recordings and minutes for video recordings. Another industry contender is CourtAudio [20], which is capable of delivering automated transcription in almost real-time. For video recordings, biometric recognition (such as facial recognition) is used to ensure accurate identification of various speakers during the proceedings [21]. Moreover, instead of archiving the entire audio or video recording in data centres, edge computing can be implemented for automatic transcription at the edge of the network (closer to where the recording was made) which will ensure better utilization of the broadband infrastructure and ensure cost savings on storage services. In other words, instead of storing audio and video recordings both of which require more storage resources, only the transcribed files are stored which require less storage capacity.

6) MojaPay: During the 2016/17 financial year, DoJ&CD successfully rolled out a financial management system called MojaPay, intended to address the accounting and service delivery challenges, and inadequate management and administration of third-party funds (such as child maintenance funds and deceased estates) [12]. Unfortunately, the system recently suffered a ransomware attack which denied access to all services making it impossible to pay maintenance and estate beneficiaries. This incident shone a painful spotlight on the cybersecurity maturity of government IT systems. There is an opportunity to further enhance the security posture of government IT systems by staying abreast of increasingly sophisticated cyberattacks and proactively innovating antidotes to these potential attacks. AI (machine learning and deep learning) and blockchain present a vast transformative potential to improve cybersecurity in government IT systems by enabling automatic cyberdefense [19, 22].

IV. Estonia's Digital Transformation for the Criminal Justice System

Estonia has developed a single central database architecture called E-File that integrates different information database systems (such as the police information system, court information system, jail's information system, and criminal case management registers) of the criminal justice system, to enable parties of the legal proceedings (victims, witnesses) and their representatives to electronically submit their cases and related documents and to observe the progress of their cases online [23]. E-File enables different departments within the criminal justice system to digitally exchange criminal case information and procedural acts, and to manage the progress of cases across the justice system, making it easier to digitally monitor the performance of different departments and to identify bottlenecks for accountability purposes. Moreover, E-File is equipped with a zero-touch case allocation module, which allocates a case to a judge based on their capacity and specialist knowledge to ensure a more balanced distribution of caseload for optimal utilization of human resources. Blockchain is integrated into this database to enhance resiliency, transparency, and security.

Despite all these digitization efforts, the court hearings and all other parts of the criminal justice system of Estonia still use paper documents. This is because, in Estonia, paper documents are legally considered to be the original documents and electronic documents are considered null and void during formal proceedings. The electronic documents are only accepted during the online case filing. Estonia has also invested extensively in cutting-edge audio-visual technologies and speech recognition technology capitalizing on AI to streamline the transcription processes at different stages of the criminal justice chain of events [24]. In this study, Estonia was chosen as the benchmark due to its reputation for growth and success in leading digital transformation initiatives, which is largely attributed to the government's political willingness to offer more convenient public services. The government has taken necessary steps, such as implementing innovative policies, making changes to policies and laws, introducing the required regulations and making investments to drive and expedite digital transformation [32]. This highlights the possibilities of the extent of digital transformation South Africa can achieve if a proactive approach is taken by the government by spearheading these efforts.

V. Other Opportunities Based on Current Digital Trends

This section highlights the current technological trends with a vast transformative potential for the criminal justice system. These technologies include blockchain, 3D printing, digital twins, artificial intelligence, 5G, robotic process automation, and augmented and virtual reality. Other governments have been successful in integrating these technologies into their criminal justice system.

A. Blockchain

Blockchain has already entered judicial structures as a tool for the management and storage of sensitive legal documents (dockets, sex offender registries, evidence documents, land registries, civil registries, criminal records, etc.), to provide operational efficiency (through automated workflows) and document security, while increasing accountability and transparency [25, 26]. China has successfully integrated blockchain into its community correction programs for real-time location tracking of parolees and sex offenders [27]. Another application of blockchain is to tamper-proof videos taken by police body cameras, which usually provide crucial evidence of alleged police misconduct [28].

B. 3D Printing

3D printing, also known as additive manufacturing, is the construction of 3D objects from a digital file or computer-aided design (CAD). This technology is superior to traditional casting methods because of its great accuracy and speed of construction. With 3D printing, objects can be scaled up to make small features more visible, or conversely, scaled down to make the object more portable. In the context of the criminal justice system, 3D printing has been widely adopted to recreate detailed models of crime scenes, fingerprints, facial reconstruction and weapon reconstruction. For instance, Hong Kong law enforcement is using 3D printing to make crime scene models, which helps them understand the crime and build stronger cases. Law enforcement agencies in Ohio and New York have been successfully using 3D printing to solve cold cases (some of which are a decade old) and preservation of evidence, by using facial reconstruction on top of 3D models of badly decomposed skeletal remains [29, 30]. The remains are considered evidence, and thus, forensic artists cannot build on top of them, making 3D printing the ideal alternative.

C. Digital Twins

Digital twins are the next big thing in the fourth industrial revolution for the development of new products and services. This technology uses real-time data collected from IoT sensors, along with AI and software analytics, to create a digital copy of an asset (such as a process, product or service) to optimize the performance of the asset before real deployment. Digital twins have traditionally been used to optimize manufacturing processes. However, this technology has started to extend beyond the factory floor and is penetrating other industry verticals such as healthcare, construction and justice and protection services. Some of the use cases of digital twins in justice include creating forensic digital twins [31], which essentially is the simulated replica of crime scenes used to test theories and hypotheses with changing environmental factors. This ultimately improves crime investigations and prosecution. Another benefit of forensic digital twins is that it helps with the digital preservation of crime scenes for as long as a case remains relevant. Digital twins are also gaining traction in public safety where data models are used to create live digital blueprints of cities to achieve real-time visibility of cities which enables better response to emergencies.

VI. Conclusion

This paper highlights the current activities of South Africa's Justice and Protection Services (JPS) cluster towards a digitally transformed criminal justice system and provides visibility of what is happening in the cluster. It also closes the gap where a lack, of publications in the literature that review current digital transformation initiatives and maturity levels of the South African justice cluster, was identified. The paper also presents current technological trends (such as 3D printing, digital twins, artificial intelligence, and blockchain) that have transformative potential for the justice system. From our review, the JPS cluster has made significant strides towards modernizing the justice system to tackle the most time-consuming and menial tasks and has found solutions to replace these with automated systems. Most of the transformation efforts by the cluster are towards a paperless integrated criminal justice system to improve operational efficiency and the quality of justice services provided to the citizens. However, there is still room to improve the current initiatives through the adoption of intelligent technologies. For instance, the e-docket and estate administration system can potentially benefit from blockchain technology for security enhancement, while the court recording system and MojaPay can be improved by integrating AI and NLP for automatic transcription and security respectively, lastly, the audio-visual remand needs a robust telecommunication infrastructure, which can potentially be achieved using 5G and SDWAN technologies.

The paper also highlights some of the major initiatives by Estonia towards the digital transformation of its justice system. The country has made significant investments in the digitisation of its criminal justice system through the implementation of the E-File system. Unfortunately, the adoption of this system is quite limited due to stringent legislation which requires paper-based court proceedings. It is important to note that changes to the existing criminal justice system may require lengthy legislative procedures, which warrants a thorough and targeted analysis of the legislative implications of adopting each of these digital technologies and an in-depth and detailed study of each of these technologies. This paper is a first step towards such an analysis.

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***Abstract*— Many organizations are exploring the options of modernizing their mainframe systems instead of completely moving away from the mainframe environment. Mainframe modernization unlocks the benefits of becoming more agile and responsive through the adoption of modern technology features in the current disruptive business environments without engaging in complete cloud migration. However, many CIOs struggle to develop modernization strategies and plans that best capitalize on their desired benefits. This ultimately led to modernization effort failures, cost overruns, and delayed schedules. This study provides valuation information for developing a complete mainframe modernization strategy and plan. It provides factors to consider before embarking on a modernization journey. The study also examines various modernization approaches as a component of the modernization strategy by looking at ease of implementation, time and impact on cost and business processes. Lastly, trends in mainframe modernization initiatives are also presented. It is observed that many organizations opt for encapsulations and rehosting approaches for their affordability and ease of implementation.**

Keywords—mainframe, modernization, trends, strategy

I. Introduction

To date, mainframes still occupy an important place in the e-business environment and play a central role in the daily operations of many of the world’s largest corporations in, for example, banking, finance, insurance, public entities, government, and many other public and private enterprises. Thus, mainframes form part of the mission-critical systems of these enterprises and have been extended over many years to support business processes or, at times, business processes have been modified to function with the mainframes systems [1]. According to Accenture analysis [2], critical business logic and data remain on mainframes with 92% in insurance and banking and 72% in retail industries. Even though mainframes have proven to remain robust, resilient, reliable, and secure, they do not match cloud-native technologies in terms of agility, scalability, and cost-effectiveness as required in today’s disruptive business environments [2].

Additionally, proficient and experienced professionals with the technical skills required to maintain mainframe systems are becoming scarce. Therefore, skills, cost considerations and the need for flexibility and agility impact the viability of mainframes as the long-term technology solution. This is one of the reasons many organizations are evaluating the option of migrating from mainframe systems to the cloud. However, the migration process has high risks that could lead to devastating consequences as there is no room for error when migrating. Any outage during migration has the likelihood to disrupt mission-critical operations. Hence, many organizations are considering to modernize their mainframe environments instead of migrating to the cloud altogether.

As summarised in Table 1, In the IT domain, the concept of mainframe modernization can vary in interpretation among various individuals [3].

TABLE I. Different Perspectives on the Meaning of Mainframe modernization [3]

Profession	**Perspective on the meaning of mainframe modernization**
Chief Technology Officer	Respond to business needs faster by delivering new features and incremental updates to existing features more quickly
Customer experience officer	Open up new experiences for clients in a way that fuels growth, expands market share, adds value to their clients and increases customer loyalty
Chief financial officer	Maximize the return on investment in the use of the mainframe and the surrounding system by increasing value without increasing expense.
Enterprise Architect	Integrate various technologies, platforms, and applications across the enterprise seamlessly and in a transparent manner
Infrastructure Architect	Use new technologies and features to ensure the highest levels of reliability, availability, and simplification.
Security Architect	Ensure the highest levels of security and data privacy by using new ways of protecting enterprise data and monitoring access
Application architect	Make it easier to use products and services on the platforms of choice and simplify the application designs.

According to Huskin [4], mainframe modernization is a process of upgrading and adapting the legacy mainframe system footprint in several aspects, such as interface, code, performance, maintainability and cost to deliver better business value, be more agile, and be responsive to customers’ expectations. We are of the same view and thus, this paper adopts this definition of mainframe modernization. Mainframe modernization is about scrutinizing these three areas of the mainframe: the application, infrastructure, and processes. Application modernization focuses on changing the applications(apps) for the better to support new user needs and business functionality [3]. Infrastructure modernization focuses on making the mainframe apps available wherever the business needs them. On the other hand, process modernization focuses on the “how” part of providing the means of creating and updating systems themselves (i.e., the processes) and ensuring that the business can respond to the needs with speed and accuracy. Therefore, mainframe modernization is about optimizing the mainframe infrastructure, applications and processes without disturbing the core business operations. It is a way to unlock the value of data residing in the mainframe system, while at the same time, paving the way to transform applications with new digital capabilities.

Although digital transformation has been the core motivation behind mainframe modernization to enable mainframes to incorporate the latest technologies, Covid-19 has fuelled the need to accelerate mainframe modernization initiatives. For example, due to the global pandemic, the government sector has realized that delaying modernization programs is no longer an option [5]. For instance, as part of the COVID relief proposal, the US government emphasized the launch of efforts to modernize its legacy systems and networks [6]. The UK government announced that it will increase opportunities to include modernizing digital technology in its planning system [7]. It is not only the government sector that came to this realization, but other organizations at large. According to the 2021 barometer report on mainframe modernization [5], 78% of organizations have started at least one modernization program as a result of the pandemic. However, the report further reveals that 77% have started but failed to complete at least one modernization program. This figure increases up to 84% for government organizations. Some of the failures are attributed to a lack of relevant skills, a lack of understanding of available options and evaluation of modernization solutions, poor planning, lack of funding, and commitment from leadership teams due to fear of change [6]. For government organizations, failures are mostly attributed to that, they are generally forced to evaluate and qualify modernization programs based on the request for pricing (RFP) processes than on successful demonstrated solutions.

Each organization is unique and when it comes to mainframe modernization, there are a variety of options available. Choosing or developing a modernization strategy depends on the issues an organization would like to address and the enhanced capabilities it will like to add. Therefore, conducting a holistic assessment of the mainframe system is necessary to determine which modernization strategy will work best for an organization. Understanding the strengths and weaknesses of each of the available modernization techniques is vital for selecting a relevant modernization solution and for the overall success of a modernization effort [8]. However, many organizations, more especially government organizations, struggle with the pressure to modernize their mainframes and find it difficult to answer the question of which modernization strategy best capitalizes on their desired benefits [5]. Furthermore, GOA found that most government entities do not have a complete plan and strategy for modernizing their critical legacy systems [9].

This paper unpacks aspects necessary to develop a mainframe modernization plan and strategy. It examines a range of approaches available to modernize mainframes, and the challenges that come with each modernization approach, and presents key trends as adopted in mainframe modernization to provide key inputs to a successful modernization strategy. We adopt an exploratory research method using a literature review and observations from the industry (by seeking the understanding of techniques and trends for mainframe modernization) to explore techniques used for mainframe modernization.

The main contribution of this research paper is to document activities necessary to aid government entities to establish plans and strategies that identify and describe work necessary to modernize mainframe systems. Complete plan and strategy to avoid the likelihood of modernization programs failures, cost overruns, schedule delays and overall project failures.

Section 2 of this paper reviews related work. Section 3 provides the mainframe modernization journey. Section 4 concludes this paper.

II. Related Work

Mainframe Modernization is a task, which occurs frequently in industrial practice. The commercial market provides a variety of ‘general’ mainframe modernization solutions, but their solutions do not focus on gaining a profound understanding of users’ pain points to define correct assumptions for a relevant solution. Various reviews on modernization approaches exist in the literature. For example, Comella-Dorda et.al. [8] surveyed legacy system modernization techniques focusing on the user interface, data and logic modernization to provide the strengths and weaknesses of each technique. Baghadi & Al-Bulushi [11] describe a modernization framework for selecting a technique for wrapping legacy applications to web-based service-oriented architecture. Their work provides a review of different wrapping techniques as well as a practical application approach to implementing a wrapping solution. However, their study was limited to wrapping techniques.

Most of the research on modernization has studied different methods based on Service Oriented Architectures (SOA) for application modernization [12, 14]. Even though there exist several literatures that provide available techniques for modernization, there is no work that provides an understanding of the changes in both business and technology which is required for developing/choosing a successful modernization strategy. Thus, this paper aims to explore and examine options available for modernizing mainframes focusing on the impact of each option on business and technology. The key research questions that this paper attempts to answer are:

- What are the key factors to consider before embarking on the modernization journey?
- In the era where cloud native developments are considered the new standard, what are the available options for modernizing mainframe environments to transform and align with the future?
- What are the key trends in mainframe modernization?

III. Mainframe Modernization Journey

This section presents approaches and valuation information concerning mainframe modernization. The first subsection presents the key aspects to consider for developing a mainframe modernization strategy and plan. It deals with the research question: What are the key factors to consider before embarking on the modernization journey? The second subsection explores the modernization approaches as part of the key component in a modernization strategy. It answers the question: in the era where cloud native developments are considered the new standard, what are the available options for modernizing mainframe environments to transform and align with the future? The third subsection provides the key trends adopted for modernizing the mainframes based on the observed modernization initiatives from industry.

A. Key factors to consider before embarking on the mainframe modernization journey

Research has proven that the risks to holding onto legacy mainframes are many (e.g., high costs, lack of innovation, agility) but modernization is also not easy or cheap. Also, the mainframe modernization journey takes time and should not be pursued solely for modernization. It has to be part of the organization's overall strategy and that strategy must align with business strategy too. Furthermore, modernization is not only about having a set of right technical tools and technical expertise, it is about skills, culture, business process and technology change. Therefore, the strategy should address all these aspects. According to [13, 16], the following, as depicted in Fig. 1, are the best industry practices to follow when developing a modernization strategy.

Review architectures and Identify mission-critical applications. As a primary step, identify and list all high-value assets and assess their business value, criticality, and determine opportunities to modernize, to benefit from better security, scalability, and performance. Architecture and infrastructure elements, performance, and Return on Investment should be reviewed to assess where new technologies can deliver better outcomes. From this assessment, it should be clear what each architecture, application and its interdependencies, and infrastructure element does, what problems and opportunities it presents, its maintenance costs, and how it could benefit from modernization. Thus, as an output of this step, the requirements and the problems to be addressed by modernization, as well as the target state of the mainframe environment should be clearly defined. A first step to successful modernization is possible if the problem to be solved is clear and well-defined.

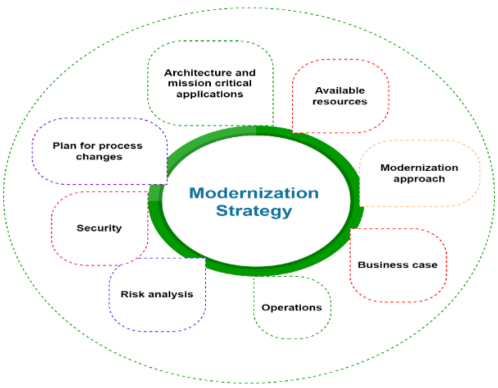

Fig. 1: Components of a modernization strategy

Consider available resources. Because modernization is a transformation effort, leaders who possess granular detail about the mainframe environment should be identified to guide the modernization efforts. This should also include the identification of skillsets within the mainframe environment team. The team's skillset must be utilized to understand the modern mainframe modernization methods and how the team can support the modernization goal.

Decide how to approach modernization. A relevant modernization approach that aligns with the organization's requirements and needs should be defined. Various approaches (as covered in the next section) should be explored to identify the best approach that meets all the modernization requirements.

Devise a convincing business case. Evaluation of spending should be performed to find budget burdens and ways to optimize resources to support current operations and prepare for the modernization journey. The budget should be approved to ensure financial support and commitment to the modernization journey from business.

Operations. New skill sets, training, and processes need to be determined and factored into the modernization costs. This should align with the operations of the modernized environment.

Risk analysis. Possible disruptions to the business and impact on business processes and organizational culture against the desired outcomes of modernization should be identified and evaluated. The risks of keeping the mainframe environment as-is should also be analysed and evaluated against the risks of modernizing. The risk of failure should be mitigated.

Devise a Security plan. Avoid data loss, outages, or exposure by devising a security plan that defines methods to protect systems before, during, and after modernization. The security plan should confirm adherence to governmental and industry compliance with regulations in the modernized mainframe environment.

Plan for Process changes. As reported in the 2021 barometer report on mainframe modernization [5], and the GAO report [9] most organizations lack complete plans and strategies to modernize their legacy systems. This could lead to schedule delays, modernization project failures as well as cost overruns. Therefore, after considering all of the factors above, organizations must define efficient project plans and be intentional about the specific problems they intend to solve. The plan should address the initiation date of the modernization effort, the resources required as well as management of risks that could delay successful execution and lead to project failures. Additionally, organizations need to look to their peers, understand the trends for mainframe environment modernization, adopt best practices, and collaborate with people who understand the modernization journey to enhance mission outcomes.

Track performance improvements. Modernized infrastructures, processes, and applications have several breakpoints. Therefore, post the initial mainframe modernization phase, applications, infrastructure, and processes have to be monitored to ensure quality performance and examined for issues and errors to understand the impact on end-user performance or business continuity. This will aid in determining areas which need further optimization.

Although these factors are important they do not represent everything that must be considered for the mainframe modernization journey, as per the summarized industry practices on modernization [15, 18]. They will positively help to steer your organization toward achieving success during the modernization journey. The following section describes various approaches employed for modernization approach.

B. Mainframe modernization approaches

When an organization has decided to embark on modernizing its mainframes, it needs to determine the best way to do it. Generally, from a high-level view, there are two modernization options: (1) to abandon the existing mainframe and develop a new system from scratch or (2) to rebuild from what you already have. Although, sometimes it is a viable option (for example, when your mainframe is overloaded and security risks are unavoidable), the first option comes with high costs and risks. Therefore, it is mostly not preferable. The second option, on the other hand, involves steady improvements that allow for flexible changes with manageable risks and without service downtime. It is mostly the best option when the current mainframe system is still working but not as competently as it could.

According to Gartner, there are seven modernization approaches [19]. These approaches fall under the 'rebuild what you already have' category. As illustrated in Fig.2, these approaches are ranked based on ease of implementation, time, cost, and impact on business processes.

Encapsulation through Application Programming interfaces (APIs) is the simplest approach. This approach enables the support of both the on-premise and cloud-based applications by adding an API transaction layer on top of the mainframe system. The API layer enables bidirectional communication between the mainframe and cloud-native applications and thereby abstracting complexity between the modern cloud environment and the mainframe system [20]. Although using this approach will not enable the benefits of technology advancements and hardware flexibility, it is ideal if your mainframe code is well-written and well-maintained. Therefore, it enforces one to build information flow and maintain the structure of software separation. It is easier and quick to implement and has a low impact on business processes and fewer risks.

Rehosting is about moving some parts of the mainframe system to another physical, virtual or cloud server to leverage the cloud technologies. There are a couple of options available within this approach, namely, the hardware emulation, which focuses on replacing the mainframe's hardware with an emulator while the operating system (OS) and its applications remain unchanged with no need to recompile the source codes [21]. The middleware emulation focuses on emulating OS APIs and middleware APIs while the source codes are recompiled. The rehosting approach is ideal for resolving scalability issues as it allows for the addition of new features and more users. However, by adopting this approach, old issues are inherited because the same codes are used in the new hosting system.

The **replatforming** approach is used to move applications to a new run-time platform. It allows for code to be changed for adaptation purposes but the code structure, functions, and features remain unchanged. As with the hosting approach, replatforming doesn't make changes to the code itself, and therefore, the same problems as before replatforming remain. The good thing is, replatforming only the core functionality will enable you to keep business processes running while getting some time to work on other parts of your platform.

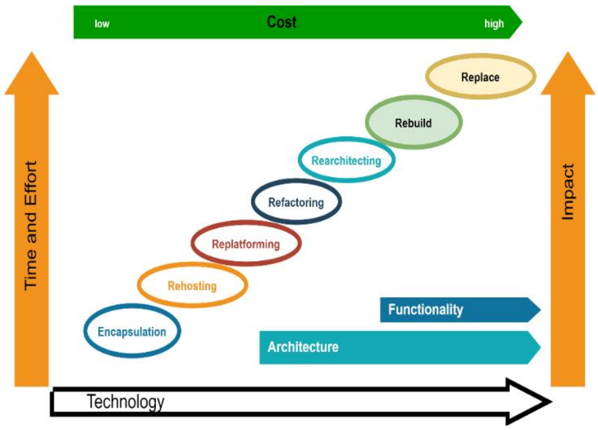

Fig. 2: Modernization approaches [19]

The **refactoring** approach is about optimizing and restructuring existing code without changing external behaviour. The main purpose of refactoring is to make code simpler, readable, and maintainable, and remove excessive and redundant code. Refactoring is ideal for removing technical debt, and to improve features and structure of components [22].

The **rearchitecting** approach deals with materially altering the application's code to transfer it to new application architecture with better capabilities. With rearchitecting, the mainframe system is first separated into layers. Layers that would benefit from being migrated or integrated into new features are then recoded and modified. For example, if data breach is the issue, then data alone can be moved to a secure platform and the rest of the system remains unchanged.

The **rebuild** approach is about building or writing an application or its components from scratch using new languages and technology stacks while keeping the scope and specification of the application unchanged.

Replace approach is about replacing components of the mainframe system that don't work or building a new system from scratch. This can be achieved by either developing the new system or component in-house to provide for new requirements or choosing a third-party cloud-based solution. This approach is mostly an option when all of the above-mentioned approaches won't work. According to [23], the replace approach is considered very risky and prone to failure but has the potential rewards of massive improvements to your application's behavioural components. Also, building a component by yourself ensures that you have exactly what need.

Choosing the best modernization approach depends on the problem one is trying to solve. Therefore, the best approach should solve the issues at hand and have desired effect and value in terms of technology, architecture, functionality, cost, and risk.

C. Trends in the mainframe modernization efforts

This section reviews key trends based on modernization initiatives that businesses have invested in. These initiatives focused on modernizing mainframes environments to enable a platform on which the enterprise's valuable data are leveraged for new business insights, customer applications and product innovations.

According to [24], most organizations have invested in modernizing the legacy mainframes by adopting approaches such as encapsulation and rehosting, thereby, adding modern functionalities instead of replatforming. Replatforming is viewed as being more expensive as it involves new on-premise hardware and or/ public cloud instances. Even though there are many initiatives which focused and invested in different things, such as, to mention few, new mainframe hardware/software, the use of modern mainframe tools, the use of Linux/open source, microservices or containers, and DevOps & agile, according to the IDC whitepaper [24], the following are the top three functionalities that businesses invest on for modernizing mainframes by adopting either encapsulation or rehosting approach [24].

Artificial intelligence (AI). More organizations are increasingly investing in their abilities to train AI algorithms by enabling mainframe applications with inferencing capabilities on AI and thereby leveraging new capabilities to move their business toward the intelligent enterprise.

A hybrid cloud is perceived as the 'enabler' or a prerequisite of all other modernization initiatives. Thus, organizations are increasingly enabling the use of mainframe data in the cloud while keeping the data on mainframes for security and regulatory reasons.

Internet of Things. Initiatives in this category have invested in mobile enablement and the use of IoT technologies on the mainframe platform. Focus is put mainly on incoming data volumes from edge devices. Incoming data streams are consumed, analysed, and leveraged for real-time decision-making.

As a result of the modernization initiatives on mainframes, it was reported that organizations were able to run more cost-efficiently while growing their businesses [24]. By understanding the trends and modernization initiatives of other peers, organizations are armed with the necessary information that is relevant for making informed choices about their modernization journey and thus become aware of the available options.

IV. Conclusion

This paper has highlighted valuable information on aspects necessary for developing a successful mainframe modernization strategy. The paper described factors to consider before embarking on a modernization journey as well as, various modernization approaches to evaluate for devising a relevant modernization approach. From our review, it is evident that it is possible to embark on a successful and fruitful modernization journey if organizations are meticulous about their modernization strategy which adequately covers plans and problems they are striving to solve. Also, it was noted that each modernization journey is unique for every organization. Therefore, the key in choosing a relevant modernization approach is to weigh all options to determine the extent to which each will have the desired effect, with minimum effort and maximum positive impact. It is also evident that the strategy has to be approved and supported by the business before embarking on the journey to ensure commitment and avoid modernization efforts failures.

The paper also highlighted the trends in mainframe modernization efforts as invested by different businesses. It was noted that most organizations have invested in adding more modern features to their existing mainframes, instead of, replatforming and ultimately moving away from the mainframe's environment.

This paper is a step towards providing necessary information and guideline for answering the question faced by many CIOs of private and public entities: 'Which modernization strategy best capitalizes on their desired benefits'. For future work, evaluation of trends in specific mainframe modernization technologies adopted by different initiatives is necessary. Such information will equip decision-makers on technologies to adopt to align with the future.

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Reinforcement learning as a force multiplier

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***Abstract*—Humankind has created and used tools since the dawn of time. These tools have subsequently increased in both complexity and value, providing a distinct competitive advantage to both the builder and user of these tools. Reinforcement learning (RL), as a tool in the hands of the South African National Defense Force (SANDF), can be a force multiplier. RL is particularly good at making optimal, sequential decisions under uncertainty, as illustrated using the 2048 game. The implication is that the SANDF can gain operational insights from its own data, which would otherwise require a much larger and technically educated workforce. These insights, if used to their advantage, would strengthen the capability of the modern South African soldier.**

Keywords—reinforcement learning, optimal sequential decisions, uncertainty, 2048 game, insights, force multiplier, SANDF, South African National Defense Force.

I. Introduction

The manufacture and use of tools is ubiquitous in human culture today. From the dawn of time, humans have made and used tools to gain a competitive advantage for our own survival in diverse and crucial activities, for example agriculture, politics, economics, and warfare. As our world became more competitive, these tools became more complex and the margin of advantage ever smaller.

In the present information age, the global battlespace is about data and insights. Machines that can learn insights from data are already providing competitive advantages to those pioneers who have harnessed the power of *artificial intelligence* (AI). According to Forbes, the global AI market is expected to reach $15.7 trillion by 2030 [1]. Not surprisingly, machine learning (ML) is being used productively in a wide range of domains such as agriculture [2], politics [3], economics [4], and warfare [5][1].

South Africa has a rich history of technological innovation and adoption, given the profound role that science and technology has played in shaping South Africa's history [6]. However, it has been widely reported that the SANDF lacks sufficient levels of funding and skills [7]–[9] especially in cybersecurity. This researcher suggests that the adoption of RL in the SANDF will act as a force multiplier, especially considering the present financial and skills shortages.

This paper introduces RL, demonstrates the use of RL in a sequential decision problem (SDP), and presents conclusions from the evidence to support the argument for the adoption of RL, by the SANDF, as part of its strategic skills development and force preparation plans.

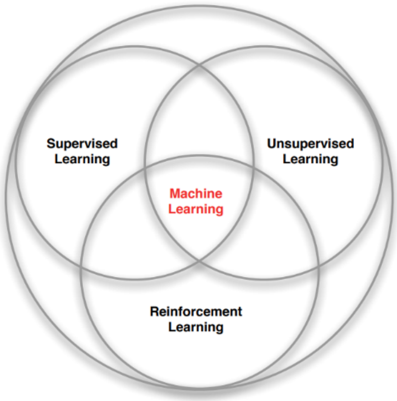

Figure 1 - Three branches of machine learning [10]

II. Reinforcement Learning

ML consists of three branches viz., supervised learning, unsupervised learning, and reinforcement learning (Figure 1). <u>Supervised learning</u> is learning "*from a training set of labeled examples provided by a knowledgeable external supervisor*", whilst <u>unsupervised learning</u> is about "*finding structure hidden in collections of unlabeled data*" [11].

RL is very different from its two older siblings and it is responsible for some of the most recent and important breakthroughs in AI and ML; such as super-human performance in speech & image recognition [12], playing board games like "Go" [13], and driving *driverless* cars [14].

IBM's victory over Gary Kaspersky [15], used massive computational power and smart human encoding to defeat the reigning chess grand master. RL does not rely on human knowledge, but rather learns from scratch through trial and error by maximizing the reward signal it receives.

In RL an agent in state S_t interacts directly with an environment (Figure 2) by taking a random action A_t which influences the environment internally and yields a positive or negative reward signal R_{t+1} and puts the agent into a new state S_{t+1}. In this way, the agent *learns* what works and what does not work.

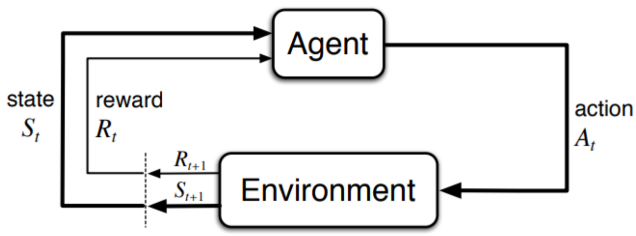

Figure 2 - Reinforcement learning agent and environment [11]

[1] This is not a comprehensive list.

By making tradeoffs, between *exploiting* optimal actions it has already learned and *exploring* sub-optimal actions that it has not tried yet, the agent obtains reward signals that help it make better action selections in the future. If the agent trains for long enough in this manner, it will learn an optimal sequence of actions called the *optimal policy* [11].

III. A SEQUENTIAL DECISION PROBLEM

Making decisions under uncertainty is a common activity and occurs in a vast range of problem domains, spanning more than a dozen distinct communities. Despite this, the core task of solving a sequential decision problem (SDP) remains the same; viz., selecting the optimal solution by optimizing selected metrics over time. Sequential decision analytics (SDA) is the field focused on solving these problems.

A. A Mathematical Model

More formally, an SDP can be written as [16]:

$$(S_0, x_0, W_1, S_1, \ldots, S_t, x_t, W_{t+1}, S_{t+1}, \ldots, S_{n-1}, x_{n-1}, W_n, S_n)$$

Where:

- S_t is a **state variable**, representing the state of the system at time *t*. S_0 is the initial state and S_n is the final state at the computational horizon after *n* iterations. It describes what we need to know about the system at that time.
- x_t is a **decision variable**, representing a binary, discrete, continuous, or categorical decision, made using a *policy*[2] $X^\pi(S_t)$ and the assumption that $x_t = X^\pi(S_t)$ is feasible at time *t*. The policy 'function' π, with tuneable parameters θ, determines the decision.
- W_{t+1} is any **new information** that becomes known at time *t+1*. This may be stationary, nonstationary, exogenous, or state-/decision-dependent information. The distribution of W_{t+1} may be a known mathematical model or data driven (i.e., observations from an exogenous source) with $W_{t+1}(S_t, x_t)$ depending on the current state and decision.

Additionally, we there are two important functions that are central to an SDP:

- **Transition function** $S_{t+1} = S^M(S_t, x_t, W_{t+1})$ such that the next state is a function of the current state, decision and the new information that becomes known as a result.
- **Objective function** $C_t(S_t, x_t)$ which is the contribution made because of decision x_t and the information in state S_t.

Powell [17],[16] demonstrates that *any* SDP can be modelled using this *universal framework*. He supports his argument with an observation that despite a fragmented effort across 15 research communities, 8 different notational systems, and overlapping algorithmic strategies, these different areas of practice have in fact independently developed common approaches to solving SDPs.

A key contribution of Powell's universal framework is the designing of the policy function $X^\pi(S_t)$. Using policy search or lookahead approximation, Powell identifies four classes of policies and claims that any "… *of the four classes of policies can contain the optimal policy for specific problem classes*". The modelling and implementations of policies requires "new algorithmic strategies" [16].

These four classes of policies have simultaneously emerged as specific methods in RL research [11], [17], [18]:

- Policy Function Approximations (PFAs) – using *policy search*, PFAs are analytical functions that map a state to a decision. Can include lookup tables, parametric functions, and non-parametric functions. For example, policy gradient methods.
- Cost Function Approximations (CFAs) – using *policy search*, CFAs are parameterized optimization models modified to improve over time under uncertainty. Essentially, a CFA entails solving an optimization problem that has a tunable parameter. For example, reducing regret using upper confidence bounding in Bandit problems.
- Value Function Approximations (VFAs) – using *lookahead approximations* and the Markov property, VFAs use the "value" of being in a particular state S_t to select the optimal decision x_t that optimizes the expected return on the objective function. For example, Q-Learning.
- Direct Lookahead Approximations (DLAs) – using *lookahead approximations*, DLAs can be deterministic (i.e., following directions from a GPS navigation system) or can solve stochastic optimization problems within our DLA policy. For example, Monte Carlo tree search.

B. Policy Function Approximation – 2048 Game

On the 9th of March 2014, Gabriele Cirulli published a single player, sliding-tile puzzle game called "2048". This deceptively simple game has been called "Candy Crush for math geeks", "Threes on steroids" and "addictive" [19], but in terms of computational complexity it is considered an NP-hard problem [20]. Played on a 4 x 4 grid, the game starts with a random configuration of 2 occupied tiles and 14 empty tiles. The face values of each of the occupied tiles are either 2 (probability 90%) or 4 (probability of 10%).

With each move, the player must select one of four actions (i.e., swipe left, right, up, or down) which will cause all tiles in the grid to move in the selected direction. When two tiles with equal face values collide, they merge to form a single tile (e.g., 2 + 2 = 4). After every deterministic action[3], whether it leads to a merged tile or not, a random tile is placed randomly in any of the open spaces in the grid.

The goal of the game is to take actions that lead to the formation of a tile with the face value of at least 2048. The game ends once the goal is reached or when no more deterministic moves are left. The 2048 game is useful as an example of an SDP, since it has all the elements in the mathematical model, and it can also be represented as a

[2] A rule (or function) that determines a feasible decision given the available information in state S_t [16].

[3] The game state remains unaltered if the invalid decision is taken.

Markov Decision Process (MDP) [21]. This means it can be solved using RL.

"First-generation" AI, like IBM's "Deep Blue" that defeated reigning chess grandmaster Gary Kasparov in 1997, are characterized by clever programming (i.e., deep thought) and massive compute (i.e., Big Blue) to achieve super-human performance [15], [22].

The defeat of reigning Go champion Lee Sedol, by AlphaGo in March 2016, heralded the dawn of the next generation of AI which are characterized by the use of data instead of human effort to tune algorithms, and the use of commodity GPUs and cloud infrastructure instead of custom-built supercomputers. Using RL methods AlphaGo produced a breakthrough in AI far earlier than anticipated, thereby becoming a signpost pointing the way towards artificial general intelligence (AGI) [13], [23].

2048 is a well-researched problem, with several high-performing solutions that use a variety of tailored methods. Early efforts used tree search and well-crafted evaluation functions incorporating expert knowledge. Later, supervised learning and non-deep RL methods were employed with great success [24].

By contrast, deep learning methods that use neural networks have not enjoyed similar success learning an optimal policy for the 2048 game. Early efforts using deep-Q learning disappointed, with deep temporal difference learning proving to be more successful, whilst falling short of the success of tree-search and non-deep methods [25].

C. *A Promising Result*

In this research, an intelligent agent is created that uses deep RL to play the 2048 game. This was done to demonstrate how an SDP can be solved optimally using a neural network. Success in this effort translates to success in solving real-world SDPs in a military context because of lower computational complexity.

Firstly, the 2048 game is modeled as an SDP and then a policy model is generated using PFA (one of the four universal classes of policies) which is used to guide the deep-RL agent to find an optimal policy.

1) State: Primarily, the SDP state is the 4x4 game grid flattened into a 1x16 vector of face values, with each tile converted into a 1x16 onehot vector, resulting in a 16x16 binary matrix. In addition, the SDP state consists of:

- Number of empty squares. After each decision, the number of empty squares can be evaluated observing the tiles that have a face value of zero.
- Score. Each move that causes at least one merge operation, will increment the score by the value of the merge operations (i.e., the sum of the face values of the merged tiles).
- Shape. This is a numeric value representing the monotonicity of the game state.
- Largest tile value. The largest value in the set of all tiles on the board.

2) Decision: The decision space is a discrete value, each representing one of the possible moves, viz., $0 = Left, 1 = Right, 2 = Up \text{ and } 3 = Down$.

3) New information: A single tile, random both in face value (2 or 4) and location (any empty square), is placed on the board after each decision.

4) Transition function: This function governs how the 2048 game environment modifies the game state based on the decision (choice of action) by the player. This results in a *swipe* operation in the selected direction chosen from the decision space.

5) Objective function: The goal is to maximize the largest tile value until it reaches or exceeds the goal (e.g., 2048).

The class of policy chosen to solve this SDP is PFA – it uses the Proximal Policy Optimization (PPO) algorithm, a policy-gradient method, that "*alternates between sampling data though interaction with the environment and optimizing a 'surrogate' objective function using stochastic gradient descent*". PPO collects, at each iteration, T timesteps of data. It uses a surrogate loss function on this data to optimize it using stochastic gradient descent for K epochs [26].

Using PPO, we train a policy π for making optimal decisions in a 2048 environment, using neural networks which accepts S_t as input and outputs decision x_t. Our goal is to search for an optimal policy using the objective function:

$$\max_{\theta} \sum_{t=0}^{T} C(S_t, X^{\pi}(S_t|\theta))|S_0$$

Algorithm: 2048 RL environment as SDP

$S_t \leftarrow$ reset environment E

while not done **do**

$x_t \leftarrow X^{\pi}(S_t)$; choose action from trained policy.

$$W_{t+1} = \begin{cases} 2 & p = 0.9, \\ 4 & p = 0.1 \end{cases}$$

$S_{t+1} \leftarrow S^M(S_t, x_t, W_{t+1})$

$S_t = S_{t+1}$

Not all decisions in a 2048 decision space are valid in every situation. Some decisions will not yield a deterministic action. To ensure faster learning by the intelligent agent, a variation of PPO was adopted in this research, where a decision mask is used to filter out these invalid decisions [27]. The Python code for "*PPO with invalid action masking*", used in this implementation, is publicly available via the "Stable-Baselines3 Contrib" repository [28].

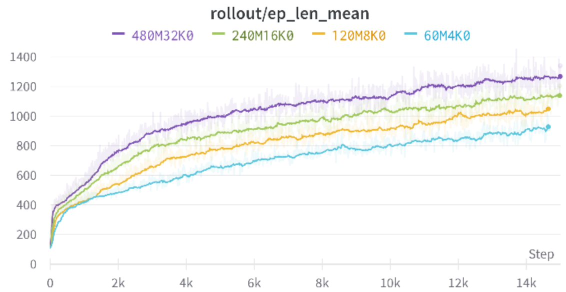

Figure 3 - Mean episodic length.

This researcher developed a custom Gym-like environment [29] for the 2048 Game and used Weights and Biases (v0.15) to build the models and generate the graphs in this document [30]. The ML framework used was Pytorch (v1.13) and the programming language was Python (v3.8).

The deep-RL agent was trained with the same set of hyperparameters for increasing amounts of timesteps until the agent achieved 2048 at least 50% of the time. This was to keep the total training time as feasible as possible.

In Figure 3 the relative performance of the 4 training runs is presented:

1. 60M4K0 – 60 million timesteps with batch size of 4096 which produces data for ~15K steps. Running time: ~1 day 14 hours.
2. 120M8K0 – 120 million timesteps with batch size of 8192 which produces data for ~15K steps. Running time: ~2 days 22 hours.
3. 240M16K0 – 240 million timesteps with batch size of 16000 which produces data for 15K steps. Running time: ~5 days 2 hours.
4. 480M32K0 – 480 million timesteps with batch size of 32000 which produces data for 15K steps. Running time: ~9 days 5 hours.

Mean episodic length is a good measure of the performance of the deep-RL agent because the longer a game lasts, the higher the maximum tile value is. The minimum number of moves an RL agent requires to win a game is ~940 [21], which becomes a good target to track as the agent learns policies that reach a maximum tile value of 2048. Clearly, run #4 performed the best due to its much longer running time. Further testing will probe how far this deep-RL agent can go with larger timesteps and running time.

To evaluate the result of run #4, 1000 games of 2048 were played using the trained model that was saved by the deep-RL agent. 100 games were played for each random seed, and the highest score was recorded along with the largest tile value and the number of moves it took to reach that tile value:

Playing 1000 games of 2048 with 10 random seeds
[01] Seed= 51747 Top Score=61216 [Tile=4096 Moves=2824]
[02] Seed= 38354 Top Score=71440 [Tile=4096 Moves=3263]
[03] Seed= 76370 Top Score=66100 [Tile=4096 Moves=2957]
[04] Seed= 51366 Top Score=62840 [Tile=4096 Moves=2953]
[05] Seed= 51991 Top Score=78680 [Tile=4096 Moves=3648]
[06] Seed= 90341 Top Score=71224 [Tile=4096 Moves=3260]
[07] Seed= 51478 Top Score=72904 [Tile=4096 Moves=3371]
[08] Seed= 68069 Top Score=59476 [Tile=4096 Moves=2722]
[09] Seed= 96902 Top Score=60496 [Tile=4096 Moves=2819]
[10] Seed= 12619 Top Score=79572 [Tile=4096 Moves=3679]

Tile Distribution:
64: 0.10% 1
128: 1.00% 10
256: 1.70% 17
512: 9.20% 92
1024:32.90% 329
2048:47.90% 479
4096: 7.20% 72

It is worth noting that the agent reaches 4096 within 100 moves at least once, across all random seeds. Overall, the agent reaches the 1024 tile 88% of the time (880), the 2048 tile 55.1% of the time (551), and the 4096 tile 7.2% of the time (72). Further experimentation, with more computing power and longer running time, should discover the performance limits of this deep-RL agent.

Several tweaks were used to produce the result shared in this paper, such as invalid action masking, reward scaling, learning rate annealing, and pre-processing of neural network input using one-hot encoding. The PPO algorithm has several tunable hyperparameters which were tested and adjusted to get better agent performance for this problem [31]:

- Random seed: every run used the same random seed (1024) to ensure valid comparisons could be made between each run. This will help for debugging your implementation.
- Learning rate: an intial learning rate of 0.0003 was used. This value tends to zero over the duration of the run due to learning rate annealing [32].
- Batch size and number of steps: a larger batch size improved performance of the agent. Through experimentation, the batch size was calculated by dividing the number to timesteps by 15000. The $batch\_size$ and n_steps PPO hyperameters were keep as the same value because a single environment was used to train the model.
- Number of epochs: 20 epochs were used in these runs. This is an arbitrary value but larger than the PPO default. More testing needs to be done.
- Value function coefficient: This hyperparameter is set to 1. This perfoms well but further testing needs to be done.
- Entropy coefficient: The default value of 0 was used in these runs. However, through experimentation it appears that this hyperparameter influences the degree to which the deep-RL agent will explore non-optimal choices versus exploit optimal choices from experience. Values of 0.0001 seemed to yield better reward signals than 0.1 and 0.001. This helps prevent premature convergence of one action probability dominating the policy and preventing exploration [33].

In Figure 4, the convergence of the learning can be clearly seen. This is a promising result. The results suggest that the performance of this deep-RL agent might scale with increased training time.

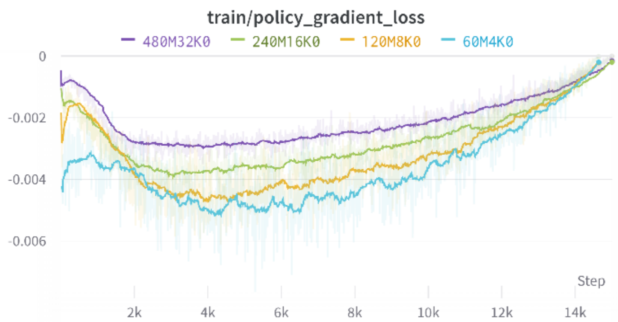

Figure 4 - Convergence of gradient descent loss

IV. FORCE MULTIPLIER

The US Department of Defense (DOD) defines a *force multiplier* as "*a capability that, when added to and employed by a combat force, significantly increases the combat potential of that force and thus enhances the probability of successful mission accomplishment*" [34]. The Joint Standing Committee on Defense confirms that the South African government and SANDF is already convinced of the *technology as force multiplier* effect and its role in the defense of our nation [35]. However, significant hurdles to achieving this effect exist in the form of financial and human capital realities [36].

DOD funding during the early part of the digital computer revolution (1950s to 1970s) was a major driver of the computer, communications, and semiconductor industries. This means that the most significant advances in the commercial technology industry were first developed as military systems. Major weapon systems typically have long development cycles (10-15 years) and even longer shelf lives (20-40 years). However, the computer technology behind modern military innovations advance by a generation nearly every 2-3 years, so we must not neglect this strategic imperative or risk falling behind in the "*informationized*" and "*intelligentized*" arms race [37], [38].

In the South African context, given the well-documented financial and manpower shortages [7]–[9], to achieve and sustain effective national security we must find a way to overcome these hurdles. In the view of the author, the adoption of the emergent tool of RL-powered SDA will enhance SANDF performance in achieving mission success.

RL-powered SDA has several applications within the military context, where making decisions under uncertainty occupies a crucial role in attaining strategic objectives and managing resources effectively. For example, planning, logistics, supply chain management, risk management, training, and simulation. Today, the global battlespace functions on data and insights. Machines that can learn insights from data are already providing competitive advantages to those pioneers who have harnessed the power of AI. AI-powered tools can potentially be a *force multiplier*.

A. RL-powered SDA as Force Multiplier in Cyber Security

For example, RL-powered SDA can be applied in the field of cybersecurity to ensure the confidentiality, integrity and accessibility of information and systems. This can be achieved by placing intelligent tools in the hands of a smaller, well-educated, well-trained, and industry-certified force.

The SANDF faces many vulnerabilities across their networks and systems. RL-powered SDA can aid in prioritizing and managing vulnerabilities based on their severity, exploitability, and potential impact. Skills such as penetration testing, vulnerability management, incident response planning, and user behavior analytics are potential avenues of cooperation between Man and Machine.

Figure 5 depicts a motivated actor who exploits a vulnerability as a threat to cyber security. To mitigate or remove this threat, RL-powered tools could autonomously detect and report vulnerabilities to a Security Operations Center. This will greatly enhance their probability of mission success, by providing early warning to patch vulnerabilities before they can be exploited.

It is envisaged that *autonomous cyber vigilance* can be achieved by modeling vulnerability management as an SDP so that RL can be used to find an optimal policy, using one of the four universal models discussed in III.A. Central to this effort will be representing the Lockheed Martin Cyber Kill Chain (CKC) as a Markov Decision Chain (Figure 6).

In addition, the intelligence agent envisioned in Figure 5 will make use of the OODA Loop at each state in the CKC by *observing* it's environment, *orienting* itself to the context, *making a decision* about how to respond to environmental feedback, and then *taking action*. Successful actions move the state of the target system to the next phase (or a prior phase) of the CKC.

A major advantage of RL-powered cyber security is the proven ability of RL agents to learn optimal behavior in complex environments in both faster and at a higher performance level than their human counterparts [13], [23]. Furthermore, in continuous decision environments the time required in the OODA Loop to take an action can be reduced through training an RL agent using offline learning as illustrated by the author with the 2048 game in III.B. Explainable RL [39] can also be used to train SOC personnel and optimize their incident response times to strengthen the SANDF's cyber resilience.

B. The silicon-hat hacker

A black-hat hacker will exploit a vulnerability in a target system, motivated by self-serving reasons such as financial gain, anarchy, or revenge. A white-hat hacker will also exploit vulnerabilities in a target system, but for ethical reasons, and performs this role as the antithesis of the black-hat hacker.

An RL-agent that has learned how to exploit vulnerabilities in target devices will function like a white-hat hacker but will not require human assistance. This "silicon"-hat hacker will be trained on known exploits (e.g., using the Metasploit framework) and monitor networks and systems as a silent, autonomous sentinel as shown in Figure 7.

This autonomous vigilance, because it is built on RL, is envisioned to be sufficient to find known exploits and potentially learn new *zero-day* vulnerabilities that are yet to be discovered. RL has already demonstrated this kind of success in other domains like chess, shogi and Go [13], [23].

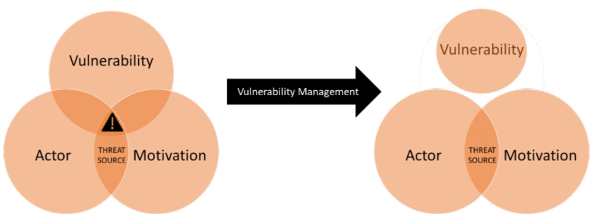

Figure 5 - Autonomous Cyber Vigilance

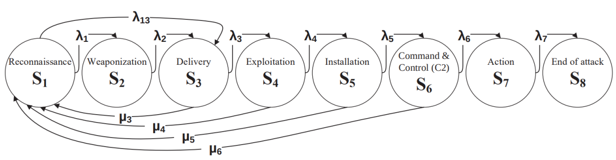

Figure 6 - State Transition Diagram for Cyber Kill Chain [40]

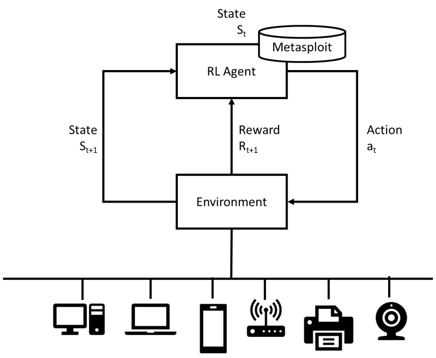

Figure 7- Silicon-hat Hacker Architecture

V. CONCLUSION

In the present information age, the global battlespace is about data and insights. Machines can learn insights from data providing competitive advantages to those who can harness the power of AI. Making decisions under uncertainty is a common activity in the military sphere of operations, which involves finding the optimal solution to an SDP by optimizing selected metrics over time. SDA is the field focused on solving these problems.

In this paper, RL-powered SDA was demonstrated using the canonical example of the 2048 game, which is a good example of an SDP. These methods can be transferred to military-contextualized domains with targeted recruitment and intentional investments in education and training. The use of RL is a good bet for the future given the super-human performances already achieved in domains such as vision and natural language processing. As the industry moves inexorably towards the holy grail of AGI, the value of SDA will be realized.

South Africa has a rich history of technological innovation and adoption. The South African government and SANDF is already convinced of the *technology as force multiplier* effect and its role in the defense of our nation, however, significant hurdles to achieving this effect exist in the form of financial and human capital realities.

The adoption of RL can act as a force multiplier, considering the present financial and skills shortages reported to be in the SANDF today. With a solid higher education foundation, and enhanced in-service training and industry certification, a small armed force like the SANDF can make use of RL-powered SDA as a tool to augment its productivity and effectiveness.

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Towards A Learning Analytics Reference Framework To Predict At-Risk Students At The Faculty Of Military Science

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Abstract— **Learning analytics (LA) is a relatively new field of application in the Analytics domain. Its main aim is to analyse teaching and learning (T&L) data from various sources to provide users with insights towards improving T&L. One of these T&L improvements is a greater focus on student success and more accurate methods of limiting student failure. This process starts with the identification of students at risk of failure (so-called "at-risk" students) through a prediction methodology which commonly falls within the knowledge sphere of Artificial Intelligence (AI), more specifically Machine Learning (ML). In contemporary information systems, the supporting platform for this is provided by an LA information system (LAIS) that relies on an underlying virtual learning environment (VLE), which in turn uses T&L data from a learning management system (LMS). A reference framework (RF) establishes a common foundation for future implementation of a system for developers and users. It provides appropriate guidance to users in a specific field of knowledge. Guidance is, however, generic in nature to secure reusability. This research focused on developing an RF to implement LA in the Faculty of Military Science (FMS) of Stellenbosch University (SU) for at-risk student identification. It is the conclusion of the study that the RF for LA in the FMS will provide suitable guidance for future implementation of LA in the faculty to effect timely identification of at-risk students and fitting remedial actions towards greater throughput may be implemented.**

Keywords—learning analytics, reference framework

I. Introduction

The first International Conference on Learning Analytics and Knowledge (LAK'11) defined learning analytics (LA) as, "the measurement, collection, analysis and reporting of data about learners and their contexts, for purposes of understanding and optimizing learning and the environments in which it occurs" [1, p. 3]. LA, the application of analytics in teaching and learning, has the potential to enhance institutional improvement and accountability [2].

There are four main types of analytics, namely descriptive, diagnostic, predictive and prescriptive [3]. LA, as an application of analytics, conforms to these categories [4]. The value versus the complexity of the intended LA system must be considered to prioritise the implementation of each (see figure 1). The types of LA range from the least complex and lowest value of descriptive LA to most complex and highest value of prescriptive LA [5].

The modern learning environment is characterised by the use of technology as enabler to such an extent that it is commonly known as the virtual learning environment (VLE) [6]. Amidst ever-increasing adoption of VLEs at higher education institutions, the need to provide meaningful data to teachers and students alike has grown exponentially [7],[8].

In the modern learning environment, inhabited by the "digital native" [9, p. 1], technology in education has become the perceived panacea for all learning challenges, nowhere more evident than in the student's perception of what an ideal learning environment should provide [10]. As part of the VLE, learning analytics (LA) aims to enable both student and teacher to actively track, intervene and react to student challenges to optimise student success [11]. Expectations for student success, commonly measured as number of completions, continues to rise, as does the demand for institutional accountability [6]. Learning analytics could ideally provide much richer data and intelligence to not only reactively report on success, but also be a means to proactively influence the student results [1].

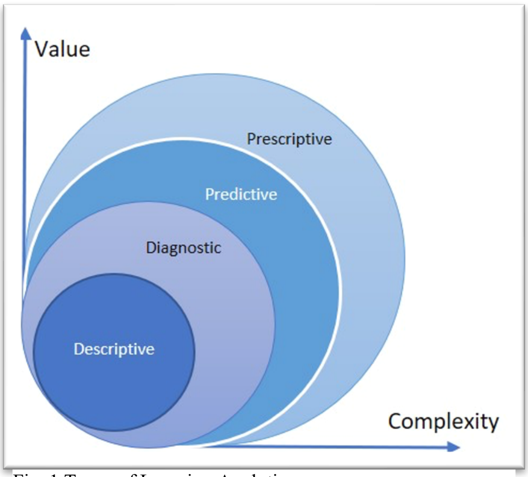

Fig. 1 Types of Learning Analytics

At Stellenbosch University (SU) learning analytics is encapsulated in its Strategy for Teaching and Learning (T&L) 2014 – 2018 [12]. SU acknowledges that "this provides new, technology-mediated forms of collaboration and mentoring, leading to different learning processes" [12, p. 5]. In some respects, LA provides a forum for dialogue between at-risk student and mentor which will adjust learning to the benefit of the student's education, i.e., they are more likely to pass than fail [13]. Various cases exist of LA making significant contributions towards student success and adding to institutional throughput. These include the Michigan University E-coach, Student Explorer and Grade Craft projects [14], the Signals system at Purdue University [15], identifying at-risk students at New York Institute of

Technology using data-mining and inference from an independent data management firm [16] and Early Alert at the University of New England [17].

According to Campbell and Obliger [18], LA assists the student in improving their learning behaviour and results, whilst also assisting faculty in analysing T&L data to identify at-risk students and areas for improvement [2],[19]. However, learning analytics has not lived up to its promises, especially in predictive analytics, as there exists a significant gap between learning analytics and evidence of its effectiveness [20]. Additionally, Willis, Slade, & Prinsloo [21] identify a significant lack of ethical standards in the implementation of learning analytics which in turn creates concerns in LA users and leadership alike. Furthermore, teaching creates vast amounts of data, especially with the advent of VLEs, which is rarely used to improve teaching and learning [19]. This study will provide a framework to address these problems.

II. Contextualisation of the Study

A. *Institutional Picture*

The institutional picture of the Faculty of Military Science (FMS) is derived from various institutional documents. These include the SU Vision 2040 [22], the SU Strategy for Teaching and Learning [23], the FMS Standard Working Procedures (SWP): 2011 [24], and the FMS Telematic Standard Working Procedure [25]. The FMS is a faculty of Stellenbosch University. It provides military contextualised higher education to mainly uniformed military personnel in the residential face-to-face (F2F) mode and distance telematics mode respectively. Residential students are full-time students attending classes on this detached campus of SU, but they also utilise the SunLearn virtual learning environment (VLE), built on the Moodle platform, using the blended learning approach(BL). Distance students are part-time students who receive education through the hybrid learning (HL) approach. Their T&L involves limited face-to-face contact sessions, with predominantly telematics education (TE) in synchronous and asynchronous modes via SunLearn.

B. *Purpose of the Study*

The purpose of this study is to propose a framework for implementation of LA in the FMS that would satisfy the requirements of the institution for identifying at-risk students pro-actively, hence enabling it to devise appropriate responses to such students.

C. *Problem Statement*

The problem is, stated simply, that the FMS does not employ LA today. As a result, it is unable to measure learning success sufficiently. This means that data that could be made available to assess student learning and progress is not being utilised. This data could be used to help at risk-students timely and accurately. For the same reason, it also does not put the FMS in a position to help at-risk students timely and accurately. To help at-risk students of FMS, this faculty must proactively detect at-risk students. LA can help to solve this problem.

D. *Research Question*

How can learning analytics provide an effective means to provide pro-active learning predictors of at-risk students at the Faculty of Military Science?

E. *Brief Description of Research Methodology*

A design science research methodology (DSRM) has been used as an overarching research methodology. This methodology is effective to produce an artefact that can serve the purpose of the study [26],[27]. In this study the research artefacts are:

- Artefact 1: A model for a pedagogy to support LA.
- Artefact 2: A model to design and implement VLEs for LA.
- Artefact 3: A model to identify at-risk students.
- Artefact 4: A model to implement LA.
- Artefact 5: A framework for ethical LA.
- Artefact 6: A reference framework for LA

F. *Research Design*

The DSRM describes the procedures and methods to carry out IS research that is consistent, provides an accepted process model, and a cognitive research model for IS research [27]. DSRM is therefore highly suitable as research methodology to solve this specific research problem [28]. Additionally, DSRM provides a detailed step-by-step process to attain the intended objectives of this study through IS artefacts intended to solve identified organizational problems [27],[29].

In this study, DSRM was used with qualitative arguments and exploratory questions, in support of qualitative enquiry. Barker, et al. [30, p. 6] suggests three conditions must be met for DSRM to be used, namely, that “little [is] known in a particular research area; existing research is confusing, contradictory, or not moving forward; and/or the topic is highly complex”. These conditions were met in this study, as the topic represents a relatively new research field, relatively little research addresses this specific topic, and the topic has many interrelated issues, which makes the topic complex.

G. *Research Approach, Techniques, and Tools*

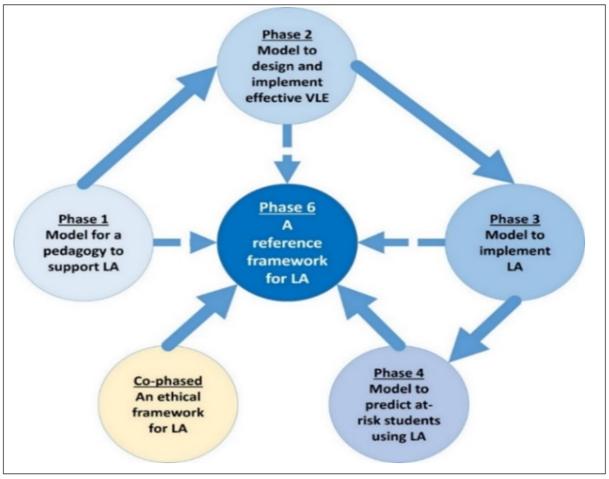

Fig. 2 Phases of the Design and Development of the Artefacts

The RF and design methodology developed by Lawrence Wilkes [31] was identified as appropriate for this study. Permission was obtained from Everware-CBDI to use the methodology in this research. This detailed methodology and structure would serve the purposes of this study best, as the artefact that would be produced would also best address the purpose of this study. Each phase of the RF development provides a building block (or model) that supports the reference framework. Each phase and resulting model that serves to support the deliverable of the next phase in the theoretical framework and serves as direct input in the design and development of the main artefact – the LA reference framework (LARF) (see figure 2**Error! Reference source not found.**). A framework for ethical considerations in LA is also defined as a co-phased activity; an input in direct support of the LARF.

III. Research artefacts

A. *Artefact 1: Pedagogy to Support Learning Analytics*

In evaluating which teaching and learning model is most suitable, one must establish the fundamental principles of education [32]. Teaching and learning models are numerous. Therefore, to decide on the most suitable, one must investigate its epistemological origins (that we can know and how we can know it) and ontological origins (what kinds of things exist) [33]. The field of educational philosophy addresses these fundamentals within philosophy. This serves as a starting point to describe the origins of the eventual teaching and learning model that is applied in this study. Current T&L models are based on educational philosophies which have their origin in ancient, pre-modern, modern and contemporary philosophies [34],[35]. For brevity, only contemporary philosophies are discussed here that were appropriate to the specific case study at the FMS.

1) *Contemporary Education Philosophies*

a) Behaviourism

Behaviourism postulates that human behaviour can be modified through reward and punishment. It followed therefore that human behaviour was entirely determined by its external environment. Originating in the 1900s from the work of Ivan Pavlov and John Watson [36] - [37].

b) Cognitivism

Cognitive theories of learning refer to those focused on understanding the mental processes of learning, searching for reasons for different learning experiences [41]. Evolved from cognitive psychology, which focusses on describing learning through an understanding of the mind and experimental evidence of mental functions [39] - [41] .

c) Constructivism

Constructivist theories of learning are based on the concept that knowledge of the student is built on the student's prior knowledge [34]. Some characteristics of constructivism [41] - [45]:

- Teachers must establish learner's previous knowledge and build on it.
- Modern teaching practice include cooperative learning, blended learning, problem-based learning, discovery learning, scaffolding, proximal learning, communities of practice, jigsaw learning, case study learning, spiral reflective learning, and project learning.
- Teaching focus is on the building of knowledge by the learner based on their existing, own knowledge.
- Strong emphasis on the importance of consciousness, free will and social influences on learning.
- Modern teaching technologies, like the LMS, have made it possible to implement virtual environments where such interactive learning was the cornerstone of the success of students.
- A modern category of a technological implementation of constructivism is the so-called eXtended-Massive Open Online Course (xMOOC) platform.
- Students structure their learning and have more opportunities to gain experience from one another through online forums, discussion groups, group work, peer learning and teacher guided activities.
- Two current examples of providers include edX [50] and Khan Academy [51].

d) Connectivism

Connectivism has its roots in the idealist and existentialist teaching philosophies. It postulates that knowledge cannot be constructed for the student, and that sense-making of knowledge is a process that happens through the interactions of students with others and the environment. Knowledge is therefore not finite and discreet, as set out by the teacher, but must be explored and expanded as the course progresses [52]. Some characteristics of connectivism [46] - [51]:

- The opinion of the learner is essential to build knowledge.
- Four major activities for learning to take place namely aggregation, remixing, repurposing, and feeding forward.
- The emphasis is on students defining the learning space and content through interaction and collaboration, rather than prescriptive lectures and content.
- Intensive social interactions between students are essential.
- Traditional classrooms often do not have the resources to facilitate such courses.
- Connectivist courses are social media reliant and require extensive social media analytics.
- A modern category of connectivist implementation is connected-Massive Open Online Courses (cMOOC).
- Notable examples are Coursera [57] and FutureLearn [58].

2) *An Insitutional Pedagogy Model*

It is evident from Drachsler and Kalz [59] that the pedagogical model used in teaching must support the capturing of data for the LA system. This approach is supported in the LA and pedagogy framework defined by Greller and Drachsler in which "pedagogical behaviour" (i.e., actions by teachers/students) feed into the LA design which informs the defining of "pedagogical consequences" (i.e., learning design adjustments) and feeds back into pedagogical behaviour again [59]. In this study the working prototype would be in the form of a VLE that would provide data for the LA model which in turn would provide feedback for learner and teacher.

a) Classroom Approach

The behaviourist-instructivist approach is most frequently used successfully to implement and test LA systems [60]. Generally, this approach requires self-directed learning, facilitates a high degree of interactivity, offers continuous feedback, uses a blended teaching approach, utilises a guiding structure, requires continuous progress assessment and requires some collaboration between students in the learning process [52] - [54]. Measures of student engagement are separated knowing (SK) which refers to evaluating knowledge in an "objective, analytical, and detached manner" [62, p. 58], and connected knowing (CK) which refers to a relational approach that involves the "discovery of a personal connection between the individual and the thing, event, person, or concept under consideration" [62, p. 58]. This approach is characterised by self-directedness of students [23], a high degree of interactivity through the concept of "teacherbots" [64], continuous feedback between teacher and student [55] and collaboration between students and teacher [23].

b) Blended Learning and Hybrid Learning

E-learning has evolved to become a mainstream category of teaching which encompasses a wide range of teaching approaches called blended learning (BL), a mix of face-to-face (synchronous) classes with technology aids and online resources [46]. This methodology has in some cases produced significant improvement in student performance [67]. Additionally, significant improvements in efficiency can be achieved through synchronous and asynchronous activities to optimise time [46]. Hybrid learning (HL) is the progression of BL to a campus characterised by fully online synchronous and asynchronous classes and resources. Hybrid learning is especially useful in the fully distance education environment [46].

c) The Flipped Classroom

Flumefelt and Green [68] describes a "new" teaching approach that may be used to identify at-risk students effectively. The flipped learning (FL) approach is described as an effective method to "flip" traditional lecture time into time for higher level learning engagements [13] , [58] - [60]. Bruff [72] described the FL process as a blended approach which uses "computer-mediated" activities to engage students in a highly structured environment by using self-regulated activities before, during and after synchronous contact sessions. The process is illustrated in figure 3.

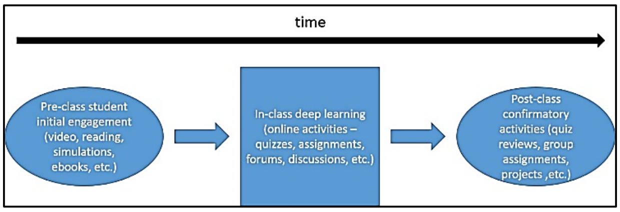

Fig. 3 The Flipped Classroom Approach

d) Gauging Student Self-efficacy and Affective Responses

The direct relationship between student perceptions of course quality, affective indicators and motivation have a direct influence on student success [73]. Therefore, a model to gauge students' level of satisfaction and motivation must be devised. This includes students' ongoing perceptions of course quality, lecturer proficiency, level of support and students' level of motivation throughout the course. It is of course difficult to gauge continuously, and time-consuming, but a realistic methodology would be to gauge levels at specific intervals. Students need to engage in a reflective practice cycle as part of a feedback portfolio to the teacher [74]. This is especially useful in developing students' self-regulation in improving their learning [75].

e) Progress Tracking

Progress tracking should provide for the needs of teacher and learner to track progress for diagnostic, remedial and motivational purposes effectively [76]. Several tools on the SunLearn platform are available to facilitate progress tracking, which include a progress bar and completion graph. Additional tools that could supplement progress tracking are a gamification plugin and an experience point plugin, both of which serve as indicators of effort and participation, yet also serve as motivational tools [77].

f) A Model to Provide Data for LA Prediction

The requirement for such a model would be to provide descriptive, diagnostic, and predictive analytics of at-risk students. It would also have to provide the teacher with real-time monitoring capabilities based on pre-defined at-risk indicators. Typical indicators from practice include task completion rate [78], level of participation and engagement [79], milestone results and overall results [78], VLE activity usage [7], time on task [80], formative and summative assessment results [81], to name a few. It is clear from research that each course may have different indicators of success, and therefore also of at-risk students. These different indicators are influenced by students' preferences, their educational and social backgrounds, and various other factors, but may also be influenced by poor learning design or pedagogy [82]. The proposed model should make provision for a comprehensive list of indicators from literature, empirical studies, and case data from diagnostics to indicate suitable indicators of at-risk students. This will feed into dynamic redesign of learning content and the adaptation of pedagogy and will assist ultimately in at-risk student identification [83].

B. *Artefact 2: A Model for VLEs to Support LA.*

An elegant framework to ensure learning and teaching effectiveness is provided by Piccoli, Ahmed and Ives [84] in their "dimensions" and "antecedents" of VLE effectiveness (see figure 4). This framework considers two dimensions with various antecedents that must be considered when implementing a VLE that would satisfy the learning effectiveness requirements of a particular course. Other

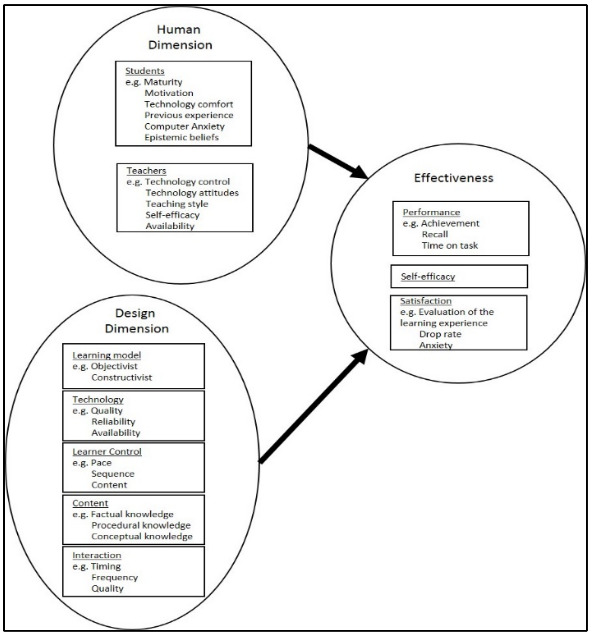

Fig. 4 Dimensions and Antecedents of VLE effectiveness

authors who support this multi-dimensional approach towards effectiveness include Entwistle [85] and Liaw [86] who include "good design" as a determining factor. The Piccoli, Ahmed and Ives model was adapted for the FMS as preliminary model to be expanded on as new at-risk and success indicators are identified in future research.

C. Artefact 3: A Model to Implement LA.

1) Predictive LA as an Application of ML

Tucci [87] describes the types of AI algorithms used in AI, and applications of AI (figure 5). Some of these types of AI are used in various fields of LA for different purposes. Machine learning (ML) is defined as, "a subfield of artificial intelligence that includes software able to recognise patterns, make predictions, and apply newly discovered patterns" [88, p. 2]. ML can be sub-divided into supervised and unsupervised ML algorithms [89]. ML has proven to be effective in predicting the probability of student drop-out [90].

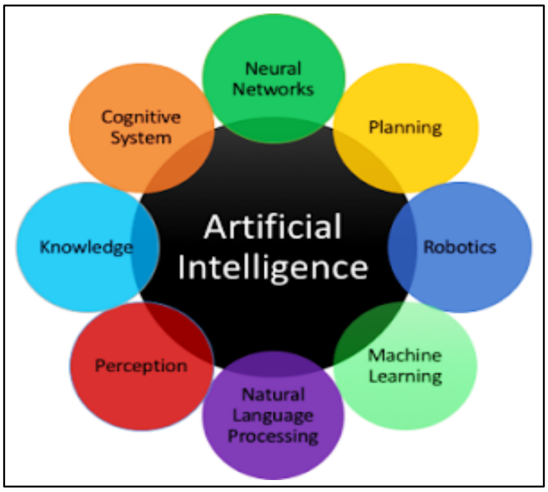

Fig. 5 Types of AI applications

Machine Learning (ML) technologies in education are frequently used in the areas of "adaptive assessment, grading, performance prediction, and student retention" [91, p. 136]. Pattern recognition has been used for adaptive assessments, for automated grading of text assignments and for identifying at-risk students [80] - [82]. Vaculík, et al. [95] also showed that ML may be used for automated assessment feedback, with suggestions on ways to achieve the learning goals. Anand, et al. [96], Alam [97] and Dalton [98] have also demonstrated how ML can successfully predict at-risk students, identify their strengths and weaknesses, and suggests ways to improve in assessment or learning practices.

2) Accuracy of Predictive Techniques in LA

The application of various ML algorithms in LA have shown high levels of prediction accuracy. Classification techniques have shown accuracy exceeding 80%, regression exceeding 90% and clustering more than 70% [99]. Muhammad, et al. [100], in identifying at risk-students using ML, found accuracies of more than 88% through using K-Nearest Neighbours (KNN), Gradient Boosting Analysis (GBA), Boosted Decision Trees (BDT), Artificial Neural Networks (ANN) and linear regression. Results vary depending on the algorithm used, the datasets available and individual circumstance of these studies. But, the research of Akçapınar, et al. [101], Er [102], Marbouti [103], and Zeineddine, et al. [104] have confirmed that the application of ML in predictive LA shows promise for future use in user applications.

3) Overview of Technologies for LA

Various proprietary software is available from major vendors, but a few open-source platforms are also available. Source data for LA may be obtained from various Learning Management Systems (LMS), for instance, Moodle, an open source LMS, and the well-known commercial LMS, Blackboard. For the purposes of this study, it is assumed that the existing LMS in the FMS will be used to generate data as needed. Additionally, various technologies to capture biometric data of learners are available commercially, with specialised capabilities, including Gaze technologies [105]. For the collection, storage, and cleaning phases of the life cycle, the tools available range from Microsoft's BI suite to the open-source Pentaho BI platform [106]. Various LA specific tools are also available on the market, including Google Analytics [107], Loop for Moodle [108], SmartSparrow and Bluefin Signals [109] and Blackboard LA [106]. Various visualisation and alerting software are also available, for example IBM's Many Eyes and Tableau [106]. Software for the alerting phase is limited to what is available in previously listed platforms. They therefore require a specialised implementation based on the institution's unique requirements, i.e., Java applets [106].

4) Generic LA Prediction Process

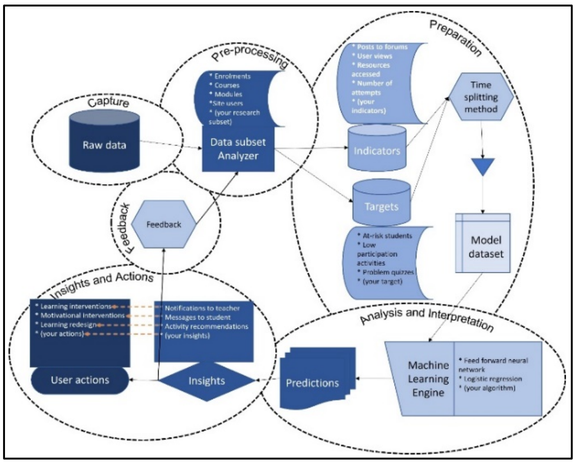

Fig. 6 The Generic LA Prediction model

The capture and pre-processing processes provide inputs to the preparation for the prediction process in the form of unified data sets. These data sets are processed into candidate indicators that are measured against set targets to establish through the prediction process which are valid indicators [98], used to provide insights to make decisions regarding appropriate interventions (actions) [110]. The interpretation process, also called the training phase, of the LA prediction process creates models to predict future success of students based on its AI techniques that actively analyse student activity data which, in turn, generate current sets of indicators of student success. This method is called supervised learning [110]. Examples of AI techniques that may be useful to predict student behaviour are Naïve Bayes, Neural Networks, Machine Learning (ML), Logistic Regression (LR), Linear Discriminant Analysis (LDA) and K-Nearest Neighbours

(KNN) to name but a few [86] - [88], [90]. The analysis phase, also called the prediction process, aims to build a model to accurately predict future student behaviour that can be used by the student to improve their behaviour and for teachers to intervene when required [110]. The LA prediction model is depicted in figure 6.

D. *Artefact 4: A Model to Identify At-risk Students.*

At-risk students are those students whose performance and progress are indicative of possible failure to complete the course [111]. Van Harmelen and Workman [111] and Baker [112] expounds that identifying at-risk students should be done early enough to make it possible to intervene in their learning to increase the possibility of their passing the course. This requires a model to predict student failure based on a set of parameters that have been validated through the LA process [111]. These parameters are called indicators [98].

1) *Factors for Predicting At-risk Students*

Broadly speaking, techniques for prediction of at-risk students can be categorised into three approaches, namely, prediction based on external factors, for example, past results, biographic factors, teacher profile [113], prediction based on student in-course behaviour, such as course participation, engagement and temporal behaviour [114] and prediction based on affective indicators, among others, self-efficacy, motivation, and perseverance [115]. Although prediction based on external factors could be indicators of student success, these fall in the sphere of academic analytics, and are therefore excluded from this study. Prediction of at-risk students based on in-course behaviour and affective indicators will be the focus of this study as these predictions can be made from active course data which falls within the LA sphere.

Hirschy [116] introduces the concept that institutions should develop at-risk models that account for unique institutional contexts. Furthermore, faculty staff must be engaged with empirically based models within institutional context that may help accomplish student success [117]. The process to develop this model requires the identification of indicators of student failure through an analysis process, used as input towards measuring student progress against set targets [78]. You [78] expounds that the process of identifying indicators requires student data that would inform the model, and that the anticipated data analysis methodology should be based on the requirements of the institution. For example, lecturers who want a measure of progress of students in particular activities that might predict at-risk students, may require a simple descriptive statistical report at any time during the course, whilst faculty administrators might require a report of at-risk students based on regression analysis to identify indicators from previous course data [118]. A more sophisticated method can also be used through which machine learning is used to determine which combinations of activities are indicators of at-risk students [102].

a) *Descriptive progress indicators*

Also called visual analytics [76], are defined as indicators based on student activity which is summarised for the teacher as various types of progress reports. For example, the completion of activities may be implemented based on various criteria that would follow the curriculum learning flow, which in turn might be presented to the teacher as a progress bar [118]. Descriptive indicators are divided into two categories, namely *attitude* and *activities* indicators.

Attitude indicators, are based on a multi-dimensional concept that describes the student's response to the learning environment; it may be positive or negative [119]. Within the attitude concept, affective, cognitive, and behavioural aspects are contained; aspects which deal with student's feelings or emotions towards their learning. Examples attitude indicators are [107] - [113]:

- <u>Intrinsic Motivation</u>. The motivation that originates in the student.
- <u>Career Motivation</u>. The degree to which students are motivated by their career prospects.
- <u>Self-determination</u>. A student is self-determined when her/ his needs are fulfilled for competence, connection, and autonomy.
- <u>Self-efficacy</u>. Refers to the student's belief that s/he can achieve the desired learning outcome before they have even attempted such learning content.
- <u>Grade Motivation</u>. The degree to which student results drive them to perform.

Activity indicators are descriptive indicators of at-risk students that are based on current student activity and interaction data that can be obtained from the VLE [118]. Examples of descriptive activity indicators are [105], [109] - [114]:

- Activity progress based on target dates for submission.
- Experience points based on a pre-defined algorithm with various levels of achievement.
- Badges achieved based on pre-defined types and achievement criterion.
- Completion statistics determined by the overall target for course completion-based activity, completion rules and/or course pass mark.
- Progress mark using the gradebook, excluding empty marks, i.e., not completed yet, to give a running total.

b) *Predictive Indicators*

These indicators are determined through a process of data analysis by means of a mathematical method to develop a model to predict student success [133]. A typical method would use historical course data that would be classified into various categories of factors that could influence student success. Examples of predictive indicators are [112] - [120]:

- Assessment data (number of attempts, time taken for assessments, final assessment outcomes, assessment results).
- Social interactions (forum social polarity, posts, replies, positive votes, negative votes, and discussions started).
- Formative activity data (average time on tasks, lesson plans and automated tools; results obtained; number of re-attempts).
- Summative assignment data (number of late submissions, time on task, number of re-submissions, number of times accessed).
- Resource views (videos seen, video repeated, time spent. podcasts views, synchronous sessions attended).

- Activity completion, especially in scaffolded content.
- Activity views (gradebook, posts, activity results, overall). Although this is not a good indicator on its own, it can provide additional depth to the analysis of other indicators regarding student effort.
- Amount of create, read, update, and delete (CRUD) activities.
- Mastering of specific activities or topics that have contributed more towards achieving outcomes.
- Absenteeism relates directly to lack of student understanding and activity completion.
- Level of overall activity (clicks, posts, submissions, and number of logins).

2) At-risk Remedies: Affective E-learning Interventions

VLEs can effectively influence student motivation by using various embedded gamification tools. In Moodle (version 2.5) these include:

- LevelUp! A tool to define, track and award student experience points, and to award experience level awards. [142].
- Scaffolding through access restrictions based on conditions in the VLE. [143].
- Badges which allow the facilitator in Moodle to define a system of incentive badges based on a set of criteria. [142].
- Social interactions through forums and chat rooms. [144].
- The progress bar block as gamification element that can be used as tool to identify students lacking sufficient progress [145].

E. Artefact 5: A Framework for Ethical LA

Chatti, et al. [146] pointed out that the ethical issues associated with LA are not unique to this field. Inevitably, as a teaching institution matures in the use of data-driven teaching, the amount of administrative, academic, and learning data grows exponentially, which requires detailed management processes and procedures [4]. Issues of ethical use of data, data privacy and stewardship point to the fundamental concerns of users, motivated by their perceptions that LA will be intrusive [147]. Chatti, et al. [146] also point to our responsibilities to prevent misuse, protect users, establish the boundaries of LA, and our responsibility to take action when the field of LA expands [146]. The responsibility rests with all stakeholders, including teachers, students, and particular organisational representatives, as they must establish procedures and policies that define who has access, where and for how long data is kept, and how the use of data is extended after this period [148]. This institutional grounding also serves to enhance the adoption and acceptance of LA, because that will establish trust in the system [149]. The proposed LA ethical framework contained in the LARF describes the ethical dilemmas [150, p. 128], ethical approaches [150, p. 128], ethical issues [150, p. 129], and an ethical framework description with examples from practice [150, p. 130]. The LA ethical framework serves as controlling mechanism in the LA systems as it is meant to moderate, mediate, and guide the users at all levels to ensure the ethical use of LA.

F. Artefact 6: A Reference Framework for LA

1) Metamodel for LA Architecture

Figure 8 depicts the overarching metamodel for the LARF as a system of interlinked drive gears encapsulated in a ring gear which represents the LA system. The drive gears represent the model for learning design, the model for the LA system, the model to design and implement effective VLE, the model to determine engagement and the model to identify at-risk students. The LA ethical framework is depicted as a gear break to indicate that it has a control function. These models, adapted for the FMS, are defined in the LARF.

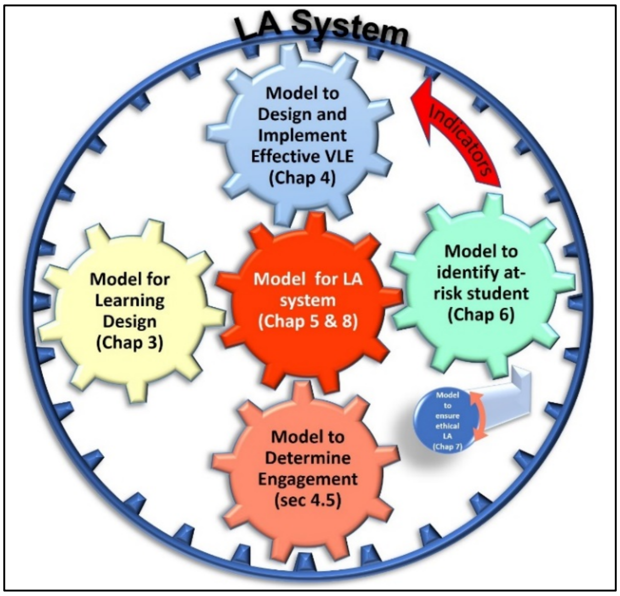

Fig. 7 The LA System Metamodel

2) Developing a LA Reference Framework (LARF)

The aim of an RF is to establish a common foundation for future implementation of a system for developers and users [31]. It guides projects through a formalised outline of what should be contained in the eventual system [31]. Organisations and researchers may refer to the framework when they develop systems to support the business processes, as it contains the details of what should be done and describes how it can be done, but does not contain the detail of these domains and does not prescribe any specific approach [151]. Wilkes (in [31]) elaborates that a RF should:

- Specify the common aspects to all similar systems.
- Create a consistent approach to the system development.
- Identify those areas that can be deviated from in the RF.
- Define a management approach to create standards, policies, and patterns.

Everware [31] describes the RF development process depicted in figure 9. This process was followed in developing the RF framework for the development of an LA system to identify at-risk students in the FMS. The “Plan Integration with Candidate RF” and “Plan Provisioning of RF” stages of the process were not conducted, as the intended RF is not for implementation purposes, but rather for research.

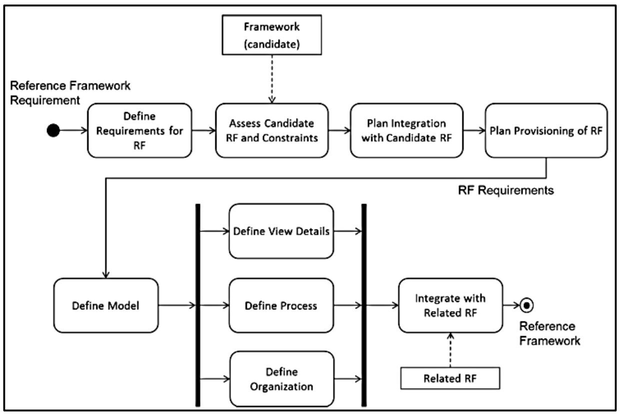

Fig. 9 RF development process

Research artefact 6 was developed using this process and contains the main sections depicted in figure 10 in the LARF document.

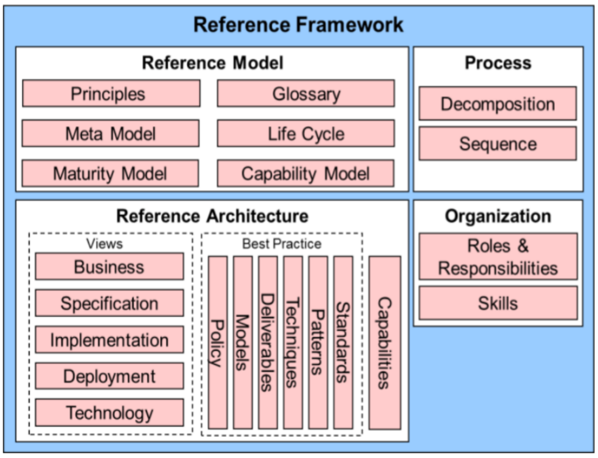

Fig. 8 Everware reference framework sections

The tabular form of the framework is contained in table 8.8 in the LARF [150, p. 188] but for brevity is not included in this paper.

IV. Findings

As part of the verification and validation phase of the DSRM the implementation of three courses on SunLearn served to generate data to verify, through demonstration, the models described in the RF. These serve as case studies to demonstrate the viability of such implementations and proof of concept. The three courses were CIS114, CIS154 and CIS214 (previously called CIS344). The design and implementation phase of the courses complied with the pedagogy model in the RF, specifically, the scaffolding, flipped classroom, performance and progress monitoring, and gamification elements were implemented in the constructivist-instructivist teaching approach.

Descriptive LA elements that were used included the progress bar, badges, and experience point (LevelUp!) displays. Specific tools that were used to measure the contribution of these were motivational surveys and affordances feedback. The results of course feedback from students using the questionnaire tool in SunLearn is summarised in graphs in figure 10.

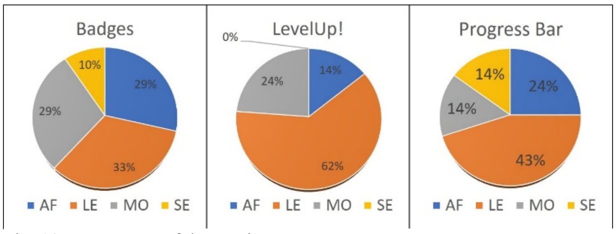

Fig. 10 Occurrence of themes in responses

The four theme categories derived from textual analysis of student responses are Learning Efficacy (LE), Motivation (MO), Affective (AF) and Self-efficacy (SE). Figure 10 shows the distribution of how much each tool contributes toward the specific theme for the students. It is evident from student scores in these categories that they had an overall positive perception of these affordance in contributing towards their learning experience. Median responses on a Linkert scale out of 5 were: Badges tool (median of response=2-3) contributes least towards the four themes, LevelUp! (median of responses is 3-4) and Progress Bar (median of responses is 3-4). Overall course feedback on the quality of the course and general impression scores were consistently above 80% which verified an effective VLE.

Predictive LA was limited to a demonstration of the implementation of the Moodle Inspire plugin in Moodle as only the standard indicators for the ML training phase could be modelled using the Python ML. Also, the data from the three courses over a three-year period was insufficient to train the model as it could only provide a maximum prediction accuracy of 50% on average. Python ML uses Google's Tensorflow library using a feed-forward neural network with a single hidden layer using supervised learning. Future research will focus on specifying a student engagement model for the FMS based on larger data sets and verification using different ML algorithms.

V. Recommendations and Conclusion

It is recommended that further research at the FMS is conducted to validate the models using longitudinal data. Also, a validated LA prediction model based on verified institutional indicators of at-risk students needs to be designed to increase the accuracy of predictions.

Furthermore, the FMS research can be used as proof of concept for inclusion in the larger SANDF as a reference framework for effective VLEs, a pedagogic model, ethical framework, at-risk student model and LA model for future implementation.

This research intended to establish a reference framework for LA at the FMS with the aim of predict at-risk students. It succeeded in proposing various supporting models to provide suitable data for LA and a preliminary implementation model for LA implementation. These models form the foundation for the LA reference framework.

Acknowledgment

Presented with permission of the Dean Faculty of Military Science as part of the author’s thesis towards the degree of MMil at Stellenbosch University. Supervisor: Dr L.M. Khoza. Compiled from original thesis by the author [150].

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Applicability of Recent Advances in HF Communication Towards C2 and Border Security

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***Abstract*— High Frequency (HF) communications is currently going through a renaissance phase. This renaissance is due to recent technological enhancements coming together with a shift of international focus towards the possibility of peer-on-peer conflicts, thus resulting in a greatly renewed interest in HF communications across many military domains and use case scenarios. This paper puts forward the view that these recent advances lend themselves well to (Landward and Maritime) Command and Control (C2) and Border Security applications. Recent technological advances in HF packet data, geographic diversity systems, and wideband HF techniques are firstly described, followed by a results section from a measurement campaign, where the applicability of these techniques within the South African domain are shown.**

Keywords—HF communications, Diversity, STANAG 4538

I. Introduction

High Frequency (HF) communications is defined as radio frequency (RF) communications in the frequency band 3 MHz to 30 MHz by the International Telecommunications Union (ITU) [1]. Developments in HF communications continue unabated even though it has been employed for long distance communications since World War II. These developments and innovations are due to the immense strategic and tactical value of the unique beyond line of sight (BLOS) capability inherent to HF communications. This in turn makes HF communications very appealing to armed forces which either do not have access to dedicated military satellite communications (SATCOM) or require a satellite fall back or backup options for scenarios where space assets are vulnerable [2]. The value of HF communications in these situations as well as anti-access area denial (A2AD) scenarios is discussed in [3].

Exploiting the HF spectrum has challenges. For example: HF spectrum is limited (< 30 MHz); it can be congested or contested; the associated long wavelength results in physically large antennas typically being necessary; and the variability in propagation due to ionospheric phenomena can result in extremely strained link budgets and the need to communicate in 0 dB or worse signal to noise ratio (SNR) conditions. These extremely strained link budgets often necessitate the need for high optimised tuned circuits when interfacing the RF circuitry of transceivers to antennas, which can result in the availability of only very narrow instantaneous RF bandwidth in practice. HF communications therefore requires its own specialised set of waveforms and techniques in order to maximise the potential of the HF spectrum.

Typical Command and Control (C2) user applications require a reliable, robust, guaranteed communications channel that is able to transfer small messages (of the order of 100 bytes) with low latency. These are not the characteristics that are normally associated with HF data communications. Certain roles within the Border Security context may entail long range communications, from remote austere environments, by soldiers using man portable or vehicle mounted HF transceivers. The antenna configuration of man portable transceivers while on the move (whip) suffers with a skip zone (where communications from 0 km to up 200 km can be severely compromised because of the low take-off angle of the whip antenna). Alternatively, antennas with high launch angles (for near vertically incident skywave NVIS propagation) defeat the skip zone problem, but cannot support frequencies above 12-15 MHz and do not offer maximum range communications. These difficulties can make HF data communications a challenging medium in the border security role where use cases and end user expertise do not always correlate with the hardware or antenna configuration.

It is the position of this paper that recent advances in HF data communications techniques makes the HF medium well suited to C2 applications in both the landward and maritime domains, including applications such as border security, by providing solutions to the challenges described above.

The recent advances in HF data communications described in this paper include: wideband HF, packet data waveforms, and diversity reception. The underlying physics of HF propagation requires a multidimensional interpretation of link availability as HF waves propagate different distances as a function of time of day, frequency, and antenna take off angle. The diversity reception component exploits the frequency, geographic and antenna domains, in order to maximise link availability. Combining diversity with advanced modern HF waveforms is collectively referred to as the *Resilient HF Network Architecture* and was first introduced in [6]. This paper first describes the typical challenges associated with HF data communications in detail and then proceeds to give empirical test results from the South African domain. These test results are presented as evidence of how the Resilient HF Network Architecture counters these challenges and is able to provide reliable “data pipe” for C2, Border Security, and many other BLOS military communications applications.

The remainder of this paper is organised as follows: Section II outlines the recent advances in HF data communications. Section III describes typical HF communications challenges and how the proposed techniques counter these challenges. Section IV presents the results from tests conducted within South Africa. Finally, Section V provides an analysis of the results before concluding remarks.

II. Recent Advances

A. Wideband HF

Wideband HF, also known as WBHF, refers to a communication system that operates within the high-frequency (HF) spectrum and follows the specifications outlined in the military standard MIL-STD-188-110D. This standard defines the requirements and parameters for the implementation of wideband HF communications in military applications. WBHF systems designed in accordance with this standard employ advanced modulation techniques and signal processing methods to achieve higher data transfer rates and improved reliability compared to traditional narrowband HF systems. MIL-STD-188-110D establishes guidelines for waveform design, transmission protocols, error correction, and interoperability, ensuring compatibility and efficient communication among different military platforms and organizations. By leveraging the benefits of wideband HF technology, military forces can enhance their operational effectiveness, enable seamless information exchange, and maintain reliable communication capabilities in challenging and austere environments.

WBHF defines multiple bandwidths, starting from 3 kHz and extending up to 48 kHz wide. It is important to note that to fully exploit higher data rates with WBHF, the underlying link budget must be available to support it. For example, a 10x data rate increase from 10x bandwidth increase, requires either: 10x (10 dB) more output power, or 10 dB antenna gain, or 10 dB lower noise floor (or some combination leading to 10 dB link budget improvement. Practical example: a 9600 bps increase to 96 kbps, from 2.4 kHz to 24 kHz bandwidth expansion, requires 100 W transmit power increased to 1 kW output power).

B. STANAG 4538 Packet Data Protocols and 3G ALE

The STANAG 4538 standard defines both a packet data mode (xDL), for user data transmission, as well as a third generation (3G) automatic link establishment (ALE) protocol.

In the experience of the authors, as well as reported in [4], the ability of the STANAG 4538 physical layer to rapidly adjust modulation and coding settings, and ability to automatically re-establish communications on an alternate frequency (i.e. ALE performance), is more critical to user throughput, than out and out bits per second performance of the modem. For this reason, the STANAG 4538 packet data mode (xDL) is often a better data bearer in practice over the more traditional approach of STANAG 5066 2G ALE with MIL-STD-188-110C/D streaming modems. STANAG 4538's unique embedded traffic burst waveforms (xDL) which are tightly coupled with the very efficient 3G ALE protocols result in a much more agile waveform. Also, the very low data rate modes available within the standard are also exceptionally robust, and can operate in SNR regions well below where clear single side band (SSB) voice would be intelligible. This factor contributes significantly to the overall establishment of a resilient data service over HF.

Additionally, the 3G ALE operating in synchronous mode results in much shorter linking times possible compared to asynchronous mode, and the resulting beneficial decrease in latency of the system. A well performing ALE engine can be considered to unlock another form of diversity in the network, that being frequency diversity, which is key to the establishment of the resilient HF data network.

Additional system level innovations were made, firstly the ALE protocol was optimised to support up to 6 kHz wide channels (for enhanced data throughput when conditions support this mode). Secondly, an embedded radio level implementation of STANAG 4538 was created where two transceivers connected only via an IP link could work together in split site mode whilst using synchronous ALE.

C. Resilient HF Network

An overview of the system architecture is given in [5]. This figure depicts a Command and Control (C2) / strategic messaging application headquarters (HQ) networked to multiple fixed sites. These sites are interconnected via a secure IP backbone and together form a system which provides much higher message delivery reliability through geographic diversity reception. The best transmit site and frequency is also automatically determined through the 3G ALE process, further enhancing system performance. A detailed description of the system is given in [6].

A traditional architecture consisting of a one-to-one link operating on a single frequency, requires that single link to be available for the system to work. Now with the resilient architecture, with (for example) 4 fixed sites and 12 frequencies in the ALE list, there are 4x12 = 48 possible links, of which only one needs to be available for communications to be available, thus resulting in a *Resilient* HF Network with much higher availability.

D. Future Direction, Wideband Packet Data and 4G ALE

The evolution of STANAG 4538 packet data to wideband operation (up from 6 kHz to 24 kHz) together with 4G ALE which is able to optimally adapt both frequency and bandwidth (in order to maximise channel capacity) is envisaged as the next major innovation within HF communications techniques.

III. Traditional HF Communications Challenges

The table below indicates the challenges that HF, as communications medium, presents to the user and how the HF Resilient Network is used to address these challenges.

TABLE I SUMMARY OF HF COMMUNICATIONS CHALLENGES AND HOW RESILIENT HF NETWORK ADDRESSES THESE CHALLENGES.

HF Communication Challenges	**Resilient HF network Counter**	**Comment**
Low SNR on links	S_4538 (LDL)	S_4538 waveform functional down to -10dB SNR
High SNR on Links	S_4538 (xDLW)	S_4538 wideband to allows high speed data on good links
Cluttered band (other users)	S_4538(LDL) + 3G ALE	S_4538 use ALE to look for clean spot or operates in the cluttered environment with the low SNR waveform
Frequency change: Time of day	S_4538(FLSU) 3GALE	S_4538 running in Synchronous scanning allows very fast link setup to maintain connectivity
Frequency change: Station location	S_4538(FLSU) 3GALE	S_4538 running in Synchronous scanning allows very fast link setup to maintain connectivity
Antenna choice on mobile platform	Optimum antenna + Geographical diversity	Most mobile platform use whip antenna, they have low take off angle so have skip zone, if we place base/shore stations so that mobile platform does not see skip-zone – network reliability is improved.
Additional Benefit	**Relevent Resilient HF network Feature**	**Comment**
Redundancy	Gateways / geographical diversity	Using the Geographical diversity with base/shore stations linked via Gateways allows the network to use best station to deliver the data/receive data
Link Throughput	Gateways / geographical diversity	Additional gateways allows more network traffic to be exchanged i.e. 3 mobile stations want to send data to base, if only 1 base then only 1 mobile can send at time, if 3 base all 3 mobiles can send at same time.

IV. EXPERIMENTAL SETUP AND PERFORMANCE RESULTS

A. Robustness of STANAG 4538

The results of a STANAG 4538 stress test to prove robustness are presented in TABLE I. The test configuration is summarised below:

1. 3 stations operating in low sunspot cycle.
2. ALE mode: 12 channels, 2.245 to 11.62 MHz
3. 3 stations (Centurion (AVH), Lynwood Ridge (Pretoria) (PS), Durban (JW))
    a. START : 30/10/2021 7:53
    b. END : 01/11/2021 19:09
    c. 2 days, 11 hours, 16 minutes, 59 hours (rounded down)
4. 2 stations (Lynwood Ridge (Pretoria) (PS), Durban (JW))
    a. START: 29/10/2021 16:12
    b. END: 01/11/2021 18:54:42
    c. 3 days, 2 hours, 42 minutes, 74 hours (rounded down)

TABLE II. MESSAGE THROUGHPUT STRESS TEST RESULTS

TX Station	**RX Station**	**TX Text messages (no.)**	**Files (no.)**
AVH	PS	2102	157
AVH	JW	2134	145
PS	AVH	234	15
PS	JW	331	24
JW	AVH	834	1
JW	PS	1072	70
Totals		**6707**	**412**

Highlights of this test campaign are given below:

1. 74 hour continuous connectivity
2. No Look for quite RF site, just operate from Reutech Communication Centurion office (light industrial area), and suburbs.
3. Stressed test on occasions with 1sec submission on TEXT message to PS & JW from AVH.
4. Nights tests with AVH sending TEXT at 30 sec interval + 25 kB Image at 5min interval to PS & JW stations with both stations also sending at 5 min interval TEXT messages.
5. Transmitted 37, 64 kB messages. (AVH to PS)
6. No Message loss.

To verify highspeed capability – performed morning tests to Boekenhoutskloof (Pretoria North) (RF quiet area) (53 km link range):

1. Achieved 6544 bps average throughput on an ARQ link transferring 64 kB file (79sec).
2. Achieved 6066 bps average throughput on an ARQ link transferring 525 kB (11min 32 sec).

B. Evidence of diversity receiver benefit

In order to demonstrate the benefit that arises from the use of diversity receivers, the following test configuration was used:

1. 3 base station to Mobile unit (2.7 m whip)
2. Rooiwal (Pretoria North) (Wideband)
3. Durban (Wideband)
4. Cape Town (whip)

TABLE III SUMMARY OF TEST FOR DIVERSITY VERIFICATION

	Time Slot (UTC+2)	Remote Callsign	Channel Frequency	SNR	To/From	
	Rooiwal (Wideband) to Landy (whip) (80km away)					
Main base	11:00-11:59	LANDY	5.360 MHz	5	To	
Gateway 1	CPT (Whip) to Landy(whip) (1600km away)					
	11:00-11:59	LANDY	18.179 MHz	21	To	1 kW
	11:00-11:59	LANDY	18.179 MHz	11	To	125 W
Gateway 2	DBN (wideband) to Landy (whip) (600km away)					
	11:00-11:59	LANDY	10.296 MHz	11	To	
	11:00-11:59	LANDY	11.62 MHz	11	To	

A Mobile unit 87 km from the Rooiwal test site was deployed (in the skip zone). The Link Quality assessment from Mobile unit to the 3 base stations was recorded. The hypothesis is that any one link from the mobile unit to any one of the 3 fixed sites will not be reliable over the course of the experiment, but rather at different times of the day, different fixed sites will be optimal. Should the link budgets at all three sites be sufficient to carry traffic, an additional benefit in 3x network capacity, that is, it is possible for 3 mobile stations to simultaneously communicate to the 3 fixed sites.

The results of this measurement campaign are giving in TABLE II which is a Link Quality Assessment (LQA) table in Signal to Noise Ratio (SNR - dB) units. The major findings were:

1. From the above LQA table it can clearly been seen that the mobile unit will have two sites that provide better link margin.
2. From the LQA table it can also been seen that with the ALE all 3 sites has connectivity with the mobile unit and at the Durban site two frequencies provide the same link margin.
3. From table it can clearly be seen that if we had 3 mobile units deployed we could have had simulation communications with all 3 mobile unit in the Robust network.

C. Blue Force Tracking Capability

Blue Force Tracking is efficiently performed using the advanced HF communications described in this paper. Frequent and reliable position updates while a vehicle is in motion is possible, this results in a pleasing resolution of position over time on a digital map. A record of which is recorded in the screen shot of an example user application in Figure 1. The Land Rover test vehicle was utilised as the test vehicle and drove up to 80 km away from the Rooiwal test site.

Figure 1. Blue Force Tracking Screen Shot.

D. Antenna Selection Impact

The choice of antenna, for both the mobile and fixed landward sides, can have a dramatic effect on system performance. An over the air test scenario was devised in order to demonstrate this effect. A mono cone antenna (BM330) was evaluated side by side at Rooiwal with the standard wideband dipole (WDA200) deployed in an inverted configuration and a 2.7 m stainless Steel whip on a container roof. Five locations were used:

1. East London (1000 km)
2. Langebaan (1600 km)
3. Durban (600 km)
4. 30 km test location A
5. 100 km test location B

TABLE IV. ROOIWAL (PRETORIA) TO EAST LONDON. (1000 KM) (FREQUENCY = 7.115 MHZ)

	Monocone	WDA200
RX (PTA) from East London	48 dB (S4 better)	24 dB

	Monocone	WDA200
RX (East London) from PTA	30 dB (S3 better)	12dB

*Resonate Dipole in East London.

TABLE V. ROOIWAL (PRETORIA) TO DURBAN: (600 KM) (FREQUENCY = 6.784 MHZ)

	Mono Cone	WDA200	2.7m Whip
RX (PTA), Durban TX	30 dB (S2 better) WDA (S1 better) Whip	18 dB	24 dB
TX (PTA), Durban RX	36 dB (S4 better)	12 dB	12 dB

*Whip (manpack) in Durban

TABLE VI. ROOIWAL (PRETORIA) TO CAPE TOWN: (1600 KM) (FREQUENCY =10.296 MHZ)

	Mono Cone	WDA200	2.7m Whip
RX (PTA), CPT TX	30 dB (S2 better) WDA (S1 better) Whip	18 dB	24 dB
TX (PTA) CPT RX	36 dB (S4 better)	12 dB	12 dB

*Whip (manpack) in Cape Town

TABLE VII. E. ROOIWAL (PRETORIA) TO 30 KM NORTH (LANDY) (FREQUENCY = 17.34 MHZ)

	Mono Cone	WDA200	2.7 m Whip
RX (RW), Landy TX	30 dB (S5 better) WDA (S1 better) Whip	1 dB	24 dB
TX (RW), Landy RX	30 dB (S4 better) WDA (S2 better) Whip	3dB	18dB

*LandRover 2.7m Whip

TABLE VIII. ROOIWAL (PRETORIA) TO 100 KM NORTH (FREQUENCY = 6.784 MHZ)

	Mono Cone	WDA200
RX (RW), Landy TX	3 dB	18 dB
TX (RW), Landy RX	None	18 dB

* Landy Loop Antenna

Findings:

1. The Conical MonoPole (monocone) Antenna can provide up to 24dB (S4) better Transmit (TX) on long distance links compared to the Wideband WDA200 and the antenna also provides 12dB (S2) RX gain compared with the WDA200.
2. The deployment size of the Conical Monopole (BCM330) vs WDA is the same in the one axis i.e. 50 m, so if looking at gain vs deployment area the BCM330 should be the choice for long range communications.
3. The Conical Monopole Antenna cannot overcome the physic of near vertical take-off angle for NVIS comms, i.e. in the skip zone the WDA totally out performs the BCM330 (comms and no-comms).
4. With the high link margin, the Durban & Cape Town stations could communicate with Pretoria in low power (2.5 W) with whip deployment.
5. High power amplifier is maybe not always the answer, good antenna may outperform a high power transmitter on an non optimal antenna. Example 100 W transmitter on Monopole antenna is still 14 dB better than a 1 kW transmitter on WDA antenna.

V. ANALYSIS

A. *Capability provided by the Resilient HF Network*

A Summary of the capabilities provided by the Resilient HF Network under test are summarised in the list below.

1. C2 message delivery (150 bytes), typical throughput 1 message every 5 min for 24 hours from mobile station to fixed station.
2. Ship/mobile to ship/mobile data exchange.
3. External e-mail connectivity over HF
4. Any binary data can be transferred via the HF medium
5. Blue Force Tracking of the moving node
6. 3rd Party Interface (C4I applications) to Network
7. GSM SMS to and from the HF network
8. Message reception at the moving station while it is in EMCOM State
9. Secure communications interface to Civilian Domain H10 App.

VI. CONCLUSION

Recent advances in HF data communications were described, followed by a description of the typical challenges faced when trying to achieve HF communications, especially within the context of the demands of high reliability applications like C2. This paper then showed how these recent advances, embodied by the Resilient HF Network Architecture, addresses these challenges. These advances being primarily: the combined application of STANAG 4538 3G ALE and packet data with an automatic geographic and antenna diversity selection system. The results of a measurement campaign, performed within South Africa, were then presented as justification for this position. Additionally, results from an actual fielded system with the Royal Thai Navy, were referenced. The Analysis of the results showed that it also possible to significantly reduce costs of fixed site infrastructure by reducing both the number and power output requirements of the power amplifiers.

The Resilient HF Network Architecture, as described in this paper, and when properly implemented, is well suited to the demands of real time user applications such as Command and Control and Border Security. Reliable BLOS HF data communications is indeed feasible, and can also be made simple to operate, by exploiting the recent advances in HF data communications.

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Tactical Datalink: Enabling Effective Coordination Between Forward Air Controllers and Close Air Support

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Abstract — **Enabling Forward Air Control (FAC) through the Tactical Data Link (TDL) is an essential capability in modern military operations, providing effective Close Air Support (CAS). The modern TDL-based FAC system can enable faster, more reliable, and more secure communication between pilots and ground forces. Moreover, it can enhance decision-making, situational awareness, and tactical planning and reduce the risk of friendly fire. However, implementing a TDL-based FAC is challenging and includes digitising the conventional voice-based CAS-FAC communication systems. This paper shares insights on the ongoing development and experiments with digitising the conventional voice-based FAC process using the Link-ZA TDL specification. The results indicate that this indigenous TDL can enable an effective TDL-based FAC with superior accuracy and shortened latency compared to voice. The study recommends developing TDL-based FAC using protocol gateway systems and digitisation decision considerations.**

Keywords— Forward Air Control (FAC), Close Air Support (CAS), Tactical Datalink (TDL), Link-ZA

I. Introduction

As a function of Command and Control (C2), effective coordination between the Forward Air Controller (FAC) and the Close Air Support (CAS) aircraft is a crucial factor in the successful execution of an air strike [1], as it requires both accurate and timely data exchange between the two forces to engage a target and prevent strikes on friendly troops and non-combatants [2],[3]. However, traditional CAS-FAC operations are based on voice communications and, therefore, susceptible to the inefficiencies of such a communication media [4][5].

These voice limitations lead to investigating the use of other media modes for CAS-FAC operations. For example, CAS-FAC operations experiment with Tactical Datalink (TDL) instead of voice [6] through digitising the CAS-FAC procedure from speech to data [7], using multimedia, including the exchange of imagery [8],[9]. [5]. These voice limitations lead to investigating the use of other media modes for CAS-FAC operations. For example, CAS-FAC operations experiment with Tactical Datalink (TDL) datalink instead of voice [6] through digitising the 9-Liner CAS-FAC procedure from speech to data [7], using multimedia, including the enhancing the exchange of use of UAVs and video imagery [8],[9] downlink streaming capabilities [10], [11].

Given the advent of new and emerging technologies that are predominantly data-driven [12], Defence must explore ways to leverage this potential. Some studies have employed simulation techniques to determine the effect of TDL-based CAS-FAC operations; Nevertheless, most of these investigations were based on TDL, such as the NATO tactical link, with Link-16 being the popular [13],[14]. However, NATO restricted access from specific nations to Link-16, prompting those countries to develop their TDL standard. As a result, the effect of using other TDLs for FAC to support CAS is to be further investigated.

The South African National Defence Force (SANDF) is also developing and using its own TDL for interoperability between its different arm services [15]. Moreover, through the Council for Scientific and Industrial Research (CSIR)[1], the SANDF is investigating the effective use of modern technologies to enhance its capabilities to execute CAS operations [16], including their use in CAS-FAC missions.

The study is an ongoing effort by the SANDF and the CSIR to develop and experiment with these TDL-based CAS-FAC capabilities for the SANDF to support these operations. In particular, the study shares insights into developing the TDL FAC system using Link-ZA specification. Accordingly, it intends to furnish Defence with recommendations on the feasibility of modern communication technologies in augmenting missions and operations.

The paper is structured as follows: it begins by describing the development of the TDL FAC system based on the Link-ZA protocol, followed by the experiment's material and methods. Subsequently, the results are presented, their significance is discussed, and concluding remarks are made.

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[1] The CSIR is one of the leading scientific and technology research, development and implementation organisations in Africa. Constituted by an Act of Parliament in 1945 as a science council, the CSIR undertakes directed and multidisciplinary research, technological innovation as well as industrial and scientific development to improve the quality of life of the country's people. The CSIR is committed to supporting innovation in South Africa to improve national competitiveness in the global economy. Science and technology services and solutions are provided in support of various stakeholders, and opportunities are identified where new technologies can be further developed and exploited in the private and public sectors for commercial and social benefit. The CSIRs shareholder is the South African Parliament, held in proxy by the Minister of Science and Technology (www.csir.co.za).

II. DATALINK-BASED FAC USING GATEWAYS

As stated earlier, this study is an ongoing effort to establish datalink capability interoperability in the Defence [17]. Most of the studies focused on the tactical data of the datalink capability model. For example, some focused on the MAC protocol to enhance the transmission of imagery data [13], while others investigated the impact of different coding algorithms on the performance of the Link-16 waveform [18]. However, studies focused on the higher levels of the datalink capability model. For example, focusing on the impact of interoperability capability on Doctrinal processes [19]. This study focused on the information and application layer of the datalink capability model, particularly using protocol gateways [20].

Software-based gateways systems for integration and interoperability are gaining popularity [20]. As such, this experiment used a gateway system to facilitate the communication between the FAC and CAS. Fig. 1 shows the high level of the proposed datalink-enabled system. The FAC systems are comprised of hardware and software components; this includes the computer, the required applications, and the hardware to exchange the tactical over an RF link. The software implements one of the doctrines for the FAC, referred to as the CAS brief.

A. Equipment and Applications

The digital-aided CAS-FAC system can employ the following hardware equipment:

- **Computer/Tablet (hardware):** A typical specification computer (laptop) used to run the required applications: FAC application, Gateway, and the Link Control System (used for radio interfaces).
- **Voice Communication Radio:** a voice communication radio to the CAS platform, used to convey tactical messages that were decided to remain on the voice channel
- **FAC (software):** The FAC application (user interface and backend processing) implements the 9-Line brief to automate the FAC process, thus enhancing communication efficiency, precision, and overall operational effectiveness.
- **Gateway-GW (software):** As such, the FAC system utilizes the services of specific gateway software services developed in-house for interoperability between the Link-ZA-compliant nodes [21].
- **RF System (hardware and software)**: A Link-ZA-compliant UHF radio used to exchange digitized tactical messages in the form of a 9-Line brief over the RF link. This equipment includes the *required* applications to program and configure the radio.
- **CAS Platform UHF radio:** A CAS platform or node fitted with the compatible Link-ZA radio to the FAC system. In addition to the compliant radio, this platform is equipped with a C2 application to compose, view and exchange Link-ZA tactical messages.

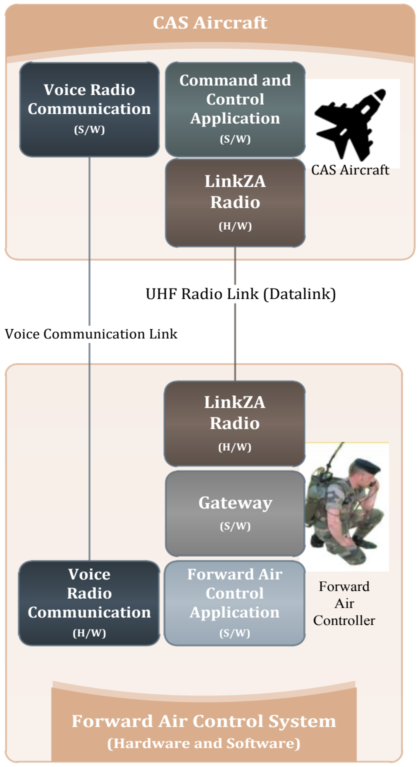


Fig. 1 Proposed datalink-based FAC.

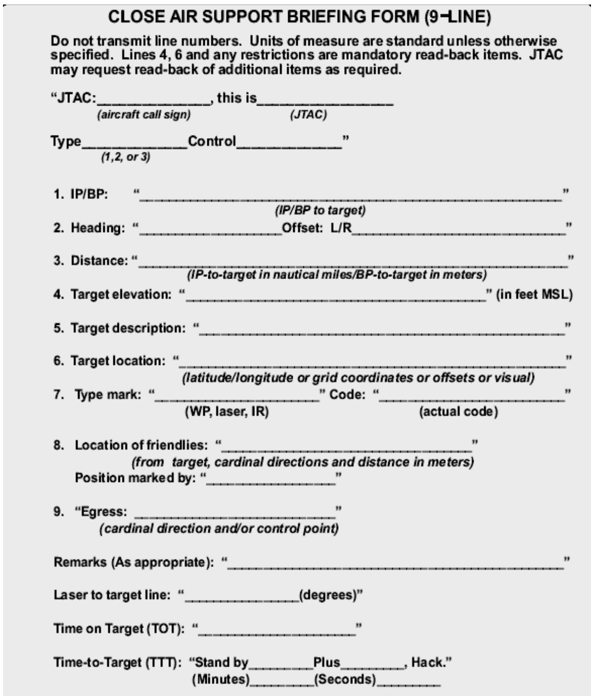
B. Standard CAS briefs

Standardised doctrines are already in place to ensure smooth communication between FAC and pilots and collaboration between various groups or nations, and there are also standardized CAS briefs to enable this. One of the reference points is the information and protocols or sets of instructions outlined in the US Department of Defense's "Joint Publication 3-09.3: Close Air Support (CAS)" for this very purpose [22]. This guide specifies different CAS briefs that can be used for various scenarios, including a 9-Line and 5-Line CAS Brief used for FAC. These briefs are detailed blueprints to pinpoint target engagement, protect innocent lives, and boost teamwork between ground and air crews [6], [22].

i. 9-Line CAS brief

In today's warfare, it's imperative to have clear communication between soldiers on the ground and aircraft in the sky. One tool that helps with this is the 9-Line CAS Brief. These are set of instructions for support from the air. Different countries might use slightly different versions, but for our study, we used the version commonly used in the US, known as the JTAC version [23].

This 9-Line brief has nine main points (hence the name). It details where friendly soldiers are, the target, which weapon to use, when to attack, and where the allied forces are. The idea is to give pilots all the information needed to carry out their missions without accidentally harming their forces [6], [22],


CLOSE AIR SUPPORT BRIEFING FORM (9-LINE)

Do not transmit line numbers. Units of measure are standard unless otherwise specified. Lines 4, 6 and any restrictions are mandatory read-back items. JTAC may request read-back of additional items as required.

"JTAC:____________, this is____________
(aircraft call sign) (JTAC)

Type____________Control____________"
(1,2, or 3)

1. IP/BP: "____________"
(IP/BP to target)

2. Heading: "____________Offset: L/R____________"

3. Distance: "____________"
(IP-to-target in nautical miles/BP-to-target in meters)

4. Target elevation: "____________" (in feet MSL)

5. Target description: "____________"

6. Target location: "____________"
(latitude/longitude or grid coordinates or offsets or visual)

7. Type mark: "____________" Code: "____________"
(WP, laser, IR) (actual code)

8. Location of friendlies: "____________"
(from target, cardinal directions and distance in meters)
Position marked by: "____________"

9. "Egress: ____________"
(cardinal direction and/or control point)

Remarks (As appropriate): "____________"

Laser to target line: "____________(degrees)"

Time on Target (TOT): "____________"

Time-to-Target (TTT): "Stand by________Plus________, Hack."
(Minutes)________(Seconds)________

Fig. 2 Example of a 9-Line CAS brief form [22]

i. The 5-line CAS brief

Every mission is unique, as are the tools and briefs tailored for them. For example, there's the Close Combat Attack (CCA) brief, one that can aid in more than one situation. This can be seen in the Rotary-Wing Close Air Support 5-Line Brief or the 5-Line LASER CAS Brief, a variant of the CCA brief. There are cases where the 9-Line CAS brief may not be used, like in the case of the 5-Line LASER CAS Brief where it is used exclusively for missions involving laser-guided support from aircraft. This brief narrows the essentials into five clear points, giving pilots a concise rundown: the exact location of the target, who is operating the laser, and the type of assistance required.

Compared to the 9-Line brief, one of its main benefits is its concise nature, ensuring faster communication in time-sensitive situations. However, it's crucial to understand that transmitting this brief isn't the same as giving a pilot the go-ahead to take action. The clearance to fire or engage remains a separate command, ensuring checks and balances are in place for operational safety [23].

III. EXPERIMENT

As stated herein, the experiment's objectives were to assess the feasibility of Link-ZA to enable datalink-based FAC in terms of data exchanged accuracy and acceptable latency for CAS-FAC operations. However, the Link-ZA protocol comprised hundreds of messages, therefore; the messages were grouped into specific categories based on their purpose and media type:

- **Free Text**: a free and unstructured message used to send a text message
- **Own Position**: structure message used to send FAC position to the CAS pilot node, and vice versa
- **Target Allocation**: structured messages that are used to send target location information to the CAS pilot
- **Image**: structured messages used to send images and related information to the CAS pilot and vice versa.

Experiments were conducted in a laboratory setting. These experiments were centred on developing, integrating and testing the FAC application using the Link-ZA viewer simulator simulating the aircraft platform. The main objective of the research was to evaluate the feasibility of the Link-ZA datalink-based FAC for CAS operations and test multiple configurations or mappings of the 9-Line CAS brief into Link-ZA messages. Some configurations send the 9-Line brief as a Link-ZA image, sending it as multiple and different Link-ZA messages or as a combination. Specific simulation scenarios were devised and carried out, influenced by the detailed doctrine outlined in the references [22]. It's important to highlight that, even within the datalink transmission mode, some parameters or brief lines were still transmitted over the voice channel; this concept is detailed further in this document.

A. Data Transfer and Accuracy Test

This test assessed the accuracy of exchanged tactical data messages between the FAC and the CAS pilot node. In other words, to determine the error rate through manual verification methods.

For datalink, this coordinated effort was achieved by compiling and sending (receiving), through the FAC application, pre-defined tactical messages to the CAS pilot over the RF link. Upon receiving the tactical messages, the CAS pilot would then compare the received tactical messages with the expected ones (pre-defined). For voice, using the same message parameters for comparison, this was conducted using the onboard voice communication radios to send the tactical messages using voice, and the receiving pilot compared the received message from voice with the expected one. In both cases, the number of times an error was observed or a message different from the expected was received was recorded.

B. Data exchange latency Test

This test aimed to assess the latency experienced during tactical data exchange. To determine the duration for the CAS pilot node to receive the complete message. This procedure also factored in the number of re-transmission requests for comparison purposes, particularly in the voice exchange.

For both voice and datalink, using the same pre-defined tactical messages and parameters as in the accuracy test, this test was achieved by manually timing the message exchange, i.e., from when the message is sent to when the CAS pilot node entirely receives the message. This procedure also factored in the number of re-transmissions due to incomplete message parameters on the receiving node.

C. Digitized FAC Messages

For this experiment, we focused on the 9-Line CAS brief because by addressing it, the results can be used as a benchmark to achieve the same results on the other related CAS briefs, such as those related to the CCA brief.

To minimize disruptions in the execution of the 9-Line procedure, and after conceptual considerations, it was decided to select 9-Line message parameters to digitize, i.e., to retain others on voice. These message parameters were selected based on various factors, including impact, criticality, and update rates.

For example, one of the crucial factors of the 9-Line brief exchange process is the initial authentication between the pilot and the FAC. This interaction serves as a verification step between the two parties. However, this is traditionally a routine verbal. Therefore, it was decided to retain the traditional voice execution. Moreover, this ensures that authentication is between humans and not an automated system, such as a bot. This approach also ensured that we re-used the effective parts of voice communications and minimized the training requirements for the CAS pilots when migrating to a datalink (hybrid) FAC operation.

IV. Results

A. Data Transfer and Accuracy results

The results data exchanged accuracy test are presented in detail in Table 1. Both voice and datalink procedures could transmit the tactical messages defined in the 9-Line brief. However, compared to voice, the datalink transmitted the messages accurately without re-transmission requests. Moreover, using the datalink, image messages were also transmitted. The latter was also used to send the entire 9-Line brief as an image to the CAS pilot node, reducing the number of transmissions to one.

TABLE 1
EXCHANGED MESSAGES ACCURACY TEST RESULTS

Exchanged messages from the FAC to the CAS Pilot		
Message Category	***Voice***	***Datalink***
Free text messages	✓	✓
Own Position messages	✓	✓
Surface Track Messages	✓	✓
Target Allocation	✓	✓
Image (not part of the 9-Line CAS brief form)	N/A	✓

The FAC could receive continuous situational tactical messages from the assigned CAS simulated aircraft node using the datalink. This is an improvement on the FAC processes as it allows the FAC to do calculations based on in-time information received from the platform. The messages are the platform's status and own position. This capability is not possible with voice. This capability of receiving updated data from the aircraft simulated platform contributes towards a complete and accurate situational awareness for both FAC on the ground and the airborne CAS pilot. Fig. 3 shows a snapshot from the FAC application, depicting the FAC personnel, CAS aircraft and target locations.

B. Data exchange latency results

Through the gateway, the FAC application proved highly efficient in providing time-sensitive tactical messages (Location-based) within the required updates rate. These update rates depend on various factors, including the display options in the CAS aircraft cockpit, the experience, and the pilot's ability to process data accurately and expeditiously. The benefit of employing a software-based FAC is that it enables this required update rate to be easily configured on demand.

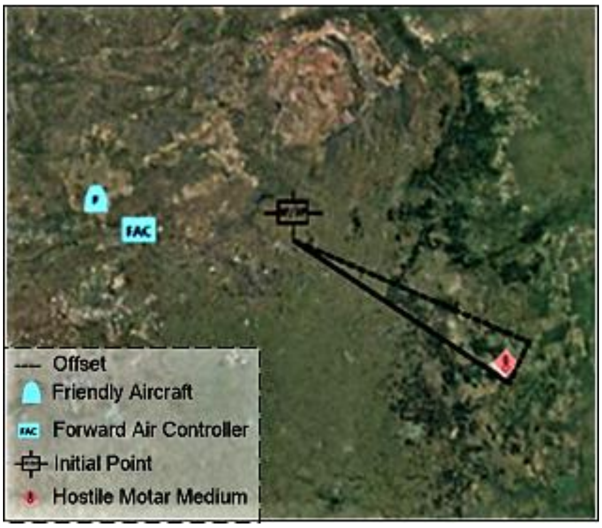


Fig. 3 CAS-FAC situational awareness picture displayed on the FAC application (displayed: FAC, CAS aircraft and the target locations)

C. Selective Digitization and Data Mapping

The results and observation of executing the previous tests also indicated that the conceptually selected 9-Line brief message parameters to digitize contributed to not only the accuracy of the digitized process but also to minimizing disruption in the execution of the process. In other words, the digitized parameters ran in the background and in an automated manner, requiring minimum effort from the FAC.

TABLE 2
9-LINE BRIEF SELECTIVE DIGITIZATION DESIGN DECISIONS

#	Selective digitization of the 9-Line brief (main parameters)		
	9-Line brief	***Datalink***	***Voice***
0	Type and Control	X	
1	IP/BP	X	
2	Heading	X	
3	Distance	X	
4	Target Elevation	X	
5	Target Description		X
6	Target Location	X	
7	Type Mark	X	
8	Location of friendlies	X	
9	Egress	X	

From the table above, only the target description line of the brief is left on voice. This is due to the sensitivity and importance of its content, and it is so to ensure clarity and immediate feedback, which will ensure mutual understanding and reduce misinterpretation. The exact reasons were applied in deciding to leave the remarks on voice, as in Table 3.

TABLE 3
9-LINE BRIEF SELECTIVE DIGITIZATION (REMARKS)

Selective digitization of the 9-Line brief *Remarks* parameters		
9-Line brief Remarks	***Datalink***	***Voice***
Remarks (As Appropriate)		X

Selective digitization of the 9-Line brief *Remarks* parameters		
9-Line brief Remarks	***Datalink***	***Voice***
Laser-to-Target line (LTL) – in degrees and magnetic	X	
Time-on-Target (TOT).	X	
Time-to-Target (TTT).	X	

The selective digitization approach allowed for real-time and in-time data exchange. This feature was instrumental in offering automatic recalculations, which proved to be critical in the timely detection of potential threats like those associated with the "danger close". While such alerts still require voice communication for effective communication, their detection was automated, further emphasizing the importance of merging digital and voice communication in enhancing the effectiveness of the overall FAC process.

D. *Different Configurations*

Since the experiments were conducted using different configurations, it is important to highlight the observations made, particularly comparing the implications of using a Link-ZA image to transmit the 9-Line CAS brief and using multiple Link-ZA messages to do the same. Some of the noticeable advantages of transmitting the 9-Line CAS brief as an image are as follows:

- **Integrity of Information**: An image preserved the spatial arrangement and relationship between the brief lines. This ensured that the CAS pilot node saw the information in its original format.
- **Efficiency**: Sending a single compressed image was faster and more efficient than sending multiple text messages at a specific interval.
- **Simplicity**: One image proved to avoid the potential of missing one of the individual messages or having them arrive out of sequence, which may be due to transmission delays.
- **Context**: Visually presenting the entire 9-Line CAS brief allowed for an immediate understanding of the complete information without waiting for all separate messages to arrive sequentially.

However, the transmission of an image alone did not significantly improve the whole FAC process compared to using multiple Link-ZA messages. The CAS pilot node still has to manually extract the information and plot them on their respective on-board display system. However, sending the brief lines individually using the tactical datalink allowed the simulated onboard systems to assign the data for the CAS pilot node automatically.

V. Discussion

The results of the experiments indicate that the proposed datalink-based CAS-FAC system can augment and enhance the traditional non-integrated, voice-based approach.

A. *Link-ZA as an enabler for datalink-based CAS-FAC*

The Link-ZA communication can be an enabler of datalink-based capabilities. The experiment demonstrated the feasibility of employing a datalink-based system based on the Link-ZA communication protocol to support CAS-FAC operations. The performance of the proposed Link-ZA-based datalink CAS-FAC system is comparable to that of the Link-16-based systems [16],[17], with acceptable transmission latency and accuracy for such operations. [16], [17], with acceptable transmission latency and accuracy for such operations. Moreover, using a datalink for FAC operations provides additional data to enrich the situational awareness picture, such as the passive CAS aircraft statutes and position, exchanging images and related data. This further emphasises Link-ZA's need and potential to enable or transit other ineffective voice or analogue systems to the efficient and accurate datalink mode of data exchange.

B. *Interoperability of CAS-FAC using gateways*

The Link-ZA protocol can also enable a connected and integrated C2 deployment. Software-based gateways are the preferred approach [25], allowing flexibility to share tactical data with C2 nodes (other than the CAS-FAC pair). These results also mean that the Link-ZA protocol, implemented through the gateway, can enable a network-centric C2 deployment, including many data sources, enriching the data quality for informed decision-making. In addition, the locally developed gateway enables sharing tactical data to the legacy, non-digital platforms, as it contains the necessary translation modules, ensuring an up-to-date situational awareness picture. Moreover, the gateways enable sharing of other media types, such as video and data, and can easily integrate into modern, high-performance commercial systems.

C. *Selective digitization of the CAS-FAC process*

While the presented multimedia CAS-FAC system performed better than the conventional voice-only system, the results also indicate that not all the steps/activities should be digitised. In other words, some of the 9-Liner activities [7], the FAC process, should either remain on voice or use both voice and data. This observation suggests that when digitising systems, an assessment of the impact of such an activity should be investigated. For instance, a risk-based approach can determine the elements or activities to digitise while ensuring that the doctrine supports them.

D. *Limitations and Future Research*

Although the study contributes to digital transformation capabilities in Defence, it has limitations. The experiment was conducted with a Link-ZA-compliant platform, which might have different link synchronization requirements. However, this implies that the FAC application must be tested on different Link-ZA platforms to ensure it can be easily configured to accommodate them. To achieve the best results, more work can be done on improving the configuration or mapping of the 9-Line CAS brief to tactical data messages. The tests might look at options such as sending the track message parts of the brief lines individually and a Link-ZA image instead of multiple text messages at an interval. This will require a radio channel that supports both the transmission of image data and time-sensitive data like the track messages on the same channel or the use of multiple radio devices in parallel.

VI. Conclusion

The recent military conflict has highlighted the importance of military capability development sovereignty, and South Africa is no exemption. This study shared insights into the ongoing development of a digitally aided FAC system using a specific datalink to support CAS operations. In particular, the data-exchange process using the Link-ZA communication protocol. It demonstrated and highlighted that Link-ZA can be an enabler for datalink CAS-FAC operations, using protocol gateways and selective digitization of the FAC process.

This research aid in the understanding of using TDLs to modernise the conventional, sometimes analogue or voice capabilities in the Defence. In other words, it contributes to the transformation of Defence capabilities towards the modern, digital, and interconnected capabilities brought by technological advancement. For example, selective digitization suggests a digitization strategy or an approach.

While the results and observations from this experiment significantly contribute to the understanding of tactical datalinks in the Defence context, the experiment focused on a single and proprietary link, Link-ZA. Therefore, the results do not apply to other links, such as Link-16. However, this limitation is also the identified gap in the literature, i.e., most of the studies are based on Link-16.

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Risk and Scenario based Communication System-of-Systems Design

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***Abstract*— Designing a communication system that can provide persistent communication in a variety of scenarios cannot be achieved through the implementation of a single technology. This paper discusses the process used to design a system-of-systems persistent communication system that can address various risks and address various scenarios. A model that provides scalable functionality across various scenarios is presented. The result provides enhanced functionality under normal conditions and provides for emergency communication under high stress situations.**

Keywords—risk, scenario, communications, systems design

I. Introduction

Scenario planning is a strategic management tool that encourages managers to envision plausible future states [3]. In this paper different scenarios that could influence communications systems are defined. The influence of the scenarios of the persistence of communications systems are then used to design a persistent communication system that makes provision for graceful degradation. Various technologies are then identified that can meet the system requirements although the functionality may be downgraded depending on the active scenario.

This approach ensures that provision of functionality during the ideal scenario is not downgraded to simultaneously make provision for less-than-ideal situations.

Comprehensive communication systems that provide broadband capabilities relies on external elements, such as power provision or fixed network infrastructure, to provide a service. These external elements may not be available under certain circumstances e.g., in the case of a major power failure. Identifying these external elements and the failure modes thereof is essential for the design of a persistent communications system.

In this paper a set of scenarios is defined, system elements that could fail are identified and the various options and fallback modes are define in order to design a persistent communication system.

II. System Requirements

The overall system requirement was to provide persistent communication for various geographically dispersed facilities as well as for a convoy of vehicles. The fundamental requirement is for voice communications between all the facilities, the convoy, entities at the facilities and entities roaming outside the facilities or the convoy. When available services such as online meetings, location sharing, and video streaming must be accommodated.

III. Scenarios

Four scenarios were defined. Green-Pastures, Fire, Drought, and Apocalypse. The scenarios are described in terms of the long-term availability of electricity, the availability or degradation of key reliant elements, and the probability of the scenario. Although certain risks are combined within scenarios it is based on plausibility of the risks realizing at the same time.

The Scenarios provides a means to easily communicate why the various elements of the total system design is necessary in order to provide persistent communications.

A. Green-Pastures

In the Green-Pasture Scenario a stable electricity supply is available, and the communication system makes no provision for power failures. In this scenario it is assumed that an external IP-backbone is available between the facilities. It is further assumed that mobile broadband connectivity is available when not connected to a facility network.

B. Fire

In the Fire scenario short term disruption of certain of the services may occur. Electricity supply may be disrupted at certain facilities, the IP-backbone may be temporarily unavailable. These outages are like a small fire that could be addressed and contained at a local level, therefore the name Fire for this scenario. For the facilities the Fire scenario includes areas within the facilities where UHF radio coverage is not available. For the convoy the Fire scenario includes areas where commercial broad-band networks are not available.

C. Drought

In the Drought scenario longer term disruption will be the order of the day. This could be large electricity outages for substantial periods (no electricity for 70% of each day), or a total breakdown of the IP-backbone. The Drought scenario cannot be addressed at a local level only. Within the context of the persistent communications system the causes of this scenario cannot be fully addressed at a local level on a continuous basis.

D. Apocalypse

In the Apocalypse scenario none of the standard services are available. Long term disruption that cannot be recovered will occur. A cause of such disruption could be for instance a nuclear detonation in the atmosphere causing a massive electromagnetic pulse [1] destroying most electronic devices.

IV. System Design

A. Green Pastures

The system design starts with the Green Pastures Scenario. The basis is devices that provide a combination of Trunked Repeater based UHF Radio communications, Wi-Fi broadband connectivity and 4G Broadband connectivity when outside the local radio and wi-fi coverage.

In the Green Pasture scenario, the facilities are connected via the IP-backbone. For the convoy a similar configuration is provided with an IP-backbone provided via the 4G network to provide the trunk connectivity. High bandwidth non-geostationary satellite communication could also be added in this scenario to provide further mobility and bandwidth [2].

B. Fire

The first provision for the Fire scenario is to provide short term uninterruptable power systems to keep the communications components powered during short term electricity problems.

Key components of the communication system are placed into separate racks and provided with short power backup.

The Fire scenario may also cause the IP-backbone to cause the radio trunk to breakdown for short periods. The system is designed such that the local repeater sites will still be able to operate independently whilst this is the case. In this scenario a satellite link could be used to provide the IP-backbone. This will however require that certain limitations be placed on the inter-site communications in order not to saturate the satellite carrier.

The Fire scenario also include other short-term events which could include a terrorist attack or a chemical explosion. In such cases the use of the 4G network could drastically increase as everybody is attempting to communicate. As indicated by [4] the success rate of a call is lowest when the traffic density is the highest, therefore the probability of loosing of the use of 4G as a communications means is high.

For the convoy loss of connectivity to the national control centre when loosing 4G backbone connectivity is not acceptable. A Satellite communications-on-the-move solution is added to the main convoy vehicle to provide the backbone connectivity in the case of no 4G service.

C. Drought

For the Drought scenario the IP-backbone may be unavailable for long terms. A replacement for the normal IP-backbone would therefore be required.

For the facilities fixed satellite communications is an option. Various options exist for the management of bandwidth across the facilities with shared bandwidth usage accounts. This reduces the overall operational cost. Long term power supplied to the base stations at the facilities must be provided. This is possible utilizing a solar with battery backup system.

In the Drought scenario, power within the whole of the country would be a problem. It is important to understand the impact on the satellite ground station. If the satellite ground station is within the country, then long term power could be an unacceptable risk. The solution used in the system design is to have the ground station situated out of country. This does have an impact on the latency of the communication. The impact is however small (<10% based on test performed) enough not to have a significant impact.

D. Apocalypse

In the Apocalypse Scenario none of the design elements of the previous scenarios would be operational. To still provide a minimal level of functionality the design elements must have been protected against the apocalyptic event. Some apocalyptic events cannot be addressed e.g., large meteorite strike but such events would also be life-ending. For a large-scale electromagnetic event the design element included is that of an HF radio capability. The HF radio's together with a limited power supply will be stored in a faraday cage protecting against the electromagnetic pulse. The radios can then be removed from storage in used to provided limited voice capability.

E. Integration

It is not always simple to explain and convince a user community that all the different elements are necessary to create the complete capability. It is necessary to provide the trade-offs between providing a high-level of functionality and the graceful degradation of the system when certain less than ideal situations occur.

Integrating all these elements into a complete System-of-Systems takes careful planning.

V. Results

A. Proof-of-Concepts

A number of proof-of-concept (POC) implementations were done to verify the performance of certain elements of the system. The POC implementations were also used to indicate the level of performance and functionality that could be delivered to the end-user.

POCs were done on satellite communications on-the-move, IP-based radio communications using a cellular phone application, fixed satellite communications and radio jamming detection.

The satellite communications on-the-move POC made use of a geostationary solution that always provided >4MB/s bandwidth. This was sufficient to provide the required services.

During the POCs the benefit of the scenario scaled implementation was verified and demonstrated to the end-user.

B. Decision Making

As the cost implication of the full-scale system is substantial it is necessary to motivate the various elements to decision makers that are not knowledgeable regarding the technology and therefore have queries regarding the number of elements that are included in the full design. The increased number of elements, from a simple design, is only seen as a cost increase.

Utilising the scenarios and the different technologies and elements that contribute to the functionality within the various scenarios provide a means of explaining the reason and requirement for the different elements. This enabled the decision makers to better understand and thereby approve the design without requiring them to understand the technology in detail.

VI. Conclusion

The scenario based approached provided a good basis for identifying various system elements necessary to provide acceptable performance over a wide range of use cases.

The scenario approach provided a means to motivate to decision makers, who may not understand the technical aspects, as to the purpose of a diverse set of options.

The scenario approach further influenced the implementation plan in terms of managing the deployment of the system depending on the perceived probability of a scenario occurring.

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An Automated End-To-End workflow of 3D model construction and Printing using Pleiades Stereo Satellite Imagery (50cm)*

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Abstract- *The advances in processing and creating 3D data is increasingly becoming more important. The South African military relies on accurate information and detailed maps like the 1: 50 000 topographical maps for planning operations and exercises. But unfortunately, these maps are two-dimensional, making it impossible to measure surface features such as building height. Even though LiDAR and aerial images can provide accurate 3D surface data, availability remains a challenge. Alternatively, satellite images such as stereo provide a large-scale area with high acquisition frequency which can provide various benefits for the military when planning an operation or exercises. However, satellite stereo images have only been applied by a few previous works for generating 3D products. Therefore, the work in this research reveals an end-to-end workflow for very high-resolution satellite-based mapping, building the basis for important 3D mapping products: (1) point cloud, (2) digital surface model (DSM), (3) digital elevation model (DEM), (4) ortho-rectified image mosaic, and (5) printed 3D models. Pleiades stereo images (50 cm) were obtained with the addition of floor plan drawings and photos. The methodology applied were preprocessing approaches including model set up and block adjustment and ground control points. Stereo images were then processed to generate 3D models by fusing the two stereo images using stereo matching, triangulation, DTM, DSM generation and point cloud classification tools in photogrammetry using ERDAS Imagine. Post processing methods to reclassify, generate solid models and improve accuracy applied in ArcGIS Pro, City Engine and Autodesk Inventor. The solid models were exported to a printable CAD format in Autodesk Inventor. For a realistic appearance of the model and accuracy check of the Pleiades stereo models generated, additional data such as floor plans, photos, mobile lidar scan was captured and rendering techniques such as enhancing building texture was applied using real life photos. Therefore, the end-to-end workflow presented in this paper offers the following: crucial planning and decisions making, vital processing techniques, software considerations, selecting file formats, procurement of consumables, limitations, and 3D products.*

Keywords— Pleiades Tri-stereo satellite images, Point Cloud, Digital Elevation Model, Digital Surface Model, 3D Model, 3D printing.

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Due to the nature of the work and the Armscor security clearance only sample data and sample images were used in this paper, but the techniques, methods and software applied during the research of the paper are true and correct. For more information regarding the actual data, process followed, and end results please contact Mr. Teboho Nyareli, 012 841 4818, TNyareli@csir.co.za.

I. INTRODUCTION

Recently, the advances in the availability of very high-resolution satellite data along with efficient data acquisition and large area coverage have led to an upward trend in their applications for automated three-dimensional (3-D) building model reconstruction [1]. The high demand for accurate 3-D building models in many applications such as urban planning, cartography, disaster monitoring, change detection and military operations, which usually require frequent updating of 3D building models in large scale, increased the urgency for utilizing remote sensing data for developing automated methods over the past decades [2]. Remote sensing and photogrammetry provide efficient and excellent tools for inaccessible regions and the challenges of collecting direct field measurements [3]. High resolution stereo satellite images is on the many sensors used in photogrammetry and remote sensing that plays an ever-increasing role [1,3,4]. The efficient use of such imagery requires software of high quality, in terms of functionality, user-friendliness and quality of results [3]. Hence, this research reveals an automated end-to-end workflow for very high-resolution satellite-based mapping using computer efficient software and tools, building the basis for automated mapping of important 3D products: (1) point cloud, (2) digital surface model (DSM), (3) digital elevation model (DEM), (4) ortho-rectified image mosaic, and (5) printed 3D models.

Military planning relies on accurate information and detailed maps like 1:50 000 topographical maps, typically 2D representations of structures such as buildings and bridges [5]. However, these maps are two-dimensional, making it impossible for many decision makers such as high-level officials, commanders, and users to translate 2D plans into 3D realities. By combining 3D models with 2D plans, planners can help clients achieve their developmental and operational goals. With the high rate of operations being a urban areas, incorporating 3D modeling allows for mission rehearsal and scene familiarization in areas that they might have access to or not [6]. Traditionally 3D models were generated by using Computer Aided Design (CAD) software and therefore creating and building 3D models is a relatively new trend in the GIS field. Three-dimensional (3D) models reflect objects or features on the surface in their present form. For a model to be accurate it is critical to obtain the most recent data and information of a building as shown in previous research done on rooftops [7]. Alternative methods such as 3D point cloud data obtain from laser scanners [8] and features captured from aerial photographs [9] may possibly enhance the accuracy of the model, but the disadvantage of these approached are its extreme intensive labour.

Dense 3-D point clouds or DSM provided by either airborne laser scanning techniques (light detection and ranging—LiDAR) or satellite/aerial stereo image matching is privileged since it allows easy discrimination of the elevated objects such as building from their ground-level neighbors. Although LiDAR and aerial imagery provide dense and accurate 3-D surface information, their availability is limited to a few specific locations in the world due to restrictions in data acquisition and authorization. By contrast, satellite images provide coverage of the whole globe with a high acquisition frequency. Furthermore, the rich semantic information contents of satellite images can enhance building detection and classification results. Despite all their advantages, to the best of our knowledge, satellite images have been used only by a few previous works for 3-D building reconstruction [3,10]. Normally when processing stereo images, the most challenging approach is image matching which is the corresponding problem where each dense pixels coordinates of the first image corresponds to the pixel coordinate in the second image which has similar object [10,11]. Therefore, automated and improve methods are required to automate the process of stereo matching which are also computer and time efficient. Furthermore, a clear End-to-End workflow for processing stereo images, generating point clouds, computing solid models form satellite images and 3D printing is still lacking in literature and requires more robust automated methods.

In this paper, End-to-End workflow for automated 3D construction and printing using Pleiades Stereo images was developed and explained in two sections. The novel workflow presented is a combination of methods and remote sensing techniques [7,8]. Firstly, using Pleiades stereo images for automated processes of generating Geometric sensor model, DTM, Orthoimage, DSM and point cloud which are used for solid 3D Model using Pleiades stereo satellite images. Then required CAD format for processing of GIS solid model in CAD software for further processing. Secondly, detailed workflow for the processing of the solid 3D model in Autodesk Inventor with additional information capturing (floor plans, photos and 3D lidar scan) to produce 3D printed and digital models. Therefore, the aim of the project was to develop an automated End-to-End workflow to construct 3D models for 3D printing using Pleiades Stereo Satellite Imagery and building the basis for important 3D mapping products. The objectives were as follows: (1) To generate Ortho-rectified image, Digital Terrain Model, Digital Surface model and Point Cloud from Pleiades Stereo Satellite Imagery using photogrammetry; (2) To classify point Cloud data generated from Pleiades Stereo Satellite Imagery and extract surface features; (3) To generate solid 3D models using classified point cloud data and; (4)To 3D print solid models of Area of Interest from Pleiades stereo images.

II. Materials and Methodology

A. Study area

The study area selected for this research is the landscape around the Union Buildings. The area of interest is in Pretoria, Gauteng province, South Africa. Latitude: 25°44'24.74"S Longitude: 28°12'43.17"E (Figure 1).

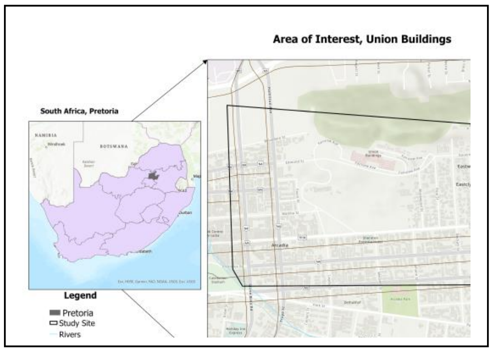

Figure 1. Study Area, Pretoria, with Union buildings as Area of Interest.

Pretoria is the capital city of South Africa with a population of approximately 2,9 million with a subtropical climate. The average annual temperature in Pretoria is 18.4 °C | 65.2 °F. The site was selected due to stereo data availability, variety of surface features such as buildings, vegetation, mountainous topography which will allow various visual and accuracy interpretation.

B. Methodology

This research proposes an end-to-end workflow crucial for 3D mapping and printing of the landscape shown in Figure 2, with the aim of deriving a robust and an automated method from satellite imagery. Variety of automated approaches have been suggested for the reconstruction of DSM from satellite images automatic methods since manual 3D processing of satellite images is time-consuming [4]. One of the recent methods is to use two images at a simultaneously for the reconstruction of a three-dimensional stereo model in which the altimetric information can be extracted [12] which was the time efficient method applied in this paper. Generation of DSM normally consist of sequence of six processing steps based on stereo images. These steps are summarised as [12]: (1) Acquisition and pre-processing of remotely sensed data (images and metadata) to determine an approximate value for each parameter of 3D physical model, (2) Collection of ground control points (GCPs), (3) Computation of the 3 D stereo model, (4) Image matching, (5) Computation of X, Y and Z cartographic coordinates from determined corresponding image coordinates, (6) Creation of regular grid spacing with interpolation or mismatched areas and eliminating points not belonging.

In this paper, further methods are introduced to process and post process satellite image for preparation of 3D printing. Prior outlining the methods. The following section is brief description of the terminology mainly used in this paper are defined below:

1) *Terminology*

a) *Stereoscopic Imagery*

Stereoscopic imagery refers to acquisition of two or more images of the same area taken from different angles such that the same scene is visible in different photographs [4]. Two overlapping images are called stereo pairs while three overlapping images of the same scene are called tri-stereo images [13].

b) *Surface models*

Surface models can be grouped into three categories namely: digital surface model (DSM); digital elevation model (DEM) and a digital terrain model (DTM).

The digital surface model (DSM) is a specific type of DEM, which represents the elevation of the actual surface of the terrain in point clouds within a grid structure. Digital Surface Model (DSM) includes buildings, vegetation and roads, as well as natural terrain features, which may be useful for landscape, city modelling and visualization applications [14]. From the theoretical side, digital terrain model (DTM) and a digital elevation model (DEM) represent the same features on the surface, which are the elevations of the surface. But in practice, these two models absolutely vary in terms of the creation methods. Where a DEM can process directly from the epipolar images (stereo images) with specific grid size, while DTM is usually processed according to filtered point cloud data, where the features over the ground surface such as vegetation, building and man-made have been interpolated. Moreover, DTM (DTM) data structure is also made up of x and y points with z-values representing elevations, however, these may be randomly spaced mass points compared to DEM [15].

c) *Point Cloud*

Point cloud data refers to a data point that was collected either by a Drone with LIDAR technology or obtained through Stereo imagery for a given geographical area, terrain, building or space. The point cloud dataset is a set of data points represented in a 3D platform and each point contains coordinate and metadata. When the points are classified and view external surface like building can been identified.

Figure 2 provides a detailed breakdown of an end-to-end workflow for solid DSM generation and 3D model design for accuracy and printing in a CAD software, respectively. This figure has several steps that have to be applied sequentially and are described in detail below. In addition, evaluation of the accuracy of the model is presented later in the paper after main results. The end-to-end workflow includes four main approaches based on methods applied by Perko [10] namely: Model set up and adjustment, Stereo pair matching, DSM and DTM generation from Pleiades Stereo Images, and additionally introduced, classification of DSM and 3D printing (Figure 2).

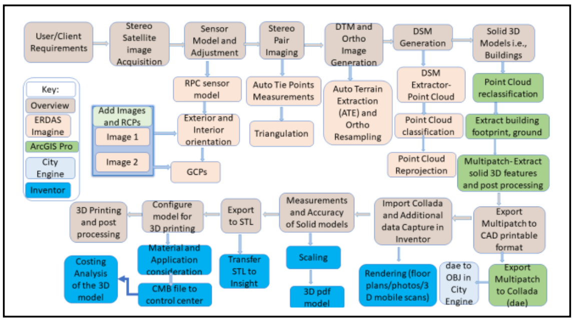

Figure 2: Detailed automated End-to-End workflow for 3D mapping for stereo Pleiades images and 3D printing with detailed tasks added for generating GIS solid model.

Imagine Photogrammetry tool from ERDAS has been utilized in the past for processing stereo images and has generated good quality products. For improvements of the models, literature has proven that obtaining images in the same year and season reduces the differences in ground features and vegetation and avoid lowering the classification accuracy [16]. The images collected in this paper were acquired during the same season [16]. Therefore, ERDAS was used for preprocessing and processing approaches for generation of DTM, Orthoimage, DSM, point cloud and point cloud classification using stereo images acquired on the same day. IMAGINE Photogrammetry toolbox available in ERDAS IMAGINE 2022 consists of various novel algorithmic approaches applied in this study namely, RCP model, auto tie points generation, triangulation, Auto Terrain Generation and DSM extractor. ERDAS Imagine 2022 software was utilized for the preprocessing of the images and the generation of the DSM, DTM, ortho images and point cloud dataset while ArcGIS pro was used to process the point cloud, reclassify, post processing and generate solid model that is then exported to CAD format for further processing in Autodesk Inventor. Autodesk Inventor was used for checking the accuracy details of the GIS model, capture floor plans with additional data, which are further fused with the model and additional data to generate accuracy model for 3D printing. The workflow is explained in detail in the subsections below.

C. *End-to-End workflow for 3D Digital Surface Model Generation from Pleiades Stereo Images*

1) *User Requirements*

The client requests a 3D model of a building or a specific floor or room of a building. The outcome results can include 3D models such as Digital Terrain Model, Point Cloud dataset, Classified surface features i.e., buildings or vegetation. Other outcome results can be a 3D pdf file and a solid 3D model of the building or the floor.

2) Data Collection: Pleiades Stereo Image Acquisition

Stereo or stereoscopic imagery refers to acquisition of two or more images of the same area taken from different angles such that the same scene is visible in different photographs [4]. Two overlapping images are called stereo pairs while three overlapping images of the same scene are called tri-stereo images [13]. For this study, very high-resolution Level-1B Pleiades cloud free stereo satellite images with a resolution of 50 cm were obtained with both acquisition date of 17 October 2019 (Figure 3). The first satellite, Pleiades-1A, was launched in December 2011, while the second, Pleiades-1B, was launched in December 2012. Both satellites, part of the French-Italian Optical and Radar Federated Earth Observation program for civilian and defense uses [17].

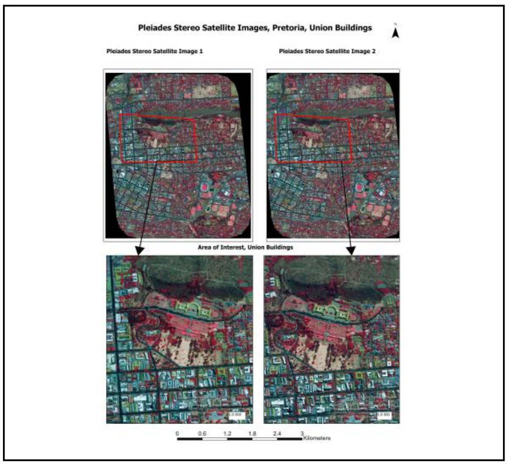

Figure 3. Very High resolution Level-1B Stereo Pleiades Satellite Image (50cm resolution) [17].

3) Pre-processing of remotely sensed data (images and metadata): Sensor Model and Adjustment

After image acquisition, the next task is to preprocess the images with related metadata by defining a geometric sensor model and adjustment of the model, in this case, rational functions model was used. During Pleiades stereo image acquisition, additional file formats were provided including a set of RPCs (Rational Polynomial Coefficients). RPCs defines the expression of 2D image pixel coordinates to 3D ground coordinates in a mathematical sensor model are scaled to two cubic polynomial expressions [18]. The provided RPCs (computed for each image) allows for automated and robust creation of the 3D surface model as it defines the rational polynomial sensor model for georeferencing (ground-to-image geometry), thus, replaced a physical sensor model [10,19]. Hence, IMAGINE Photogrammetry toolbox available in ERDAS IMAGINE 2022 was used in this study for setting up rational functions and adding the provided Pleiades RPCs for interior and exterior definition of each image for geometric sensor model. The major benefit of utilizing RPC model is that it presents the main solution for sensor modeling where novel sensors are automatically supported by identified implementation [10].

4) Ground Point Measurement

Ground Control Points (GCPs) were then added to the adjusted sensor model. GCPs tie the images to reference points to increase the map coordinates and height accuracy of stereo model [20]. Classic Point Measurement tool (CPM) in IMAGINE Photogrammetry and google earth was used to generate and tie GCPs visible in both images.

5) Stereo Matching

The most challenging part in the processing of stereo images is called the correspondence problem, where coordinate of each pixel, in this case dense pixels, in the first image corresponds to the coordinate pixel of the second image which has similar object has to be computed [11]. The process of finding these shift vectors is called image matching [10]. A classic point measurement tool in IMGINE Photogrammetry was used for stereo matching. This tool is very efficient as the process is automated and computer efficient.

a) Auto tie points Generation

Auto tie points generation algorithm in Classic point measurement ERDAS imagine was applied for stereo pair imaging as it is a very efficient algorithm. The Automatic Tie Point Generator automatically placed tie points on matching pixels in overlapping areas between images to link them together and refine their alignment [10,21]. A total of 150 auto tie points were generated for image matching. Parameters such as correlation Size, Feature Point Density, and Number of Points/Image are variables had be defined in the tool. Furthermore, this is an iteration process until the desired results are achieved where average point success rate is at least 75%.

b) Performing Triangulation

Triangulation in stereo matching is the process of defining the mathematical relationship between the images contained within a project, the camera or sensor model that obtained the images, and the ground. A triangulation divides a surface into triangles, connecting all given points to the triangle network [22]. This relationship must be defined in order to create products such as 3D point clouds, orthoimage, and elevation models from stereo imagery. A Classic measurement tool in IMAGINE Photogrammetry was used to perform triangulation. This process is also run several times to get acceptable results, in this case, lower RMSE of less than 0.2 as possible. Root mean square error is one of the important indicators to measure 3D coordinate accuracy, which is widely used in various fields [23]. The following formulae were applied for accuracy assessment:

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{N}(xi-xie)^2}{N}}$$

RMSE= root mean square error, i= variable observed, N= number of non-missing data points, x_i= actual observation time series, x_{ie}= estimated time series.

6) DTM and Orthoimage Generation

In the literature, most DTM generation approaches are designated for airborne LiDAR data, some for DSMs extracted from high-resolution airborne optical images and spaceborne optical imagery [10]. In this work, DTM extraction approach was extracted using automated photogrammetric tool called Auto Terrain Extractor. After DTM extraction, it is crucial to generate orthoimages. Orthophotos are used to reference image background important for the creation and maintenance of geographic information contained within a GIS database [24]. Orthoimages were computed using Ortho resampling tool incorporated within IMAGINE photogrammetry module for both images.

7) DSM Generation and Point Cloud

ERDAS IMAGINE DSM Extractor has two varied automated DSM extraction engines with different levels of accuracy, resolution, and speed, namely, Sparse Matching and Semi-Global Matching to generate DSM and point cloud [24]. DSM extractor tool using Sparse Matching was selected as the aim of the project was to generate high accuracy model. The Semi-Global Matching (SGM) in DSM extractor tool very dense and high-accuracy DMSs and it is an algorithm that uses pixelwise, mutual information (MI)-based matching cost and a smoothness constraint to generate dense disparity maps, from which surface modes are generated. The advantage of this technique and the tool is that it generates DSMs and point cloud (.las or LAZ) that enables extensive postprocessing options using Point Cloud tools, RGB encode from a secondary ortho image source, Point cloud operators available in Spatial Modeler, Multiple viewing options, Classification, Elevation, Intensity, Returns, or RGB, Merge, split, filter and Subset [13,24].

8) Point Cloud Classification and Reclassification

The point cloud generated was then classified using Classify tool in ERDAS Point Cloud Tool where vegetation parameters i.e., greenness, maximum and minimum height for low and high vegetation had to be defined and object parameters i.e., minimum slope, minimum height, minimum and maximum area, plane offset and roughness. The process was repeated until desired Point Cloud classification was achieved. Prior processing the point cloud in ArcGIS Pro, the las file was reprojected in ERDAS again. ArcGIS Pro was predominantly used to improve accuracy of the Point Cloud classification using reclassify tool and by applying post processing techniques such as editing tools.

9) Extracting Footprints, Solid Model in ArcGIS Pro and Post Processing

For the purpose of this work and time constraints, solid models of buildings were used because floor plans were further used for accuracy assessment and creation of accurate models in CAD for printing. Classified point cloud was filtered with building and ground points to create separate files that were used to generate footprints as rasters, later converted to vectors. Point cloud data, extracted building footprint and DEM were used to produce a solid 3D model using the Building Multipatch tool in ArcGIS Pro. Editing tools such as eliminating polygon part, regularise, enclose multipatch were used for post processing of building footprints and solid building multipatch to create a generalized and representative of the buildings. An enclosed multipatch solid model was exported to a printable CAD format Collada (dae) for further processing in Autodesk Inventor.

D. 3D Model Design Process for Accuracy assessment of solid DSM and 3D printing

The design process followed is depicted in Figure 2 and this includes details of the tasks from importing GIS file in CAD software to printing out the 3D model.

1) Importing GIS file and Additional Data capture in CAD software

From the 3D digital surface model generated in ArcGIS pro and exported to CAD format collada file and further converted to obj in City Engine, the file is then imported to Autodesk Inventor for further processing. Depending on client needs, specific areas or buildings that are of interest to the client such as a 3D model of a building or a specific floor or room of a building, 3D models of such can be generated and printed. For the purpose of this research, union buildings was used as a model to outline important tasks to execute for generation of 3D products either Digital Terrain Model, Point Cloud dataset, Classified surface features i.e., buildings or vegetation and these were outlined in the previous section. Other outcome results or 3D products can be a 3D pdf file and a solid 3D model of the building or the floor. In this case, Union buildings was used to generate 3D prints and this section will also highlight some samples due to the sensitivity of models generated. For detailed model of the building, floor plan drawing were provided by the client (see Figure 4).

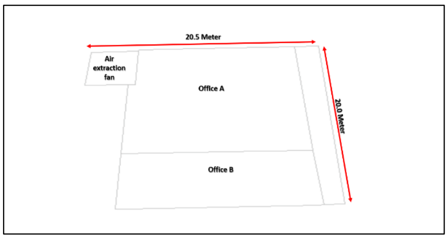

Figure 4. Floor plan drawing

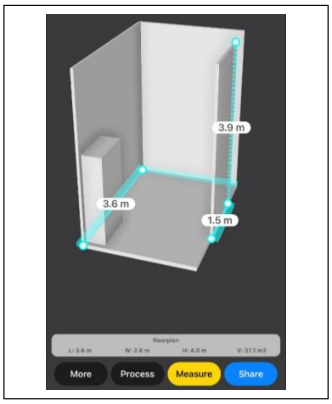

Figure 5. 3D lidar scan floor plan

In case the floor plans are unavailable, the data is acquired automatically using LiDAR technology to obtain floor plan (Figure 5).

In Addition of the floor plan we request, photographs, and video from the building. This additional information is later added onto the model to enhance the model to give it a more realistic look. This technique is call rendering and it allows the client to gain a better understanding of a design's intentions.

2) CAD Software Considerations and Data Capturing

Autodesk Inventor is CAD software known for its data capturing capabilities [25]. It enables the creation of accurate 3D models was used for capturing and processing building plans and the LiDAR scanned data. The software facilitates precise measurements, dimensions, and details for enhanced accuracy in 3D printing [25].

3) Scalling and Wall thickness considerations

The printer's limitations on wall thickness must be considered when scaling the CAD model for 3D printing. Printing walls that are too thin can exceed the printer's capabilities. Proper adjustment of the scale ensures printable wall thickness.

4) Design Confirmation and STL Export

Confirmation of design and exporting to STL format are vital steps in 3D printing process. Involving stakeholders during design confirmation helps improve quality [26]. Insight Software by Stratasys assists in slicing and print preparation [27]. These steps ensure the compatibility and optimization of the design for successful 3D printing.

5) Insight Software: Optimizing 3D Printing Quality

Insight Software, developed by Stratasys, is used for processing STL files, and optimizing 3D print settings. It allows users to configure parameters such as model orientation, support structures, and slice height to achieve desired print quality [27]. The software provides visualization tools for previewing sliced layers and addressing potential issues before printing. Using Insight Software helps optimize the printing process and ensure high precision and quality.

6) Configure Modeler: Density Optimization

Selecting the appropriate material density (solid, sparse, or dense) is crucial. Collaboration with the client during the design confirmation ensures accurate representation of their vision.

7) Print solid model

The printing of the solid model was performed using the Stratasys FDM F900mc printer. This printer is a high-performance thermoplastic 3D printer known for its ability to consistently produce accurate and precise parts or models (Stratasys, n.d.). The FDM F900mc printer is widely utilized in various industries, including aerospace, automotive, manufacturing, and defense (Stratasys, n.d.). Its reliability and versatility make it a suitable choice for creating solid models with high-quality and repeatability to choose the type of modeler, model and support materials, extrusion tip sizes, and slice height to be used (Figure 6).

8) 3D Printing: Print solid model

The Stratasys FDM F900mc printer was used to print the solid model. The Stratasys FDM F900mc print is a high-performance thermoplastics 3D plastic printer that can produce highly accurate parts or models repeatably. The Stratasys FDM F900mc printer can be utilized in the Aerospace, Automotive, Manufacturing and defense sector.

Figure 6. FDM F900mc 3D printer

III. RESULTS AND DISCUSSION

This section covers results and products obtained from the End-to End workflow detailed in the previous section, importantly generated using automated methods in three software outlined. The following products were generated, each crucial for a final product of 3D printed or digital 3D products to meet user/client requirements: DTM, Ortho image, DSM, point cloud, classified point cloud, solid building model, 3D printed and interactive 3D pdf model.

A. OrthoImage and Digital Terrain Model

Below figure shows orthoimage crucial for consistency georeferencing, generating after ortho resampling using IMAGINE Photogrammetry (Figure 7).

Figure 7. Orthoimage from ortho resampling. The orthophoto produced has very high resolution of 0.5m, good for ensuring georeferencing maintenance.

During DSM generation, the important and most challenging process is image matching and during the automated process of matching, auto tie points produced RMSE of 0.1 pixels which is good. RMSE is used to evaluate the accuracy of aerial triangulation results. The aerial triangulation accuracy of the model is evaluated in many aspects by calculating the model plane error, elevation error and 3D error and the 3D generation model RMSE results produced high accuracy with similar accuracy levels by Chen [23]. Triangulation of stereo matching achieved a success rate of 100% which then later the point cloud model was created. The figure below shows DTM generated using auto DTM Extractor tool with resolution of 0.5m (Figure 8).

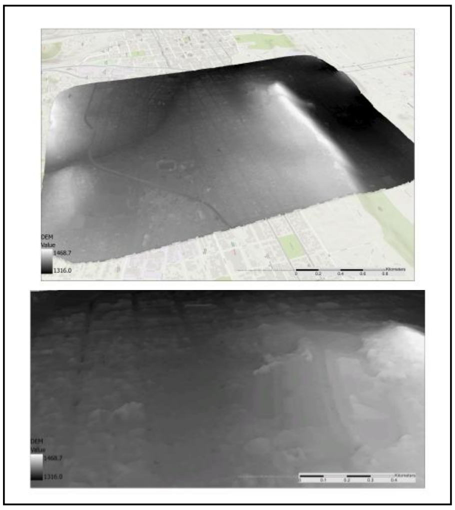

Figure 8: DTM generation from Auto DTM Extractor tool

B. DSM and Point Cloud dataset

The DSM extractor tool resulted in DSM and point cloud using SGM engine provided the following classification and multiple viewing options including Elevation, Intensity, Returns, RGB, filter and Subset for further assessment of point cloud data (Figure 9 and Figure 10). Below is a Digital Surface model generated (Figure 9 and 12).

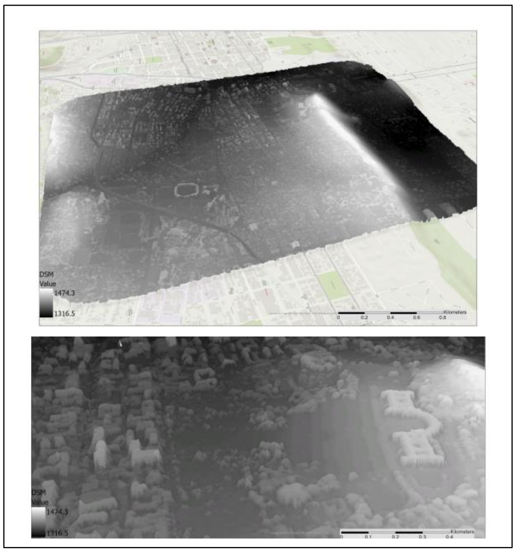

Figure 9. Digital surface Model

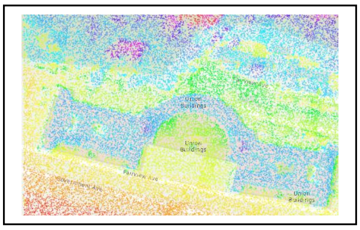

Figure 10. Point Cloud symbolized using Elevation Classified

For example, the following visualization in Figure 11 is depicted as Elevation: Red = Terrain, Blue = Building/Mountainous, Light Green = Grass. With this type of data visualization, one can be able to discriminate the shape of the union buildings.

C. Classified surface features i.e buildings or vegetation

The ERDAS IMAGINE DSM Extractor generated point cloud data that was classified in the classify module in IMGINE Photogrammetry. The figure below shows classification results where main surface features were classified i.e., low vegetation (which is grass), medium vegetation (representing shrubs) and high vegetation, buildings, water and road (Figure 11). Classification results had to be further reclassified in ArcGIS Pro using LAS/Point cloud editing tools.

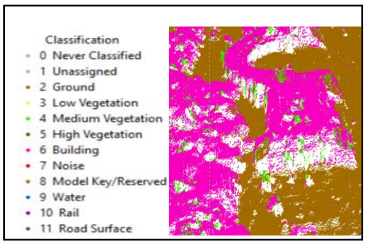

Figure 11. Classified Point Cloud

D. Post processing and Generating solid 3D Multipatch models

After classification, post processing of classified point cloud has to be performed to increase accuracy. Furthermore, generating subset of building solid model, Union buildings was used for this purpose. Building footprints were extracted and edited using reguralise and eliminate polygon part editing tools (Figure 12).

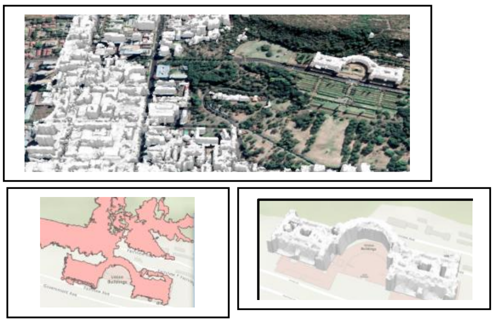

Figure 12. Post processing of footprints and solid models and Building Multipatch representing Digital Surface models of buildings as solid models

The error margin of building footprints creation was at an average of 84.76%. Then building footprints as vector, classified building point cloud and DEM were used to compute solid multipatch building (Figure 15). Editing tools were also applied additionally with enclosed multipatch process for CAD exportable format. Multipatch was converted to Collada (.dae) file and .obj in City Engine software for further processing and printing in CAD software Autodesk Inventa. City Engine is a 3D modeling software used for the creation of a virtual 3D city model has been provided by the GIS environment [4]. The figure below shows surface profile (includes elevation above sea level and building height) of Union buildings and the arch can be seen with low height values (Figure 13). Cross sectional Surface profiles that include elevation above sea level are crucial for military operations such as line of sight simulations to assess if the target will be visible.

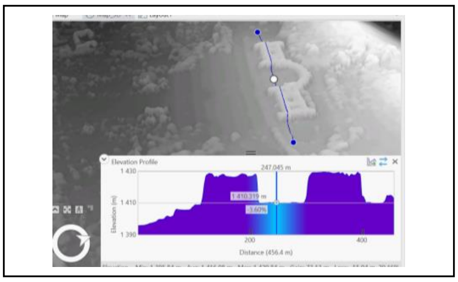

Figure 13: Cross sectional Surface Profile of Digital surface model of the union buildings

E. 3D PDF file

The 3D interactive pdf file is created in Autodesk Inventor but viewed in Acrobat. Acrobat provides the user with the option to view or hide parts of the 3D model by turning features on or off such as measurements. The model can be viewed as 3D or 2D (Figure 14).

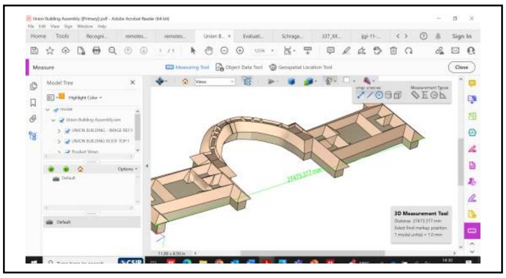

Figure 14. Interactive 3D pdf file of the Union buildings

F. Solid 3D model 3D Printed

The results in this section covers 3D printed buildings using plastic and powder printer. The union building model was printed using a plastic printer as depicted in figure 15 while figure 16 shows a sample of 3D printed building using powder printer.

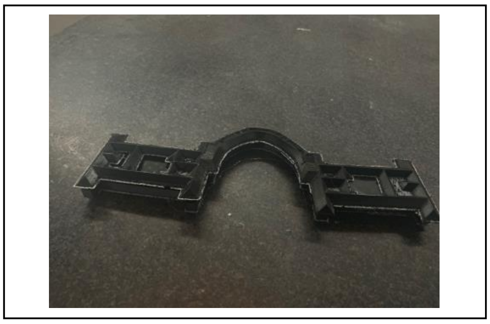

Figure 15. Union Buildings 3D printed using plastic printer

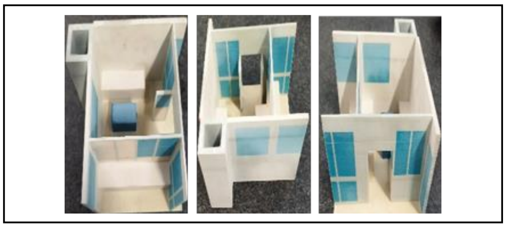

Figure 15. Sample 3D printed building using powder printer.

IV. Conclusion

The study revealed an End-to-End workflow process for generating digital 3D models of the landscape and 3D digital printed buildings by fusing the two Pleiades Stereo images using various software and novel tools for automated mapping. Deriving an automated end-end methodology and workflow for producing 3D landscape models provide a systematic and rigorous approaches crucial for military operations due to time constraints during deployments and planning. Advantages and uses of stereo and 3D landscape mapping stipulated in this paper is that it provides a large-scale area with high acquisition frequency and various benefits for the military when planning an operation or exercises. The most crucial part of this workflow is a clear understanding of user/client requirements and input data required and this study highlighted cases where additional data can be used to generate accurate 3D models. Particularly cases where there are no floor plans, provisions were made such as using 3D lidar scan video to generate floor plans directly and automatically from the scan. However, the models could be improved with the acquisition of newly launched Pleiades Neo with high resolution of 30 cm and tri-stereo (3 stereo images) 30 cm and this will also reduce time costs to post-process the solid models The Landscape 3D model products highlighted in this paper are applied for special operations during environmental reconnaissance, military geo intelligence planning purposes for simulation of various activities. The field of 3D modelling is continuously improving with future works directing more towards processing the remote sensing images using artificial intelligence and big data and furthermore generating 3D models using GIS for metaverse with advantages of remote sensing having the capability of acquiring such data particularly in inaccessible areas.

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Agile Thinking towards ICT Capability Development through Project Management in Defense

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Abstract— It can be difficult, especially for defense organizations, to balance traditional planning and system acquisition. The strain to learn and stay current with new technologies is a particular worry because they are developing at previously unimaginable rates. The high failure rate of information and communication technology (ICT) capabilities is indicative of the difficulty resulting from the poor and rigid application of project management methodologies. In the context of defense organizations, particularly the South African Department of Defense for the delivery and management of ICT capabilities, this paper examined efforts to bridge the gap between generally accepted techniques and ICT project management methodologies. The literature assessment revealed that a combination of project management methodologies was necessary to enhance the delivery and management of ICT capabilities because no one project management approach was suitable for projects developing ICT capabilities. A mixed-methods technique was used together with a convergent research design. Secondary sources were used to provide a thorough background to the problem, and the ICT function of the South African Department of Defense was used as the case study, as part of the descriptive study in this paper. These sources also served as an inspiration for the development and illumination of strategies to address the problem. The end result was the documentation of a possible approach that might be taken, while also acknowledging the particular value that ICT initiatives offer the military. The final strategy, which will be based on the best project management methodologies, will support the requirement for productive work while outlining project processes for the successful provision and administration of ICT capabilities. A unique approach for the project management of the development of ICT capabilities was developed and defined as a consequence of taking into account the unique challenges encountered by the military, the importance of scaling agility in defense organizations, and a study of project management methodologies. In conclusion, the strategy proposes a combined project management method for ICT capability creation and management in defense organizations that might, in theory, work.

Keywords—Agile, capability, defense, ICT, management, methodology, project management

I. Introduction

According to Hughes [1], Sudhakar [2], and Standish Group [3], suggest that there is a noticeable and growing trend of project failures. These failures are likely to have a negative impact on organizations' ability to achieve their goals and deliver successful projects to develop capabilities. These failures are closely linked to organizational frameworks. These frameworks encompass the structures, processes, methodologies, and strategies that guide how projects are planned, executed, and managed within an organization. The inadequacy or misalignment of these frameworks may contribute to capability development failures. Despite the observed increase in project failures, organizations are continuing to invest heavily in information and communication technology (ICT) projects to develop ICT capabilities. This suggests that even in the face of potential failures, the importance of ICT and its potential benefits drive organizations to invest significant resources [4].

The large number of unsuccessful projects demonstrates that current personnel, methods, and strategies are insufficient to guarantee success. ICT competent resources must, obviously, be properly coordinated [5], [6]. Investigations into the causes of ICT capability development failures showed that organizations have a history of failing to learn from those failures and apply those lessons to subsequent capability development projects [1]. According to Taherdoost and Keshavarzsaleh [7], the challenges and risks associated with ICT initiatives within defense organizations, underscores the need for vigilance and proactive measures to ensure success, given their importance in modern defense operations.

There is an intricate nature of managing ICT projects and capability development, especially within the challenging context of defense organizations. The integration of rapidly evolving technologies, combined with the need to meet rigorous command and control (C^2) requirements, creates unique complexities that require strategic planning, effective project management, and a balance between innovation and regulation. There is tension between the established characteristics of defense organizations, such as well-defined C^2 structures, management hierarchies, and clear objectives, and the need for agility in developing ICT capabilities. While these characteristics have their advantages, finding ways to navigate and adapt within these structures is crucial to effectively harness the potential of ICT in defense contexts [8]. The success of project management in handling ICT initiatives within an organization is contingent upon recognizing and navigating the various economic, political, and social factors at play. An organization's ability to adapt its project management practices to these elements can ultimately influence the outcome and impact of its projects to develop ICT capabilities [9], [10]. A combination of factors, including agility, communication, management support, commitment, authority, ownership, and structure, contributes to the effectiveness of a project team. Recognizing the influence of the working environment on project outcomes and addressing these factors collectively is vital for achieving project success [11], [12]. The insights from Heineken [13] and Schreiber and Carley [14], indicates the increasing misunderstandings within the context of defense organizations, which in turn leads to reduced performance, ultimately negatively impacting the effectiveness of developing ICT capabilities.

This study highlights the importance of understanding how project management influences the development of ICT capabilities within a defense organization and outlines the steps the study takes to explore this topic comprehensively. The upcoming sections of the study will cover a literature review, the research problem, the methodologies employed, and the findings obtained through an exploratory mixed methods approach.

II. Research design

The South African Department of Defense (DOD) was the context for a case study research project [15], [16]. It explains the importance of conducting case study research to shed light on the significance and influence of the studied environment and to analyze how that environment has evolved over time [17]. Case studies are particularly valuable in situations where there is a lack of well-established theories or gaps in existing knowledge, as is the case in exploring the use of project management for ICT capability development within the DOD [15].

The study is emphasized by the initial step of collecting both qualitative and quantitative data within the convergent/parallel sequential strategy [15], [18]. This strategy aims to recognize and validate existing perceptions that might need adjustment, while highlighting the advantages of employing diverse, combined, or integrated research techniques. While some researchers, such as Plowright, prefer integrated methodology frameworks, there is a recognition that certain writers deviate from conventional approaches to emphasize the meaningful differentiation between qualitative and quantitative research [19]. The study employed a convergent design in which both qualitative and quantitative data were simultaneously collected and analyzed. This was done in order to pinpoint the problems that already existed and needed to be fixed. The process required acquiring both qualitative and quantitative data, analyzing each kind of information separately, and determining whether the two pieces of information agreed with or disagreed with one another. It was evaluated whether the data guided conversations on the perceptions of applied project management for ICT capability development projects towards agility in thinking after the synthesis and interpretation of the data.

III. Literature review

A. *The Defense Organization*

In comparison to any other organization, defense organizations are viewed as special due to the kind of individuals and organizational structures that support how things are carried out. C^2 is a significant aspect that differentiates defense organizations from other types of organizations, but it's not the only difference. Defense organizations have unique characteristics and requirements that set them apart from other sectors. While C^2 is a crucial factor in defense operations, a conflict exists between the self-determining requirements of stakeholders and their position inside the organization within the DOD projects. According to Fernandes, Ward, and Araju [20], the conflict between what the organization wants and what project methods can produce when used is the constant issue in project environments. In order to support the implementation of strategic projects and the development of capabilities, defense organizations like the DOD are now making the most of project management processes [21].

There is a perception that projects, project managers, and project resources are impacted by structure and C^2. However, the success of an enterprise like the DOD in managing the development of its ICT capabilities depends on top management's agreement and accommodation of the necessary project management approach [15].

B. *Project Management*

Project management is widely applied across various industries and sectors to ensure successful and efficient completion of projects. It provides a structured framework to manage complexity, reduce risks, and achieve desired outcomes. Since projects are distinctive, employ a variety of professionals, and typically have transient activities, they actually require advanced management approaches and organizational forms [22]. Despite being inherently temporary, initiatives that are in line with the organization's strategy help the organization achieve its goals [23].

According to Stoshikj [5], Cohen [24], and the University of California [25], project management plays a crucial role in organizations. They assert that this has changed project management's position as a result of the fast-paced markets and technological advancement. According to Kerzner [26], technology-related projects are the most difficult to manage because they demand a lot of innovation and the risks that go along with it. Thus, this calls for iterative approaches, agility and creativity, which supports the idea that ICT capability development calls for a unique form of project management.

The success of projects is impacted when project management procedures are insufficient or lacking, so these flaws must be fixed. Joslyn and Müller [27] point out that there are restrictions when utilizing a project management technique in their investigation. These authors go on to say that because different organizations use different methodologies, tools, and strategies, these restrictions vary in completeness and application between them. The fact that some project management approaches are inadequate for dealing with particular project types is one of their main shortcomings [27]. Furthermore according to these authors [27], the literature is not clear on whether standardization, customization, or a mix of the two will result in improved project success. This view is supported by Wells [28], in that the applicability varies by organization, and certain standard project techniques are not appropriate for all kinds of projects. Investigating the various project management approaches is necessary to comprehend project management and what could be potentially suitable for defense.

C. Project Management Methodologies

There is a necessity to address the evolving needs for project management and execution within defense organizations, particularly in response to the changing nature of combat and shifting objectives. The challenges arise from the need for adaptable project organizations, both temporary and permanent, and the requirement for scaling agility in project management practices to efficiently deliver solutions. ICT initiatives focused on developing capabilities within defense organizations require a distinct project management methodology. Additionally, the importance of project success within the military context and the potential for adopting hybrid techniques if existing project management practices do not align with the unique demands of defense projects should be considered.

Therefore, it is plausible that control systems like C^2 within the DOD cause project management settings to fear failure and innovation. The finest project management approaches that could work for the DOD and within C^2 must be found and compared in order to define a new method of managing ICT projects for the development of capabilities in the DOD.

Enoch [29] emphasized the distinctions between modern project management and traditional project management during his presentation at the KwaZulu-Natal Regional Conference of PMSA (Project Management South Africa) in 2016. The author highlighted the differences between these two approaches, noting that traditional project management, which has evolved since the 1960s, is suitable for large, long-term projects in stable environments. In contrast, modern project management techniques are better suited for projects where requirements frequently change. Additionally, while modern methods may align better with client and organizational needs, traditional project management excels in precise planning [30].

The various methodologies were analyzed to determine which were the most suitable. Table 1 highlights the advantages and disadvantages of comparing different methodologies to determine the most suitable approach.

TABLE 1: COMPARISON OF THE IDENTIFIED PROJECT MANAGEMENT METHODOLOGIES USED IN THE DOD [31], [32], [33], [34], [35]

Methodology	Comparison
PMBOK	Advantages: • PMBOK, like PRINCE2, is an internationally recognised methodology and is widely used in the USA. • PMBOK applies an international standard to the Waterfall method (sequential flow) and is a concise methodology that can be used to manage large projects. • It supports work in a standardised way across departments and institutions. • It brings about standard terminology and - practices to project management. Disadvantages: • PMBOK, like PRINCE2, is not suitable for smaller institutions that want to work at a faster pace and is complicated due to its conciseness.
Adaptive (Agile) Project Framework	Advantages: • Agile allows for high flexibility in a project as its name suggests and is done using repetitions that allow the project to continually adapt to the needs identified. • Because the process is flexible no time and resources are wasted for a full project that could be rejected as deliverables are delivered in pieces constantly. • Agile has a high satisfaction index as feedback is essential and the customer has a strong impact on the development project. • Cross-pollination and interaction during the process prevent duplication of activities. • Continuous quality assurance and attention to detail are maintained since delivery is over short cycles. Disadvantages: • Agile normally has numerous small teams, the workflow coordination becomes a problem, which creates a huge amount of communication that needs to be considered before any work can be done. Thus, communication becomes a disadvantage. • Part of the detailed planning that is needed is to have professional teams in place that can take serious decisions when required before the process can start. This means only experienced members are suited and can take decisions. • Agile delivers in short cycles there is a lack of long-term planning, which could create a lack of vision, especially within institutions that follow a strategic long-term focused thinking approach. • The constant role the customer plays can derail the project due to demanding changes during the process.

	• This way of working requires numerous small teams there is the problem that all pieces must be integrated at the end, which might then require further changes to make everything work. • This method is weak in documentation due to the hands-on nature of customer interaction which mostly is verbal.
Event Chain Methodology	Advantages: • In the mapping of resources, you know who is available for what part of a project, making collaboration easier. Disadvantages: • Time allowances are built into each part of the project plan and thus this method will not work well for smaller projects with quick turnaround times.
Extreme Project Management (XPM)	Advantages: • This method allows institutions to save costs and time in project realisation since the focus is on the delivery of the final product. • Money is saved as less documentation is generated as problems are solved through discussion within the team. • Simplicity is a preference throughout the process, which allows for improvements at any time. • The process is visible and in turn brings accountability. • Constant feedback throughout is strong. • This method supports the development of software faster due to allowing change and regular testing. Disadvantages: • This method is focused on code and not design, thus creating problems as good designs in software projects are crucial. • Documentation is sparse and may lead to problems down the line. • XP does not measure quality assurance which could cause problems and defects later on.
Lean	Advantages: • Ideal and easy to use in manufacturing and production that deliver physical products. • There is the elimination of disused inventory and waste. • Lean allows for strong customer relationships. Disadvantages: • Traditional methods that are becoming less relevant today.
Process-Based Project Management	Advantages: • Improved project processes, which in turn increase the value and benefits of the project results at reduced costs. • Project alignment with the institution's strategic vision. • Institutions gain flexibility and processes are cross-cutting in that they reach different services within the institution.

	• Project roles and responsibilities are clearly defined to support the achievement of the goals of the institution. • There is optimised use of resources, which in turn reduces management and operational costs. • This process supports improvement in that deficiencies are quickly identified, and the associated risks reduced. Disadvantages: • This approach when implemented is a change for a traditional hierarchical institution and thus change management is crucial for success. • This methodology must be applied to the whole institution and not just single entities.
PRINCE2	Advantages: • PRINCE2 is the most used methodology in the world and thus tried and tested. • Common and understandable terminology for all projects. • It maps out phases of large projects from beginning to end, highlighting what will be delivered. • There is a focus on extensive documentation which allows for lessons learnt and auditing of projects. Disadvantages: • PRINCE2 is very rigid like all Waterfall methods, in that nothing will take place unless the preceding step has been done. • It is not for small projects or institutions that don't have the time or resources to manage projects. • The extensive amount of documentation creates a disadvantage in that changes are hard to accommodate, and documents must be redone, tying up resources that could hamper progress and deliverables.
Benefits Realisation	Advantages: • Benefits Realisation supports the success of projects that bring about change due to the focus being on the added value the project brings. • It provides a practical 'framework' for ensuring real results. Disadvantages: • Institutions do not find this method easy as managing benefits formally is a problem in institutions as shown in the literature as to why projects fail. • Members within institutions do not always understand what benefits versus objectives are, as the achievement of objectives leads to the realisation of benefits. • The structuring of benefits realisation needs to be simplified and clearer for a better understanding. • Accountability for benefits is not formally defined.

	• This method needs the active management of project plans.

It has become abundantly clear through the comparison of the top project management methodologies that a combination of some of these including PMBOK, Process-Based Project Management, PRINCE2, XPM and Benefits Realization, may be the best course of action for defining how the DOD could bring agility to the development of ICT capabilities.

For the purposes of this study, the preferred five methodologies are the most appropriate because they are: (1) structured; (2) appropriate for large organizations; (3) create the necessary audit trail; (4) allow for the achievement of objectives; and (5) can be aligned to the formal structures of organizations like those in defense environments, with particular reference to the DOD.

D. Failure of Projects

Taherdoost and Keshavarzsaleh [7] claim that there is empirical data showing that projects, especially those specifically for ICT, are vulnerable to numerous sources of hazards because they are believed to be agile, technological, and complicated in nature. This claim is corroborated by Hughes *et al* [1], as they note in their analysis, there is an incredible failure rate of ICT projects in the range of 20% to 30%, with failures being more prevalent in the public sector.

Although there has been an increase in ICT investment, the high failure rate in organizations like the DOD raises concerns because it indicates management issues with the application of suitable project processes and technological dimensions [1], [7]. In the authors Taherdoost and Keshavarzsaleh's [7] attempt to deconstruct and categorize project failure in order to better understand its root causes, it is noted that there is a correlation between the organizations and how they are structured for the development of ICT capabilities and what project management practices are used, with a specific focus on an appropriate project management practice.

E. Information Communcation Technology

International military organizations are actively utilizing ICT as a strategic capability, and as stated by Gartner [37], ICT has been highlighted as both a future component of warfare and in streamlining the operations of organizations that use ICT.

With the globalization of communication networks, infrastructure components of information technologies, as well as the increasing use of cyber systems by economic, political, and military systems in the decision-making processes for conducting warfare, cybersecurity as a component of ICT has become a matter of critical interest and global importance. According to projections, cyberspace will soon join the conventional battlegrounds of land, sea, air, and space as a new theater of conflict. The Enhanced NATO Policy on Cyber Defense, which elevates cyber defense to the status of a strategic component of the NATO concept of collective defense, was endorsed as part of the North Atlantic Treaty Organization (NATO) Summit in Wales (September 4, 2014). This idea emphasizes the function and significance of ICT, which is gaining popularity on a global scale [38], [39].

F. The Revolution of ICT

According to Ndung'u and Signe [40], the fourth industrial revolution (4IR) is about a data-driven economy fueled by digitization, AI, cloud computing, robots, 3D printing, the Internet of Things, cutting-edge wireless technologies, etc. Military innovation and productivity from a business perspective must always keep up with the latest global trends. In order to maintain their superiority in the information and cyber sector, it is actually impossible for any military to compromise on innovation and technology. ICT is utilized for shaping, sharing, communicating, studying, playing a developmental function, as well as administrative support in organizations, to mention just a few ways that technology has impacted how things are done [41]. Masa'deh, Tarhini, Hani Al-Dmour, and Obeidat [42] argue that organizations using ICT and operating in this rapidly changing environment face challenges and must find novel ways to take advantage of changes in order for them to be advantageous.

In summary, this section emphasizes the need for users to be actively involved in capability management and decision making. ICT capability management allows capacity building initiatives in multiple sectors related to security, justice, governance, and economic and social wellbeing. Thus resulting in optimum effectiveness of ICT to be given higher priority in planning and decision making in terms of both investment and implementation due to the pace of the ICT revolution. Therefore, underscoring the importance of well-defined processes and structures to support ICT capabilities throughout their life cycle [43]. It can be said that he DOD is aware of the significance of the ICT revolution and its relevance for their operations, necessitating prompt and effective interventions towards capability development, including a strategy to aid in the transition of the DOD and its personnel (culture of doing things).

G. Capability Development

ICT Capability development refers to the strategic and systematic efforts undertaken by organizations to enhance their ICT-related skills, resources, and capacities. It involves a comprehensive approach to improving an organization's ability to effectively and efficiently leverage ICT to achieve its goals and objectives. Key aspects of capability development for ICT include: skills enhancement, infrastructure improvement, upgrading and maintaining ICT infrastructure, strategic planning, innovation and research, change management, cybersecurity, communication and importantly project management [44].

Capability development for ICT is a dynamic and ongoing process that involves adapting to technological advancements, organizational needs, and changing market conditions. By enhancing ICT capabilities, the DOD can stay competitive, improve operational efficiency, and drive innovation in today's technology-driven landscape.

H. Impact of Project Management on the Development of ICT Capabilities

There is a general consensus in the literature on ICT that ICT is transforming how we work and interact, and this is visible in what we use and how we use it. Throughout the life cycles of ICT systems and related technologies, agile and creative ways must be used. There is a wealth of literature on project success in project management, with a push in the last five years to coordinate actions at different levels inside ICT projects as an essential topic in project management. [45]. Therefore, it is impossible to dismiss the development of new technologies, their applications, and the DOD's supporting systems.

Organizations are not reaping the benefits of ICT projects to develop capabilities, according to Marnewick [46], because they are unable to manage them effectively. This prevents the projects from delivering the value necessary to support the goals and objectives of the organizations. There is the presence of procedures in organizations for administering projects related ICT capability development. However, only a minority of these organizations have a formal methodology to aid in the execution of these projects. The dynamic and continuous nature of capability development for ICT is reinforced, emphasizing the need for adaptation to technological changes, organizational requirements, and shifting market conditions. It underscores the benefits of enhancing ICT capabilities, including maintaining agility, competitiveness, improving operational efficiency, and fostering innovation in today's technology-centric environment.

I. Agility

Agility encompasses a combination of exceptional characteristics related to operations performance objectives. These objectives include attributes such as speed, cost-effectiveness, flexibility, and quality. However, the author suggests that reimagining organizational effectiveness is necessary due to the requirements and possibilities presented by the concept of agility [47]. The challenges of rapid technological change, which impacts everything from communications to computer networks to cyber security, have heightened calls for increased agility in defense procurement of ICT capabilities. The DOD risks lagging behind its partners and adversaries unless they find methods to become more agile when obtaining capabilities that rely on fast-moving technical breakthroughs. If this occurs, the DOD will confront increased risks and fewer alternatives for military deployment [48].

The agility and flexibility of the DOD to adjust to a fast evolving and continuously changing environment is becoming as crucial as investing in new ICT capabilities.

IV. DISCUSSION

The findings from the case study and secondary literature are presented to show which key elements are prioritized for the defense specifically the DOD that how a conceptual project management framework for ICT projects supporting capability development could be utilized [15], [49]. This suggests that the problem's current flaws are described along with a potential fix. The conceptual project management framework for managing ICT capabilities depicts a synopsis of various solutions.

A. Project Management Methodologies

Not all of the identified project management approaches were identified appropriate for use, thus combining some of them might be suggested as a possibility when establishing a special project management strategy for ICT projects in defense organizations. The PMBOK® (Project Management Body of Knowledge), process-based project management, PRINCE2®, and benefits realization are those best suited to be used by the DOD by drawing on their advantages (as discussed previously) and are therefore utilized. The DOD uses certain methodologies for managing its projects through policies like the DAP1000 and DAHB1000, which are heavily inclined towards a waterfall method and both identify the need for a unique process to meet the need for the development of ICT capabilities [50], [51].

B. The DOD Case Study

Like many defense organizations, the DOD follows a rigorous C^2 methodology. This method poses a conflict between project participants' autonomy and their place inside the organization's routines and efforts. All corporate or transversal ICT is handled by the DOD's ICT organization, however unique ICT that is integrated into weapon systems is not included and is handled as Category 1 Matériel under the DAP 1000 procedure [50], [52]. As a result, as previously stated, a formal process for managing DOD ICT requirements is unquestionably required in order to comply with applicable government and DOD laws, as well as ICT industry standards and best practices. DOD ICT will be better positioned to enable its business more quickly, successfully align, decrease costs when appropriate, and improve management accountability by changing the ICT project procedures.

Thus, The DOD is aware of the challenges and weaknesses in its organizational ICT processes and structure that limit successful ICT project implementation. Agile and responsive project management is critical for ICT activities to meet the demand for rapid response to technology, opportunities, and hazards. This will help to meet a requirement of the 2015 RSA Defense Review addressing the project management strategy for DOD ICT programs.

C. DOD Projects for ICT Capabilities

It's worth noting that, in recent years, defense organizations, including the DOD, have started to leverage project processes to support efficient decision-making and the execution of critical programs [53]. The relevance of project management in the modernization of the military industry, which faces several obstacles, has grown in recent years. Many organizations utilize project management to boost productivity, implying that it is best suited to address support procedures for capabilities and product systems, hence increasing the organization's ability to fulfill its goal [54].

D. Towards the Future of ICT Capability Development

ICT Capabilities are essential enablers of the coordination mechanisms that must be included in the DOD's capacity building since they are the primary component of the DOD's response to crises, whether they are caused by natural or man-made disasters or post-conflict. ICT skills and requirements need to be better understood in order for all parties working with the DOD to effectively develop and coordinate their efforts. As the DOD is a bureaucratic institution, barriers must be removed to support enablement through these coordinated efforts [55], [56], [57]. The DOD might thus significantly benefit from a revised or altered project culture and approach to project management for the development of ICT capabilities. To overcome these impediments and promote change through process management to establish collaboration between personnel and the rigor of form to support ICT projects in providing the essential outputs, the DOD requires organizational agility [58]. The DOD must seize this opportunity to reinvent itself by combining knowledge and abilities.

E. Results of the Knowledge Extracted leading towards the development of a conceptual project management framework for ICT projects in defence institutions

Based on the methodologies, the research design intends to develop a conceptual framework to address ICT projects for defense organizations and specifically for potential use in the DOD in their drive to develop ICT capabilities. This framework will be supported using the advantages of the methodologies highlighted in the literature review as well as the DOD as the case study. Furthermore, throughout the discussion of the results, areas of focus that were highlighted for improvement within defense organizations led to the identification of key areas for improvement and or development. The key areas in current practices that were identified and incorporated into a conceptual framework were [49]:

- The governance of ICT projects becomes essential within the organizational culture in identifying clearly defined functions, roles, and responsibilities, whether delivering a one-time solution or a need for continuing life cycle management. This would enable defense organizations to support their ICT enablement goals in a clear manner, free from confusion or opposition from all parties.
- If project management support is diminished as the project nears completion, alignment becomes more challenging. This must be addressed in the organizational culture of the framework so that ongoing portfolio management may take care of it. The methodologies stated are widely acknowledged, and they provide everyone with a shared understanding by detailing ICT initiatives and stressing what needs to be done.
- It is obvious that project management guidelines must be followed and that the C^2 of the defense organization must not take precedence. Projects must be given the freedom to take advantage of opportunities while still serving the organization's needs. In order to justify the necessity for this to be handled in the framework, defense organizations must become more project-driven than they now are.
- It is obvious that a variety of issues that frequently operate against effective project management have an impact on defense organizations. The suggested framework must make it obvious that some ICT requirements must be managed as projects within an independent project management culture and methodology.
- It is necessary to manage the ICT requirement for the capability throughout its life cycle. It is prudent for defense organizations to use a special project management technique because they operate and maintain a variety of ICT capabilities, some of which need to be managed as projects. The chosen approaches offer a variety of special benefits, particularly for major organizations supporting the success of projects developing ICT capabilities.

The conceptual project management framework (Figure 1) for ICT projects to manage capability development combines the findings of the case study with secondary literature identified to address the key areas identified above.

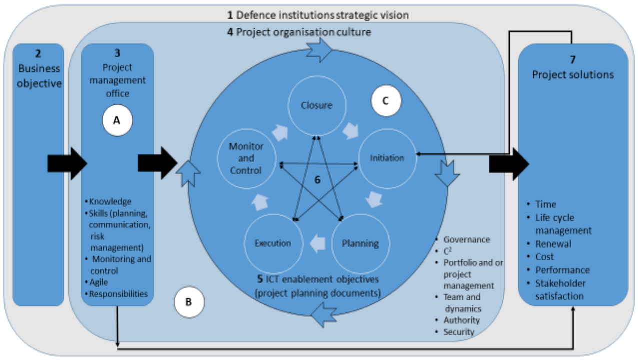

FIGURE 1: CONCEPTUAL PROJECT MANAGEMENT FRAMEWORK FOR ICT PROJECTS IN THE DOD [15]

The key areas of influence that have been integrated into a framework as represented in Figure 1 are and include:

- **Distinct Project Organization Culture**: This culture is based on project leadership and emphasizes a unique approach to managing projects. It likely involves specific values, norms, and practices that shape how projects are executed within the organization.
- **ICT Projects**: These projects are aligned with the organization's business objectives. The framework likely emphasizes the importance of ensuring that ICT capabilities are strategically linked to the broader goals of the organization.
- **Project Management Office (PMO)**: The PMO is an organizational unit responsible for overseeing and supporting project management practices. The framework highlights the role of the PMO in providing guidance, standards, and support to ensure successful project execution.
- **Adapted Project Organization**: The project organization is designed and tailored to meet the specific requirements of each individual project in the development of an ICT capability. This suggests a flexible approach that allows the structure and composition of project teams to vary based on project characteristics.

- **Systems Development Process**: The framework incorporates a structured approach to capability development, which includes planning, designing, implementing, and maintaining ICT capabilities.
- **Project Solutions**: The emphasis on project solutions in the framework addresses the outcomes and deliverables of projects for the development of ICT capabilities, ensuring that the solutions developed meet the intended objectives and requirements.

Overall, the above highlights the various components that are included in the framework, each contributing to the effective management and execution of projects for ICT capability development. The framework provides a holistic approach that considers organizational culture, project management practices, project organization, development processes, and project solutions in a coordinated manner.

This section leads on from the preceding discussion and provides a description of the conceptual project management framework for ICT projects (Figure 1). The following levels make up the conceptual project management framework [15], [49]:

- **Defense organization strategic vision**. The ability to set purpose and identify long-term milestones as a solid foundation to guide the development of defense mandates supported by ICT projects is the strategic vision of the defense organization.
- **Business objectives and projects**. It is necessary to attain these quantifiable achievements as a result of the defense organization's strategic positioning. Projects for ICT capabilities will be identified and prioritized according to the objectives, which also include the amount of resources that will be allocated.
- **Project management office (PMO) (A)**. To make sure that ICT enablement requirements are in line with the goals established and the advantages they must give, defense organizations should set up project management offices. In order to develop a better understanding of the roles, capabilities, and information needs among civilian and military components of the DOD's operations, this office plays a crucial role and is a crucial component of both the C^2 and management levels of a defense organization, and this is where mental agility should be emphasized.
- **Project organizational culture (B)**. The organizational culture of a project has a significant impact on its success. The suggested framework makes it apparent that ICT projects require an agile, independent project management technique that is established as part of the overall organizational culture and not only the currently used form of just C^2. A project culture will be guaranteed by aligning governance with authority without compromising independence.
- **ICT enablement objectives**. In order to prevent C^2 from obscuring ICT enabling objectives, project management principles are used for ICT initiatives and projects. ICT enabling requirements must have a clear return on investment and be in line with sound business practices. The arrows encircling the circle enable agility in action and the application of teachings, similar to the agility focus in components 3 and 6.
- **Project management systems development process (C)**. As previously indicated, project management guidelines are used here without being dominated by C^2. This section emphasizes the shift towards a project-driven organization in that the procedures are integrated into the organizational culture, so that ICT projects may take full advantage of opportunities while also satisfying the requirements of the organization, both of which are essential to successful ICT capability development. Since traditional linear waterfall methodologies are ineffective for ICT, projects must be able to change quickly, as indicated by the continuous feedback circle and the lines connecting the project management phases.
- **Project solutions and outcomes**. Project success in terms of time, money, and performance is referred to by this dimension. When ICT projects bring about the desired changes, benefits are realized. To satisfy the expectations of the stakeholders, a high-quality ICT solution or service is provided. Life cycle management begins when a project is completed or a solution is delivered. ICT capabilities must be handled till redundancy in order for renewal to take place. As a result, a new ICT enabling criteria for project initiation is defined. Return on investment will be tracked to ensure that the value of ICT capabilities is not diminished, and if it is, a quick choice may be made due to the process's agility.

V. CONCLUSION

The study identifies the best international practices that the DOD could use to develop its ICT capabilities in line with international norms. It is generally accepted that the development and revolution of ICT pose challenges for project management strategies used in ICT projects and cast doubt on the efficacy of traditional strategies employed by military organizations. The problems addressed brought applied project management to the forefront due to the rapidity of ICT growth and decline cycles, agility, leadership, decision-making, communication, knowledge, and human resources, amongst others, all of which are thought to contribute to the failure of ICT projects. The data from the secondary sources was combined with the context given by the DOD to identify a viable course of action.

In light of the environment of a defense organization, where projects for ICT capabilities are managed, it can be said that this study was significant in bridging the gap between generic project management approaches in use and those for the development of ICT capabilities. One of the critical criteria for the stabilization and future defense focuses in a journey to greatness is the renewal and optimization of the DOD's ICT. As a result, a potential conceptual project management framework was created for use in ICT projects inside the DOD to manage the development of ICT capabilities. The DOD and other defense organizations are expected to find the study's findings useful and informative.

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Towards Improving the Cybersecurity Skills Gap using Learning Factories

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***Abstract*— Cybersecurity is a pressing issue due to the increasing reliance on internet-connected technologies by governments, organisations, and individuals worldwide. Cybersecurity can also play a critical role in improving business drivers and helping organizations and the military attain a competitive edge using ICT. However, the cybersecurity skills gap is a significant problem that impedes progress in the field. The shortage of qualified cybersecurity professionals and lack of specialized courses, particularly in South Africa (SA) hinders the development of essential cybersecurity skills. This shortage of skills poses a significant risk to organisations and increases the chances of cyber threats and attacks. To address the persistent cybersecurity skills gap in SA, Cybersecurity Learning Factories (CLF) are proposed and the results of a pre-liminary implementation are discussed. CLF provide an efficient mechanism for training individuals with minimal cybersecurity skills in a focused and targeted manner, broadening the cybersecurity workforce and tightening the gap between education and experience.**

The aim of the study was to incorporate the missing cybersecurity component into different kinds of learning factories established at the CSIR and externally, while developing a solid Cybersecurity research development and innovation (RDI) base in support of a rollout of learning factories across South Africa. This CLF study was developed using a mixed-methods approach comprising a literature review, focus group discussions, a survey study, and expert reviews. The study was validated using an experimentation with students. The results of these studies showed that the implementation of CLF significantly improved trainees' cybersecurity skills and understanding. The CLF was implemented on tertiary students in the field of Information Technology (IT) and internship program employees from the CSIR to improve their cybersecurity skills.

Keywords—learning factories, cybersecurity, skills, cybersecurity training, cybersecurity learning

I. Introduction

Cybersecurity is a crucial concern given the indisputable reliance on internet-connected technologies by states, governments, organisations, civil societies and individuals worldwide. While the cyber threat landscape rapidly advances, the cybersecurity skills gap remains a significant issue. There are many barriers to entering the cybersecurity profession, including a lack of skills development, awareness programs and support within organisations, and few tertiary institutions providing specialized cybersecurity courses [8], especially in South Africa. This results in a lack of experienced and qualified cyber security specialists which further increases the cybersecurity skills gap [8]. Consequently, organisations can be vulnerable to cyber threats and attacks which pose a significant risk to their security, privacy, efficiency and financial stability.

To address the persistent cybersecurity skills gap and contribute towards the overall cybersecurity skills development in South Africa, Cybersecurity Learning Factories (CLF) are proposed and the results from pre-liminary implementation are discussed. A learning factory is an integrative educational environment, designed to promote learning by training individuals to practically apply concepts, tools and cognitive skills to solve problems in an environment that is set up to resemble a real working environment [4]. CLF provide an efficient mechanism to develop applicable skills by training individuals with minimal cybersecurity skills in a focused and targeted manner. Thus, broadening the cybersecurity workforce, changing current working practices and tightening the gap between education and experience.

In proposing and implementing CLF, a mixed-methods approach comprising a literature review, focus group discussions, survey study and expert reviews was taken. The literature review study provided insight on the significance of learning factories and implementation methods. The focus group comprised of experts from the Council for Scientific and Industrial Research (CSIR) manufacturing cluster and other institutions who have established different kinds of learning factories with most of the Fourth Industrial Revolution (4IR) components, except cybersecurity, and the project team leads from the CSIR Information and Cybersecurity Centre who implemented the proposed CLF. The survey study in the form of online questionnaires was completed by the CLF trainees before and after participating in the CLF. The results were captured, and analysed automatically by the CLF online platforms, and also manually by the facilitators who then offered expert reviews to determine if the trainees' cybersecurity skills improved after training in the CLF. The results indicated that the CLF are beneficial and can assist with the cyber security skills shortage problem.

The remainder of the paper is structured as follows. A background is given in Section 2. The experimental setup follows in Section 3. In Section 4, the findings are presented. Finally, the authors conclude in Section 5.

II. BACKGROUND

Cybersecurity professionals say the workforce gap remains the number one barrier to meeting their security needs and two-thirds (60%) of study participants in the 2021 ISC2 Workforce Gap Study report a cybersecurity staffing shortage [6]. This indicates that the number of cyber security professions continues to grow due to staffing shortages which can create security risks.

Figure 1 shows that cybersecurity professionals are interested in much more than technical skills and qualifications.

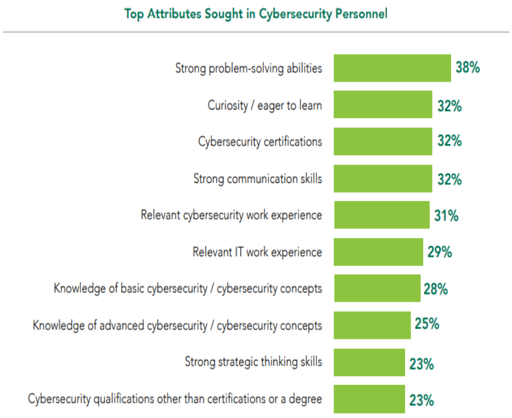

Figure 1: Top Attributes that Cyber professionals seek (ISC2 2021)

Together with basic cybersecurity concepts, there is the added facets of being able to think strategically, problem-solve, learn and communicate. Graduates that come out of universities and higher educational institutions may possess the baseline qualifications and degrees. However, some mechanism is needed that can enable practical thinking, application of cognitive proficiencies, problem solving and skills practice. The fundamental premise for knowledge acquisition in a learner is through direct experience emanating from experimentation as this perspective also promotes engagement and focus[9]. Exposing graduates or individuals with minimal cybersecurity skills to the cybersecurity defence and offence working environment has been proven to increase skills and an interest in the uptake of the cybersecurity profession [8]. Learning factories offer such a solution in that it provides a platform for participants to distil abstract concepts into application areas and practice their skills in an environment that mimics a real working environment.

The growing importance of a broader mix of skills, both technical and non-technical, underscores the reality that today's cybersecurity roles are multi-dimensional and increasingly varied across specializations, organisations and industries [6].

Learning factories may be set up to tackle real industry challenges, especially in the built environment and engineering fields. Learning factories were originally established and implemented in the manufacturing sector to offer hands-on training on how to apply specific manufacturing techniques to improve efficiency in manufacturing tasks. Learning factories were physically set up to resemble the production assembly line and manufacturing staff would train by doing the actual work they are expected to do in the working environment [1]. This method of training resulted in experienced workers, optimised production and productivity, with minimal to no waste of resources in the assembly line. Presently, learning factories are becoming widespread and no longer limited to the manufacturing sector, as they can be adapted and applied in various sectors and environments that require practical skills.

Industry now demands interdisciplinary training, which underlines the already proven education and training in learning factories [1]. Companies and countries alike are forced to think of better solutions which could enable innovation [7] .

Baena et. al propose a transformational model to create a learning factory for EAFIT University [2]. The transformational model is focussed on developing pillars (didactic, integration and engineering) towards creating a learning factory that could be replicated.

There is scant evidence of learning factories in the cyber security domain. Veerasamy et al. propose cyber security learning factories as a novel concept towards combatting the cyber security skills shortage [4].

Cybersecurity is a multi-faceted field that requires a multi-dimensional approach. Learning factories are in essence collaborative, and may involve diverse stakeholders like the:

- government
- private or public sectors
- industry experts
- academic institutions

It provides an opportunity to advance ideal multi-dimensional cybersecurity skills and innovation in the field by providing an emulated environment that trains individuals to practically apply concepts, tools and cognitive skills to solve real workplace problems. Learning factories originally emerged from the manufacturing sector to train workers. Modern manufacturing learning factories advance problem-solving skills, agility and trust as demands in the work environment rise.

III. CYBER SECURITY LEARNING FACTORY

The success of learning factories in the manufacturing industry warrants further investigation for other domains such as cyber security. Figure 2 was crafted to demonstrate the usefulness of Learning Factories as an ICT business driver to attain a decisive edge. As part of the offering of learning factories, efficient systems can be set up to provide an environment that offers strategic and complex training. This enables competency growth as well as the development of innovative thinking. Furthermore, learning factories differs from pure traditional learning in the hands-on interaction it provides for direct practical exposure to various skills.

A learning factory could be set-up in various ways depending on the domain and/or end-goal. Each implementation of a learning factory looks differently and is used for a different purpose [3]. The key characteristics [1] of learning factories in the cybersecurity domain has already been published in previous work [4], and a shortened version is shown in Table 1.

After the key characteristics were formulated, the curriculum was designed using existing platforms. The

Figure 2: Figure 2: Usefulness of Learning Factories in the Workplace.

following topics were selected: cyber security fundamentals, penetration testing fundamentals, and networking fundamentals.

Thereafter trainers were selected based upon expertise in these topics, and training platforms were selected containing both theoretical and practical labs.

Table 1: The key characteristics of a learning factory in the cybersecurity domain. Adapted from [1].

Dimension	Cybersecurity Application
Purpose	Teaching and training with skills on all areas of cyber security to address the cybersecurity skills shortage in South Africa.
Process	It involves using cyber security simulation and training tools hosted on computers.
Setting	Hybrid environment. To initiate, it will be in-house instructor led and continuation can occur using online tools.
Product	No products will be manufactured in this environment. Skills will be developed, and challenges will be completed.
Didactics	Pre and post assessments will be conducted. The initiation phase will be with the help of an instructor. Thereafter, participants will work on their own and be evaluated.
Operating Model	This project will be started using government funds and thereafter be supplemented from other initiatives.

IV. Experimental Setup

The CLF were formulated with initial training with a set of students from the Tshwane University of Technology (TUT). The software tools used for this CLF pilot were Immersive Labs and the Network Emulation and Simulation Lab (NESL). Immersive Labs is a commercial platform aimed at building cyber resilience for individuals, and there are many labs that can be assigned to individuals to strengthen skills. The labs that were selected were based on the cyber security fundamentals and penetration testing fundamentals topics. NESL is a modelling technology aimed at allowing users to design, create and access simulated networks towards network security. The parameters for setting up the CLF are shown in Figure 3. In the next section, the results from the CLF training are presented.

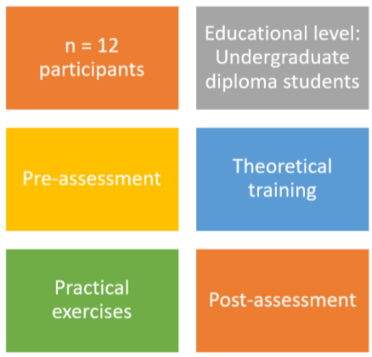

Figure 3: Parameters for the set-up for the CLF experiment.

V. Findings

This section reports on a survey that was conducted to assess the effectiveness of CLF in imparting hands-on knowledge on cyber security fundamentals, penetration testing fundamentals, and network security.

Radar graphs are presented in Figures 4 and 5 to visualize the findings related to the students' understanding of networking concepts and cybersecurity before and after attending the CLF. The results are discussed per tool, Immersive Labs and NESL.

Immersive Labs Findings

The Immersive Labs pre- and post-questionnaire survey consisted of twenty multiple choice questions related to cybersecurity concepts. In Table 2, we present the questions but the multiple-choice answers are omitted due to space limitations. Significantly, the results are expressed in percentages of correct (✓) and incorrect (✕) responses, providing a clear indication of participants' responses and enabling a quantitative assessment of their knowledge before and after engaging with the Immersive Labs platform.

Table 2: Immersive Labs Survey Questions; results in percentage.

No.	Question	Pre assess ✓	Pre assess ✕	Post assess ✓	Post assess ✕
Q1	What is Cyber Security?	75	25	76	23
Q2	Which of the following refers to the practice of protecting against and preventing cyber threats and risks from infiltrating personal and professional systems through tech devices and being secure online?	0	100	7	92
Q3	What does it mean to maintain your privacy online?	87	12	100	0
Q4	What is the act of exploiting human weaknesses to gain access to personal information and protected systems?	62	37	92	7
Q5	You are spending money or submitting a password while sitting next to someone at a coffee shop. The person sitting nearby easily obtains confidential data without your knowledge. Which of the following does this describe?	56	43	76	23
Q6	Which of the following is not considering the adequate measure for physical security?	68	31	84	15
Q7	What is the difference between cybersecurity and information security?	25	75	61	38
Q8	In which of the following fraud methods is a legitimate/legal-looking email sent in an attempt to gather personal and financial information from recipients?	56	43	100	0
Q9	Which of the following are famous and common cyber-attacks used by hackers to infiltrate the user's system?	62	37	76	23
Q10	Which of the following is defined as an attempt to steal, spy, damage or destroy computer systems, networks, or their associated information?	56	43	61	38
Q11	What is Ransomware?	81	18	92	7
Q12	Which of the following is true regarding secure password?	75	25	69	30
Q13	What is an electronic authentication method that requires the user to provide two or more forms of identity verification before they’re allowed access to a website, network, or application?	81	18	100	0
Q14	Which of the following best describes the importance of using multi-factor authentication (MFA)?	81	18	84	15
Q15	What is a simulation of a cyberattack that tests a computer system, network, or application for security weaknesses?	62	37	76	23
Q16	A weakness that can be exploited by cybercriminals to gain unauthorized access to a computer system is known as a:	62	37	92	7
Q17	What is a type of attack by which cybercriminals exploit software vulnerabilities in web applications for the purpose of stealing, deleting, or modifying data, or gaining administrative control over the systems running the affected applications?	31	68	46	53
Q18	Which of the following should be included in the scope of penetration testing?	62	37	84	15
Q19	Which of the following is a program that helps connect to a system over the network in a secure way?	43	56	69	30
Q20	Tools/infrastructure you can use for penetration testing	31	68	76	23

Figure 4 presents the students' results in percentages, based on how the survey questions from Table 2 were answered. The graph in the figure shows that overall, the questions answered from the post-assessment had higher scores than those from the pre-assessment. This observation highlights the positive effectiveness of CLF in students' learning and understanding process.

Figure 4: Pre and Post Assessment of the Immersive Labs.

The comparison of the pre- and post-assessment for Immersive Labs shows that the students made great progress. The training included 20 questions covering various cybersecurity concepts such as cybersecurity, cyber safety, privacy, social engineering, phishing, cyber-attacks, multi-factor authentication, penetration testing, vulnerability, and tools for penetration testing.

The results in figure 4 showed that the training program significantly improved students' understanding of cybersecurity concepts. The post-assessment showed an increase in the percentage of students who understood the *concept of cybersecurity* (from 75% to 76.9%), *cyber safety* (from 0% to 7.7%), *maintaining privacy online* (from 87.5% to 100%), social engineering (from 62.5% to 92.3%), *shoulder surfing* (from 56.3% to 76.9%), *physical security* (from 68.8% to 84.6%), the difference between *cybersecurity and information security* (from 25% to 61.5%), *phishing* (from 56.3% to 100%), *famous and common cyber-attacks* (from 62.5% to 76.9%), *cyber-attack (*from 56.3% to 61.5%), ransomware (from 81.3% to 92.3%), *secure passwords* (from 75% to 69.2%), multi-factor authentication (from 81.3% to 100%), the *importance of using multi-factor authentication* (from 81.3% to 84.6%), *penetration testing* (from 62.5% to 76.9%), *vulnerability* (from 62.5% to 92.3%), *SQL injection* (from 31.3% to 46.2%), *the scope of penetration testing* (from 62.5% to 84.6%), and *tools for penetration testing* (from 31.3% to 76.9%). These findings demonstrate the effectiveness of the training program in improving students' knowledge and understanding of cybersecurity concepts.

Overall, the findings indicate that the introductory cybersecurity and penetration testing learning factory was effective in enhancing the students' knowledge and comprehension of cybersecurity.

NESL Findings

The NESL pre- and post-assessments consisted of ten multiple choice questions relating to networking and cybersecurity concepts (see Table 3). Table 3 presents each of the ten questions, along with the percentages (rounded off to the nearest whole number), of students who answered correctly (✓) and incorrectly (✕) on both the pre- and post-assessments.

According to the results from Figure 5 and Table 3, the students had a solid understanding of the first, fifth and seventh questions (Q1, Q5 and Q7) regarding *networks* and *malware*, with 100% of the students answering these three questions correctly in both pre- and post-assessments. There were major knowledge gaps in some areas such as the concepts of *subnetworks* (Q2), with only 25% of the students selecting the correct answer in the pre-assessment, and *remote access to isolated networks* (Q9), with 50% of the students answering incorrectly in the pre-assessments. However, this knowledge gap was significantly bridged after the students participated in the learning factory, as visualised in Figure 5, post-assessment results for Q2 increased from 25% to 50% and from 50% to 70% for Q9.

Table 3: NESL Survey Questions: results in percentage.

No.	Question	Pre assess ✓	Pre assess ✕	Post assess ✓	Post assess ✕
Q1	What is a network?	100	0	100	0
Q2	What is a subnetwork?	25	75	50	50
Q3	What is the difference between simulation and emulation?	58	42	50	50
Q4	The purpose of a server environment is a network environment that?	83	17	60	40
Q5	What is malware?	100	0	100	0
Q6	What is configuration validation?	68	32	70	30
Q7	Which devices protect your network from malware?	100	0	100	0
Q8	What are the tasks of performing a pen test within a network?	92	8	80	20
Q9	Remote access to an isolated network is designed as?	50	50	70	30
Q10	Application testing has the following characteristics?	75	25	80	20

Figure 5 presents the students' results in percentages, based on how the survey questions from Table 3 were answered. The graph in the figure shows that overall, the post-assessment had higher scores than the pre-assessment. This a positive indicator of the effectiveness of CLF in students' learning and understanding process.

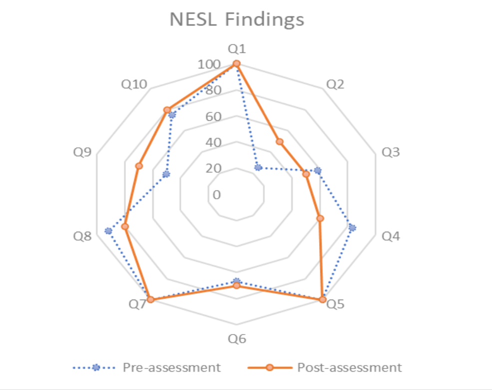

Figure 5: Pre and Post Assessment of the NESL.

The findings also revealed that some students had difficulty understanding complex concepts such as *simulation and emulation* (Q3), the *server environment* (Q4) and *penetration (pen) testing* (Q8). The post-assessment results for the above questions declined even after participation in the CLF and facilitators' explanation of these concepts. While the facilitators make various attributions to the above decline in students' performance in the post-assessment, this finding demonstrates a gap requiring further investigation whether it was knowledge delivery, demonstration, course content or other factors that yielded these negative results. Nonetheless, this highlights the benefit of a learning factory platform to expose knowledge gaps thus providing an opportunity to upskill the students and innovate the methods of teaching for continuous improvement. Given the flexibility of a learning factory setup, course content can be modified according to the needs of the students.

Overall, the results of the survey study suggest that the NESL learning factory was effective in imparting the knowledge and understanding of networking concepts and cybersecurity to the students. However, some students still required further clarification on certain topics, indicating a need for ongoing training and support. The pre- and post-assessments proved to be a useful tool for measuring students' progress and knowledge during the training sessions, while the NESL learning factory, proved to contribute significantly and positively in how students engage with imparted knowledge and improve understanding of some concepts.

While this experiment was conducted on students, it could be easily replicated within organisations and the military. The success of this experiment reveals that embedding the CLF in organisations could be beneficial to retain and overcome the cyber security skills shortage issues by providing practical exposure to cybersecurity skills. Other benefits that CLFs might offer to improve business drivers within industry include cost savings, enhanced cyber security, and an opportunity for innovation and research. Embedding learning factory challenges into operations is feasible and has promising results.

VI. Conclusion

The aim of this study was to establish the cybersecurity component of a learning factory established at the CSIR and externally, but also to develop a solid Cybersecurity RDI base in support of a rollout of learning factories by the CSIR across South Africa. The CLF were implemented on tertiary students in the field of Information Technology (IT) and internship program employees from the CSIR to improve their cybersecurity skills.

The findings revealed that CLF students' performance and level of understanding improved significantly post CLF training. Therefore, the CLF did provide learning capabilities and application to the trainees.

This demonstrates that CLF can be used as a tool to empower South African Students and workers with little cybersecurity skills with essential cybersecurity skills towards attaining a cyber safe country and contribute towards skills development within South Africa with CLF.

Future work involves clarifying the core concepts of CLF towards theorization such that CLF can be easily replicated elsewhere to contribute to the national cybersecurity skills shortage and economic development. This includes refining the CLFs learning objectives, among other tasks. Other future work involves replicating the experiment with other types of participants such as employees from organisations.

Acknowledgment

The authors wish to thank the students at TUT for attending the learning factory session for the CLF.

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