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A New Hybrid Machine Design For A 6 DOF Industrial Robot Arm

Abstract: Industrial robot arms are an essential part of automated manufacturing and are used due to the facts that they are highly repeatable; can be calibrated to be sufficiently accurate and they eliminate human error. They automate tasks such as component assembly; welding; light machining; spray painting; etc. The industrial serial robot arm architecture is by far the most ubiquitous in modern day manufacturing, as their technology is highly refined in its current state; the machine architecture provides extreme dexterity and it has a large useful workspace. This architecture however does have some problems, first the machine mass distribution is not efficient as that mass is spread throughout the arm, and the arm itself contains significant inertia. The primary reason for this lies in the location of the motors and gearboxes. A secondary effect of this mass distribution is that it leads to inaccuracy and dynamic vibration problems. This journal paper focuses on the design of a novel robotic arm design having a hybrid nature. It is labelled as hybrid due to the fact that its architecture departs from both the classic definitions of Serial Kinematics Machines (SKMs) and Parallel Kinematics Machines (PKMs). The primary goal of its design was to merge the advantages of the 2 architectures, i.e. a large workspace to footprint ratio which is found in serial robots, and the low inertia of a parallel robot resulting in increased speed. Serial and parallel robots are complementary, and as such, these design goals cannot co-exist in a single robot architecture. To realise the objectives mentioned, 2 unique mechanisms had to be created so that a full complement of 6 DOF (degrees of freedom), could be attained. Comparatively, once the design goals are met, this hybrid mechanism would be better than any industrial robot used in industry.

Keywords: Parallel kinematics, serial kinematics, hybrid machine, 6 DOF.

Introduction

What characteristics classify a machine as either a PKM or SKM? A serial kinematics architecture is one in which each driven axis follows its predecessor in an open ended curve with straight lines connecting the joints, or where each motor and gearbox is positioned at or close to the joint it controls. A parallel kinematics architecture on the other hand fixes location and arrangement of the driven axes, one for each DOF of the robot, at the stationary robot base. A number of linkages are then connected from the driven axes to the robot end effector, these form closed kinematic chains. Two examples are the 3 DOF Delta (shown below) and the 6 DOF Hexapod.

Figure 1 PKM and SKM

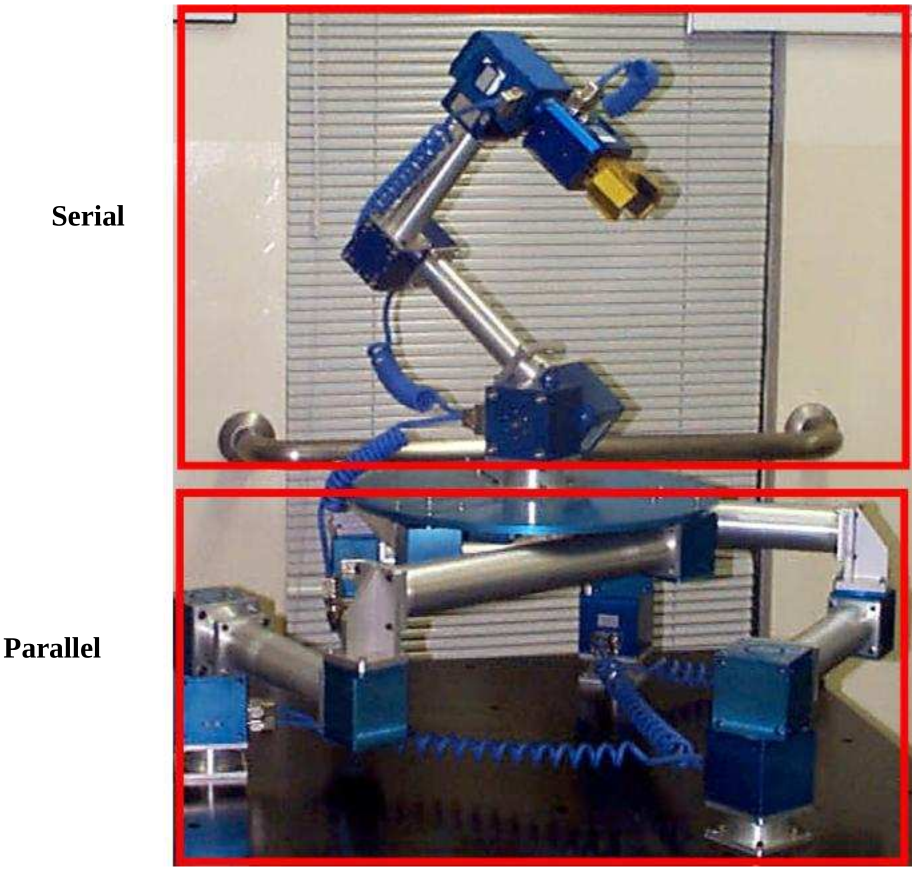
Serial kinematic machines find widespread use in industry, which include automotive, aerospace and nuclear power production plants. Some of the reasons for this are that the technology is mature, refined and has been rigorously tested, in addition to the versatility of the architecture to accomplish any programmable repetitive task. However the serial robot does have a few limitations which lead to the development of specialized PKMs and their adoption in a few industries, most notably the packaging of items, where speed or throughput and accuracy are paramount. PKMs themselves have severe disadvantages, and their attributes are generally complementary to SKMs. PKM architectures greatest strengths are speed, stiffness and accuracy whereas SKM architectures are characterized with a large useful workspaces, greater dexterity and versatility.

Improving the robotic tools used in manufacturing automation is one path to advancing manufacturing processes and this can be achieved through merging the advantages of both types of industrial robot architectures. The core focus of this paper is the presentation of potential solution to attaining this goal. The objective is to create a robot platform, that can satisfy most of industry’s demands like the SKM can i.e. being versatile, having a large workspace combined with a minimal machine footprint. In addition to that we want to add some of the advantages of a PKM, i.e. a significantly reduced inertia leading to higher speeds and lower energy consumption and greater accuracy. A hybrid machine design architecture is the only way to combine these advantages. With the increase in automation and flexible production in industry, newer applications demand greater performance capabilities from industrial robots. In their respective rights both pure serial and pure parallel industrial robot architectures have disadvantages, which cannot be overcome on their own. Hybrid structures on the other hand which aim to combine the advantages from both architectures, provide a means to achieve a greater potential for improvement.

To summarize this machine design is:

> **Important:** because faster more accurate industrial robots are essential for product manufacturers to improve product quality and throughput.
> **Innovative:** as a novel machine design concept capable of 6 DOFs, which has a light machine moving mass, a large useful workspace with greater accuracy and repeatability, and will use less energy than current serial robot technologies. A reduced energy consumption will result in a decreased carbon footprint making this robot more environmentally friendly.
> **Opportune:** since no current industrial robot manufacturer has at this moment a robotic solution that this design can provide.
> **Relevant:** as it is necessary to provide industry with better tools that can improve their manufacturing capability, which is exactly what this design can accomplish.

Figure 2 A typical hybrid machine



Global Market Figures for Industrial Robotics

To understand why robotic innovation and investment is important one must take cognisance of the current market landscape of industrial robotics, as it is market economics that drive robotics R&D. The market research will be limited to the last 2 years, as statistics are not yet available for 2011. In 2009 industrial robot sales dropped by about 47% as compared to the previous year, with roughly 60 000 industrial robots sold. This was the lowest level reported since 1994. Revenue decreased by 39% to US$3.8 billion, however including the cost of software, peripherals and systems engineering, the market was estimated at $12 billion. The automotive industry accounted for 36% of the total year's supply, with the electrical/electronics industry share at 18%, the rubber and plastics industry at 10% and the food and beverage industry at 5%. The total number of units sold since 1960 amounted to more than 2 230 000, and the IFR (International Federation of Robotics) estimates the total number of operational industrial robots worldwide to be between 1 021 000 and 1 300 000 units at the end of 2009. [*Exec sum 2010*]

Sales of industrial robots doubled in the first 9 months of 2010 as compared to the same period of the previous year. The main reasons that stimulated this recovery were a demand for eco-friendly production and products, a drive to increase productivity to be competitive on the global market and the competition for market share in rising consumer markets. [*IFR 1*]

The main drivers for the strong recovery in 2010 were automotive manufacturers and the electronics industry. In addition, the plastics industry made robotics investments, as the trend towards light weight products increased demand for plastics. [*IFR 1*] It is predicted that a further increase in sales will resume in the period between 2011 and 2013 about 10% per year on average attaining a level of more than 100 000 units. [*Exec sum 2010*]

Future potential as determined from user wants and needs

There is significant potential for industrial robots in growing industries: pharmaceutical, cosmetic, medical devices, and the food and beverage industries. There are still opportunities for the metal and solar energy industry, in which robot applications are still far from that of the automotive sector. Small/medium sized companies and even small trade companies, i.e. carpenter's shops and garages, are now capable of using industrial robotics due to the following advances: [*IFR 2*]

- Easier handling and user friendly programming which facilitates robotic automation
- Optimized quality control via Robot-Vision
- Small and fast robots are operating in confined spaces within manufacturing areas
- No need for security fences due to improved sensor technology
- The systems are now selling at a reduced cost

Industrial robotic systems are central components of automation. There are several good reasons for the manufacturing industry and non-industrial sectors to continue investing in robotic installations currently and well into the future, these are [*Exec sum 2010*]:

- Greater flexibility is needed and due to decreasing product life cycles and shorter time-to-market
- Improving global competitiveness
- Adhering to environmental regulations and labour laws with regard to health and safety
- Reducing energy, operating and capital costs
- Improving product quality, consistency and output rates
- Reducing material waste and increasing yield
- Saving space in high value manufacturing areas

Hence there will always be a market for industrial robotics. It may have been hard-hit by the global economic recession but it is poised to bounce back and achieve sales and revenue at levels prior to the meltdown, in the next 2-3 years.

A Detailed Comparison of the Main Industrial Robot Architectures

According to *Bruzzone, et. al* parallel kinematic architectures are comparatively better in terms of increased stability and arm rigidity. Additionally since there is reduced arm flexing, the architecture has high repeatability and it can additionally exert high forces in its workspace due to the high stiffness of a closed-loop kinematics structures. [*Bruzzone, et. al*]

Tasora, et. al mention that for PKM's the motors are positioned in a fixed arrangement on a fixed base, these are responsible for most of the manipulators inertia the hence the speed of displacement of the end effector is greater. [*Tasora, et. al*] *Rowe* states that PKMs have the advantage of end effector load distribution among the many legs of its closed loop structure, and it may be purely axial but this is dependent on the machine configuration. [*Rowe*]

Each link in a serial robot must support not only the masses of its link and motor, but also the masses of all the links and drive units preceding it, hence when compared to PKMs, the inertia is considerable. This higher inertia restricts the capability of the serial robot in terms of its dynamic performance and acceleration. [*Persson and Anderson*]

The flexing errors of each link in a serial robot architecture are additive, and the sum effect leads to a larger total end-of-arm flexing error as compared to PKMs. There is a general additive and amplifying effect with all errors in a serial structure and these include manufacturing errors, gear backlash, hysteresis, etc. By distinction PKM robot's multiple arm structure has the effect of averaging all errors, which can be further reduced by using large displacement compliant joints. This can improve the error averaging effect in PKMs and in some cases lead to sub micron positioning accuracy. [*Moon and Kota*]

PKMs are less sensitive to temperature, have lower energy consumption, a lower manufacturing cost and are more reliable. They offer good design variation allowing designers to stretch their creativity and conceptualize machines with varying architectures, far more than they could do with serial topologies. PKMs tend to have a larger footprint to workspace ratio which is the most significant disadvantage. This is due to the positioning of the motors and the resulting configuration. There are some exceptions, however most designs take up a large work area. Also the performance of PKMs is greatly dependent on their geometry and as such optimal design has therefore become a necessity in their development. [*Hao and Merlet*]

Table 1 A comparison between parallel and serial mechanisms

ADVANTAGE: ✓	**PARALLEL MECHANISMS**	**SERIAL MECHANISMS**
Higher Stability and Arm Rigidity	✓	
Greater Repeatability	✓	
Higher Stiffness	✓	
Greater Speed and Acceleration	✓	
Load Distribution among Actuators	✓	
Dynamic Behaviour Immune to Payload Variations		✓
Lower Energy Consumption	✓	
Lower Manufacturing Cost	✓	
Smaller Positioning Errors	✓	
Lower Sensitivity to Environmental Conditions	✓	
Larger Workspace to Footprint Ratio		✓
Geometry Independent Performance		✓
Simpler Control		✓
Simple Forward Kinematics		✓
Simple Inverse Kinematics	✓	
Predictable Dynamics		✓

Payload variations on the end effector drastically affect the machine behaviour. This is due to the fact that the ratio between machine moving mass and payload is significantly lower than in SKMs. Their complex kinematics and dynamic models also make control far more difficult than in serial machines. [*Bruzzone, et. al*]

Most PKM research have been done on machines with six DOFs and they have a small useful workspace, are riddled with design difficulties and their forward kinematics is an extremely difficult problem. On the other hand the kinematics of parallel mechanisms with two and three DOFs can be described as closed forms. Moreover not all the singularities of a six DOF parallel mechanism can be found readily, but these are rapidly identified for PKMs with two and three DOFs. It is for such reasons that PKMs with less than six DOFs have been increasingly attracting more attention for industrial applications. [*Xin-Jun, et. al*]

Novelty in Machine Design

The concept architecture for the machine uses multiple 3 bar linkages, a unique concentric gearbox and dexterous wrist. The machine will mimic the 6 DOF (degree of freedom) motion of a typical serial robot and will have an equivalent footprint and workspace. Additionally all six motors and their associated gearboxes have a fixed spatial location at the base, and through those linkages and gearboxes they transfer their torque to the intended axis, this significantly reduces the inertia of the moving arm. The inertia can be further reduced with the use of high strength, light weight linkages using composite materials. There is still substantial research that has to be done to investigate the feasibility of this solution, however this does represent a first iteration of a workable design.

Hybrid machine designs are generally composed of both serial and parallel machine sections connected serially, and one can distinctly recognize the comprising sections of the machine as a whole, this is illustrated in Figure 2. These hybrid designs aim to improve robotic manipulators by localizing a particular architecture at the point where its advantages are most necessary, thereby extracting the best features of each architecture. Typically 2 and 3 DOF PKMs are used as component building blocks. SKM components are used where a large range of motion is needed or where less complicated or a non-existing PKM solution exists. The novelty in this machine design is that there is no clear distinction between a parallel or serial nature, and hence it describes a truly unique hybrid machine. It has a full range of 6 DOF, a large useful workspace with minimal inertia, which will result in significant energy savings. To illustrate the mass and energy saving potential of this machine, the specifications of a few contemporary industrial robots produced by 2 leading manufacturers in the field are illustrated.

Figure 3 **Robot specifications**

ABB IRB 140

- **MFG:** ABB
- **Category:** Industrial Robots
- **Part #:** IRB 140
- **Max Reach:** 810 mm
- **Payload:** 6 kg
- **Weight:** 98 kg
- **Controller:** S4C

$48,000.00

Fanuc ArcMate 120iB

- **MFG:** Fanuc
- **Category:** Industrial Robots
- **Part #:** ArcMate 120iB
- **Max Reach:** 1667 mm
- **Payload:** 20 kg
- **Weight:** 220 kg
- **Controller:** RJ3

$68,400.00

Fanuc M-420iA

- **MFG:** Fanuc
- **Category:** Industrial Robots
- **Part #:** M-420iA
- **Max Reach:** 1855 mm
- **Payload:** 40 kg
- **Weight:** 620 kg
- **Controller:** RJ3

$80,400.00

ABB IRB 7600 Industrial Robot

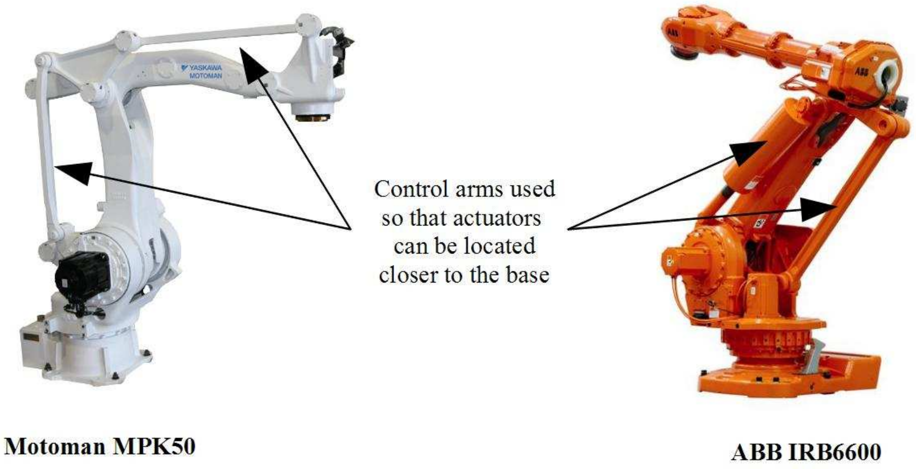
- **MFG:** ABB
- **Category:** Industrial Robots
- **Part #:** IRB 7600
- **Max Reach:** 3000 mm
- **Payload:** 500 kg
- **Weight:** 2450 kg
- **Controller:** S4C+

$162,000.00

The most important specifications of an industrial robot are its reach and its maximum payload at that reach. Additionally for serial type robots shown above, the total mass is also important as roughly 60-80% of that total mass is machine moving mass. This means that the motor responsible for moving the robot about its z-axis (vertical axis) has to move that mass (60-80% depending on the robot). This is just for 1 motor, which would be the highest rated motor (power and torque) in the robot. The remaining 2 used to position the end-effector, would scale accordingly and still need to be rated highly to be able to carry the specified payload and the mass of links and motor-gearbox combos that follow it. To simplify calculations and make an effective comparison consider a 1000 kg serial robot, this is entirely plausible as the IRB 7600 series, pictured in the bottom right corner of Figure 3 above has a mass of 2450 kg. Also we will limit our comparison to just that first motor, however the benefits of this design would filter through to the remaining motor-gearbox combos. For this robot the machine moving mass would be in the range of 600-800 kg. The energy required to move this mass is significant, and considering an automated factory running 10-25 of these robots, 7 days a week with minimal downtime, the energy cost and carbon footprint would be staggering. Now compare that to the hybrid design in question, having the same reach, payload and total mass as this serial robot. The machine moving mass is expected to be in the rage of 30-50% or 300-500 kg, as *all* the mass which is concentrated in the motor-gearbox combos is fixed in space. Furthermore there will be additional mass optimizations as the links used no longer have to be as strong as they are with serial robots due to the fact they don't carry that dead mass. This will create significant energy savings and reduced carbon emissions, and with the global drive to reduce carbon emissions this design trumps any serial robot industry has at present. Furthermore if we were to use the same motors we could reach even further, or move faster, or to some degree combine increased reach and speed. This substantially increases the robot's appeal.

Robot manufacturer's product guides have many robotic solutions and some of those have mechanisms in place that try to minimize the inertia of the arm. Two of these products are illustrated in Figure 4, other manufacturers have similar designs. These use control arms to relocate the motors, placing them closer to the base. The effect is to minimize their contribution to the inertia about the z-axis, making the robot faster and increasing its payload carrying ability. These designs however can only minimize the effect of that particular motor's mass contribution, since it is still being moved only now it is closer to the base. The design in the subject of this paper completely eliminates the dead mass/inertia problem, by fixing all the motor-gearbox combos to a static spatial location while maintaining an equivalent machine footprint, reach and dexterity. None of the major manufacturers have a product that is as capable, offering the same advantages that this hybrid design inherently possesses.

Figure 4 Robot manufactures try to minimize inertia by using control arms

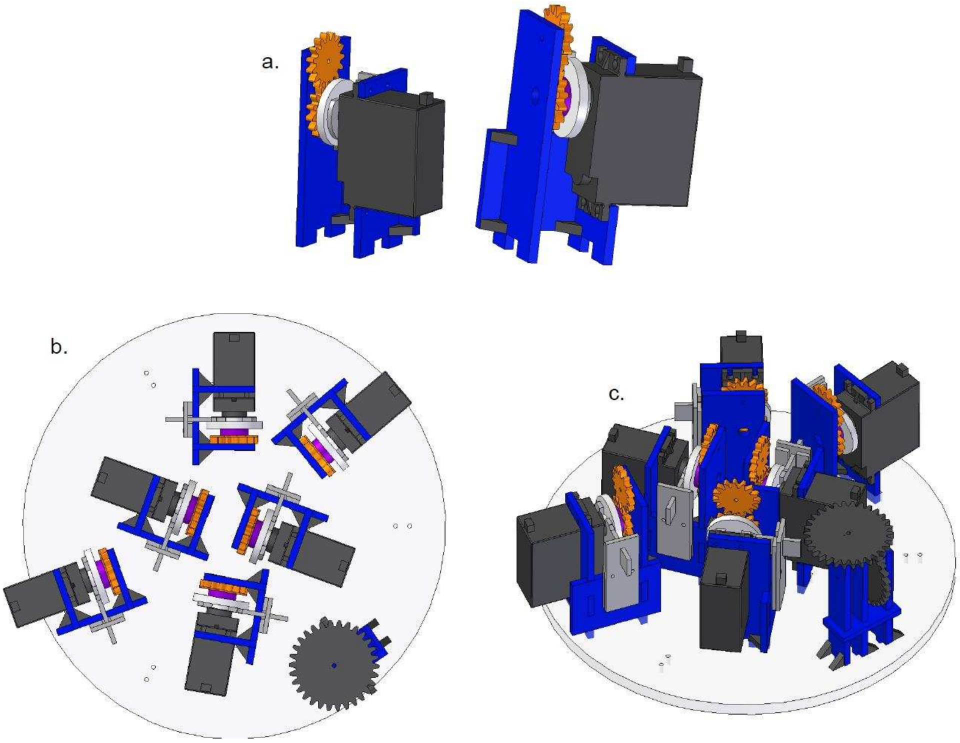


Design Description

The machine aims to achieve actuation transfer from the motor and gearbox located in one position (the fixed base which makes it similar to parallel architecture) to the target axis located elsewhere, through a series of gears and light weight connecting linkages. The 2 ways in which this actuation transfer could be accomplished is via a rigid link and non rigid link actuation transfer mechanism. The non rigid link option would require the use of toothed belts or chains. However this option would restrict the load carrying and force exerting capability of the machine, however it offers increased manipulator speed. For applications that would require the placement of light objects in a large workspace this option would be suitable. This paper will focus on a design using rigid link mechanisms. The drawings illustrated here are from a rapid prototype of the platform. All links and gears were laser cut from 2D Perspex and assembled into 3D structures. To work around the problem of not having bevelled gears the gear teeth were made large enough so that they can mesh at 90 degrees (with their pitch circles tangent at 90 degrees). This worked fairly well, even though the gears now have point contact instead of line contact, and for a working model this was sufficient. Most of the drawings that will be illustrated show this, however it must be remembered that they represent bevelled gears, which will work exceedingly better.

The design will be described from the bottom up. The motor units and their associated gear boxes, shown in Figure 5(a)), have a fixed position in space. There are 6 sets in all, this is shown in Figure 5(b) and (c). Their arrangement allows them to occupy dedicated space for themselves, and allows them to mesh with the gears of the next part of the design, the concentric gear drive. Those gears that mesh with the concentric drive have to be bevelled as they mesh at an angle, preferably at 90 degrees.

Figure 5 (a) Motors and their gearboxes, (b) Top view of motors and their arrangement and (c) 3D view of motors and their arrangement



The concentric gear drive consists of 7 concentric sections. The outermost section mounts on the fixed base and does not move relative to the 6 inner sections.

The 6 inner sections are all capable of rotating independently of each other (just one degree of freedom, i.e. rotation), while remaining concentric. Each section holds its nearest inner section in place (the innermost section does not hold anything), via a double ball race bearing (illustrated in Figure 6 and Figure 7). The inner bearings do not carry a vertical load, they simply facilitate the transfer of rotation and torque from the base motors to the designated driver gears/links. The outermost bearing is the only one that carries a vertical load, which is the complete mass of the moving machine and the payload it carries.

The 5 innermost sections have bevelled gears mounted on both the top and bottom halves of each section (see Figure 6). The 6th section (counted from the inside moving outward) has a bevelled gear on its bottom half. On its top half it has a physical mounting for 5 bevelled gears that have all their axes concentric and which mesh with the top half gears of the concentric gear drive at 90 degrees (Figure 8). The 6th section (outermost movable section, see Figure 6) is responsible for moving the mobile parts of the machine arm about the vertical axis.

Figure 6 Cross Sectional Views of Concentric Gearbox

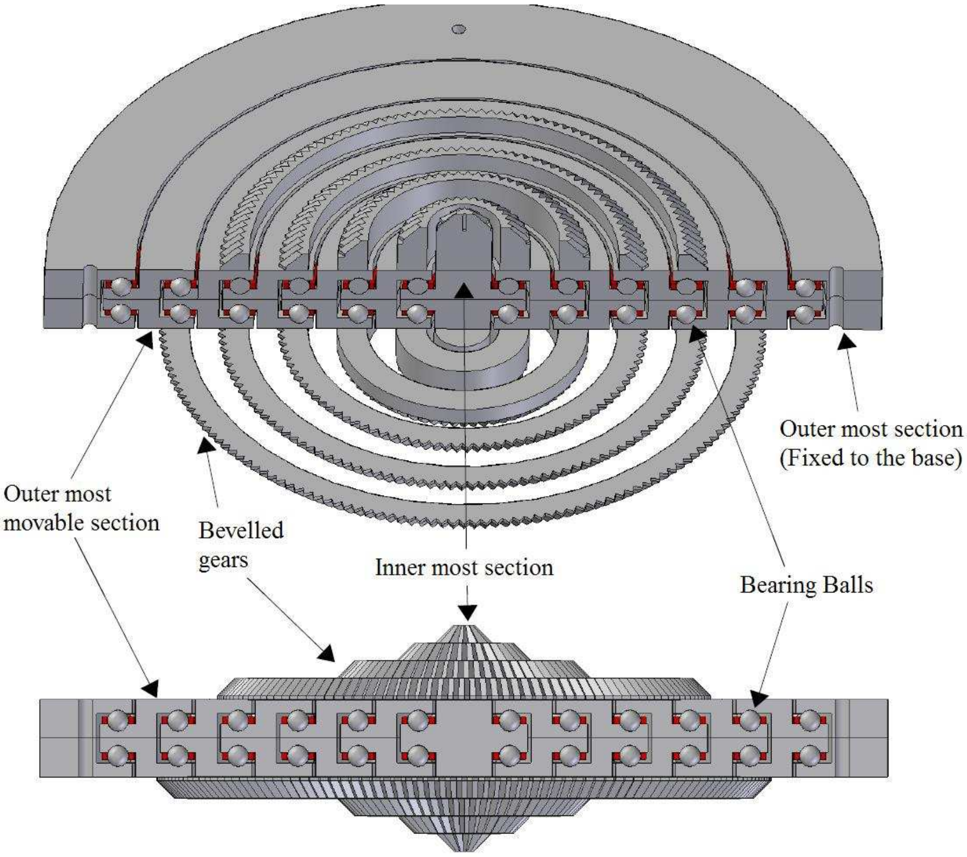


Figure 7 Exploded View of 2 Consecutive Sections

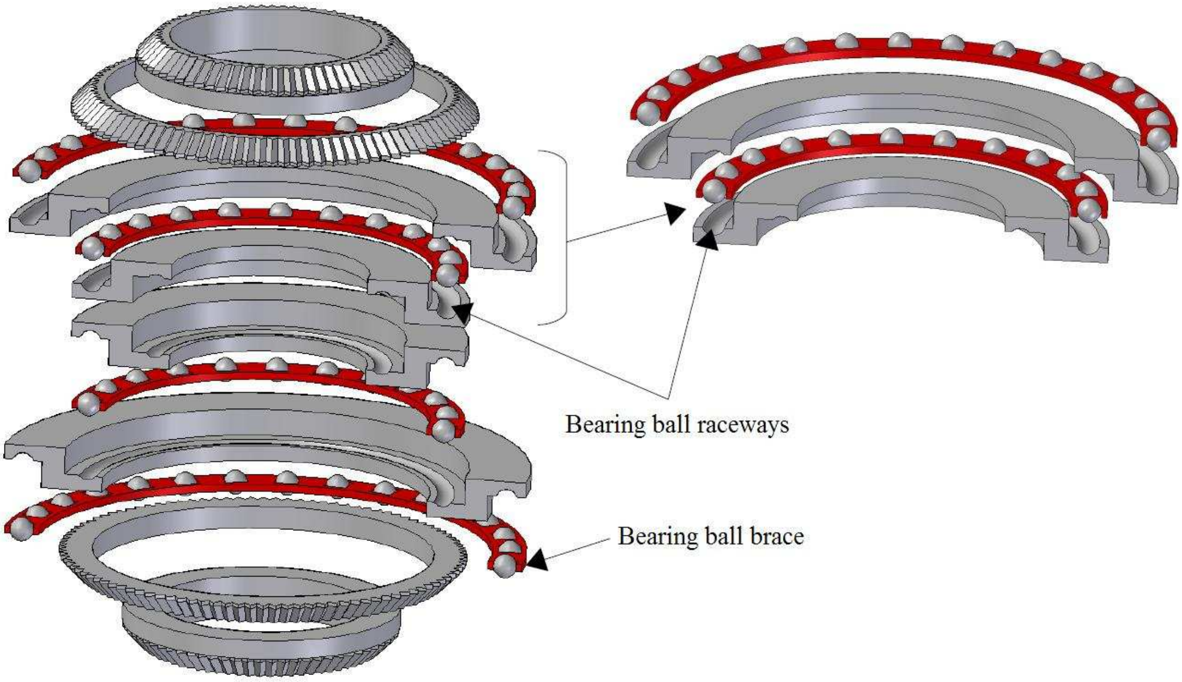
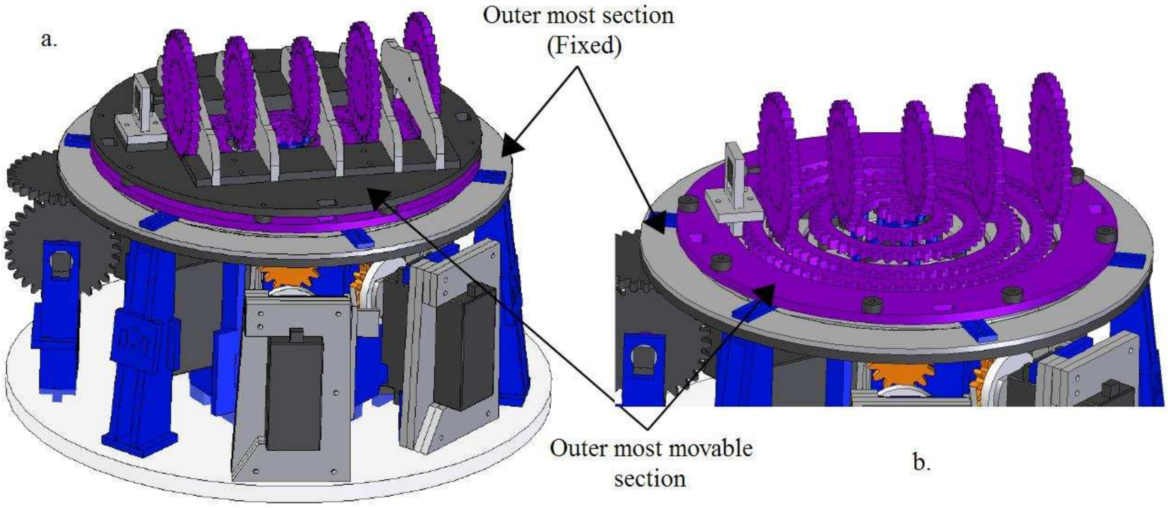


Figure 8 (a) All vertical bevelled gears, with their structural mountings, and (b) Bevelled gear meshing, with structural mounting hidden



To transfer actuation away from the base, 3 bar slider-pivot linkages were used, these are illustrated in Figure 9. The orbit of the follower need not be a 1 to 1 (the output link would trace a circle of the same radius as the driving link) or 1 to -1 (the output link would trace a circle of the same radius as the input link but in the opposite direction) match with the driving link. The follower links must however match the angular rotation of its driver (no longer positional magnitude); that is the orbit does not have to be a perfect circle but it has to circumnavigate the axis, i.e. the follower must have one complete orbit for every 360 degree rotation of its driver. This also implies that the torque (and rotational speed) delivered to the end of the linkage (which will be transferred to the wrist) will be varying.

The slider has a pivot at the midpoint (allowing the slider to rotate) of the supporting link (this minimises warping of the follower orbit and maintains a somewhat circular profile). Furthermore the follower on the end of the primary slider bar linkage becomes the driver to secondary stage. The orbit of the follower on the secondary stage is further warped but still circumnavigates the main wrist axis, and matches each degree of rotation of the driver on the primary stage.

Our initial choice for this torque transfer linkage was a parallelogram but there was no simple mechanical solution to prevent the singularity position (when the parallelogram collapses, or adjacent sides become collinear, and the exit configuration in which it could either be the parallelogram or a crossed quadrilateral – crossed configuration parallelogram). We experimented with designs in which we used extra links to create double parallelograms, with a phase offset so that when one collapses the other prevents the crossed configuration. Another solution was to maintain a crossed configuration, and for this we used a moving slider-pivot joint between the longer sides of the quadrilateral (parallelogram in crossed configuration). The 3 link slider-pivot linkage in Figure 9(a) above was the simplest solution to achieve the required objective.

Three of the inner vertical bevelled gears, being driven by the concentric gear drive then serve as the driver links for the primary slider bar linkages. These then drive the secondary slider bar linkages that eventually control the orientation of the wrist through the wrist concentric drive, see Figure 10(a) and (b). The 4th vertical bevelled gear controls the proximal arm (lower arm, as it is closer to the fixed base) whose midpoint holds the pivot axis that connects to the sliders on each of the 3 primary slider-pivot linkages (Figure 10). It controls the elevation of the lower arm (proximal arm) with regard to the horizontal plane. The 5th gear controls the driver of a 3 bar slider-pivot linkage whose follower controls the angle between the upper arm (distal arm) and the lower arm (proximal arm).

The distal arm holds the axis that connects to the sliders of the 3 secondary slider bar linkages, see Figure 11. The slider pivot of the upper arm is located at the mid-point between the end rotational joints. This reduces the warping of the secondary stage follower orbit, much like with the primary slider bar linkages.

Figure 9 (a) Primary slider bar linkage, (b) Primary slider bar linkage connected to secondary slider bar linkage, (c) Non-rigid link actuation transfer, and (d) Experimental linkages

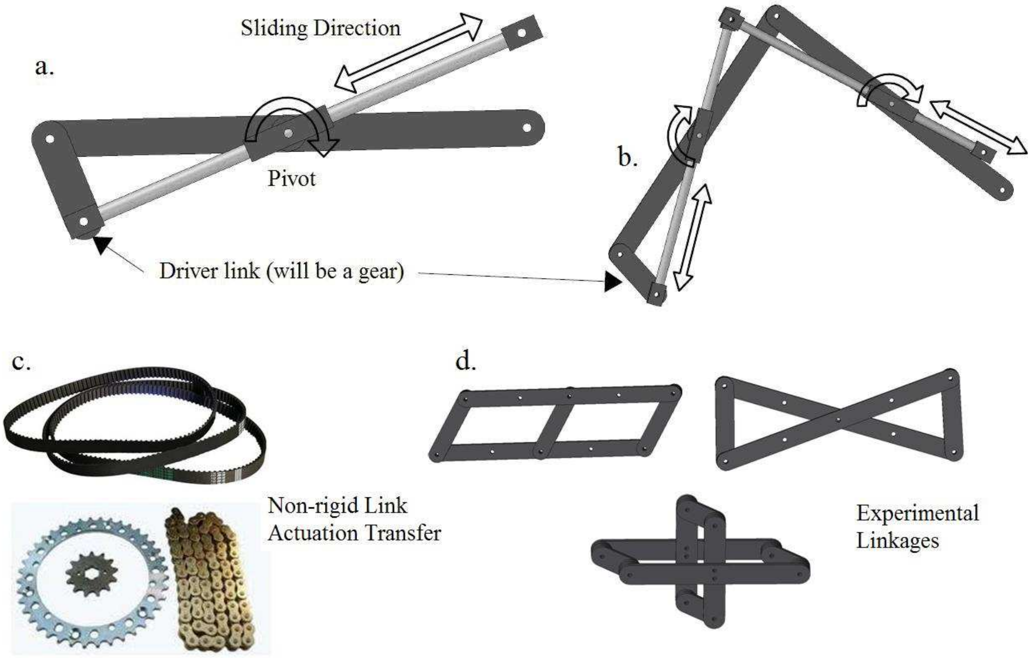
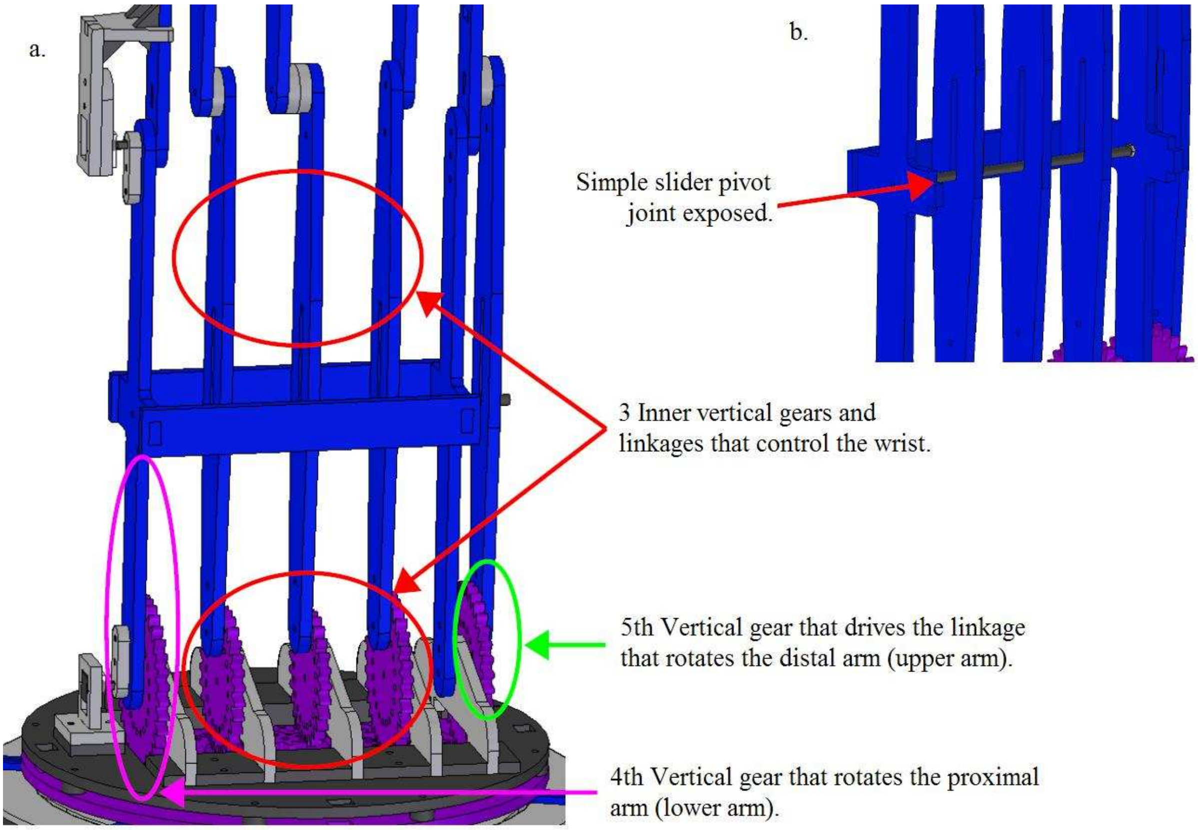


Figure 10 (a) Vertical gear connections to links, and (b) Simple slider pivot joint



The follower end points on the three inner slider-pivot linkages of the secondary stage then connect to three vertical bevelled gears respectively (which are mounted on the upper arm). Since the follower does not have a perfect circle orbit around the main wrist axis slots are cut into the gears and links allowing the follower to move in and out of a perfect circle trajectory/orbit, these are slider-pivot joints shown in Figure 12(d). Those vertical concentric bevelled gears then mesh with the wrist concentric drive gearbox having four concentric sections shown in Figure 12(a). This concentric drive again makes use of the double ball race bearing illustrated in Figure 6 and Figure 7, which allows each section to move independently of each other. The outer sections hold the inner sections in place. The outermost movable section (or the third section in the concentric gear drive for the wrist) rotates the wrist (this is the first axis) and has mountings for the inner 2 axes, of the 3 DOF wrist. With some additional gearing those remaining 2 axes are set at 90 degrees to each other and the 1st wrist axis, thus allowing a full 3 DOF orientation of the end effector.

Figure 11 (a) Upper arm showing secondary slider bar followers connecting to wrist gear drivers, and (b) Upper arm showing slider pivot joint

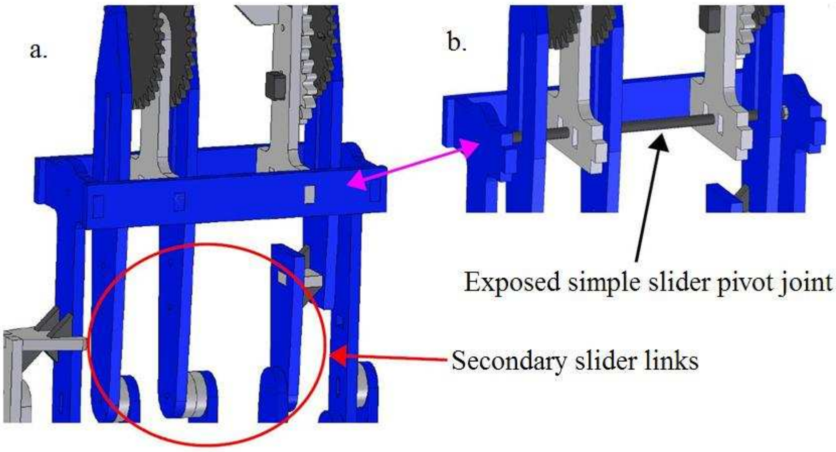
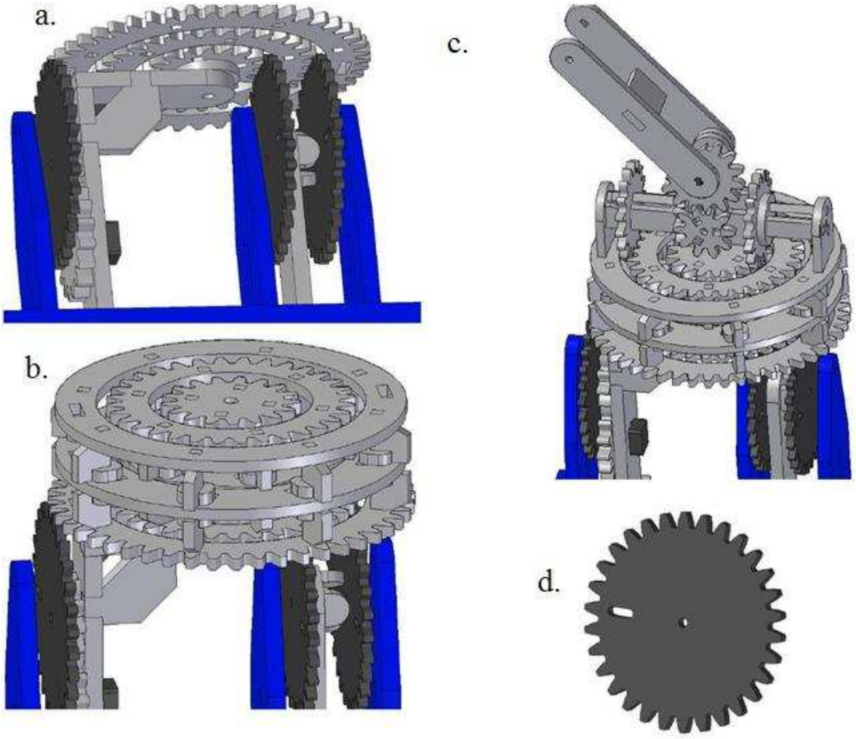


Figure 12 (a) Gear meshing at bottom of wrist concentric gearbox, (b) Top view of wrist concentric gearbox, (c) Complete Wrist and (d) Secondary follower gear with slider slot



Scaled Model Prototype - Motors, Electronics and Control

The mechanical design has been fully explained, and that was the central focus of this paper, however there are some additional points to make regarding the scaled functional model. To drive the linkages and gears model helicopter servo motors were used as the prime movers. A generic controller board with an Atmel ATMEGA128 microcontroller was sufficient for communications and PWM signal generation for the servos. A modified PC power supply was used to power everything, and instructions on how do this can be found readily on the internet. To be able to keep the servos at the fixed base they had to be modified. First the feedback potentiometer (pot) was removed and an extension cable soldered to it and the servo controller board. The feedback pot could then be placed at the joint it controls with the driving motor at another location. The mechanical stop was removed so that the output shaft could make a full 360 degree rotation. Additionally one also has to make certain that the polarity on the potentiometer is correct so that the servo drives it in the right direction to correct any positional error, if not the powered mechanical drive will destroy the feedback sensor and other linkages.

Figure 13 (a) Model helicopter servo motor, (b) Modified PC power supply, and (c) Generic controller board

Figure 14 Servo modification - removal of mechanical stop and relocation of feedback potentiometer

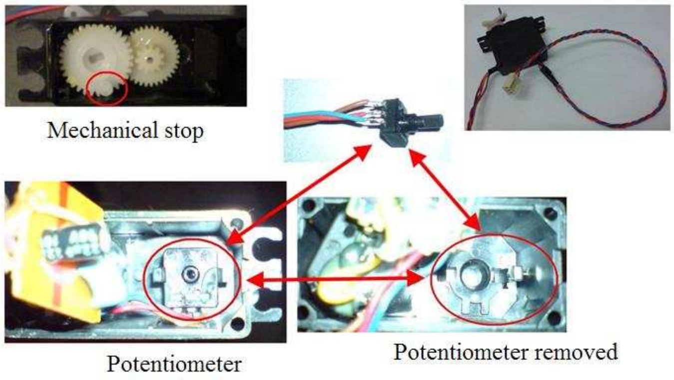
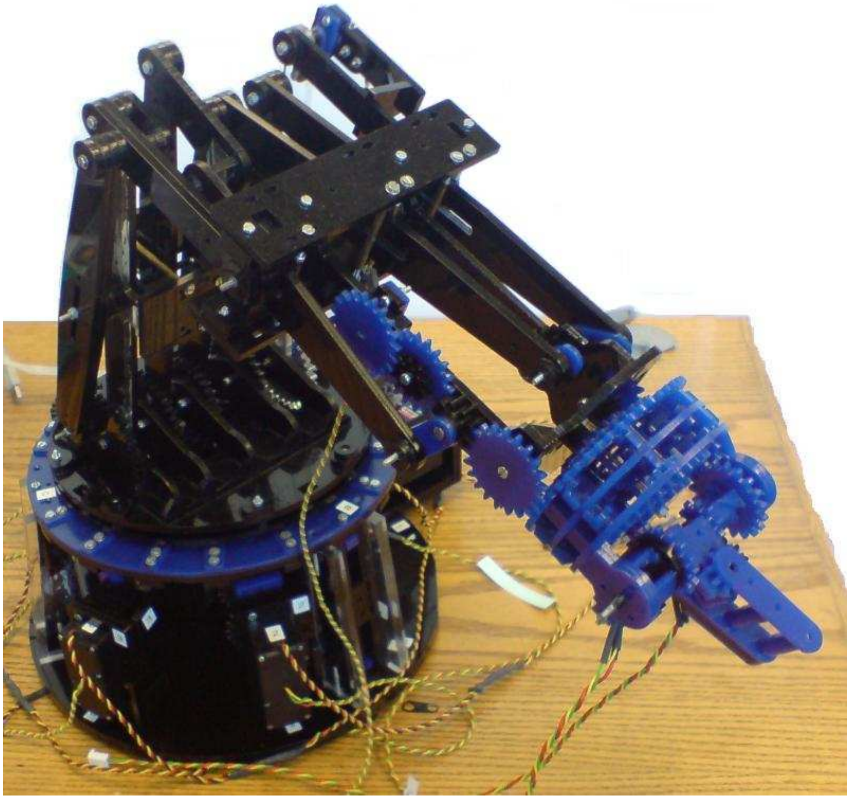


Figure 15 Perspex Model



Some Control Issues

The control will only be touched on here and is sufficiently big for a research paper of its own. Depending on how one approaches the problem the control can either be very difficult or relatively simpler, but it still requires extensive work. The forward kinematics for the 3 bar linkage is trivial, however no analytical solution exists for the inverse kinematics. One solution is to create a lookup table, which maps output angles to input angles for a certain number of discrete values. If the required angle lies between 2 discrete points the actual solution is found by numerical analysis and iteration, possibly a Newton-Euler method. This method is also used for the actual inverse kinematics of the full machine. The lookup table provides a starting point, and contains 3D spatial coordinates, the numerical algorithm then reduces the spatial coordinate error to within some tolerance. This discussion applies to feedback from joint encoders, however if an external position feed back mechanism is in place that error could be reduced to zero.

Conclusion

To conclude a novel 6 DOF hybrid machine having a large useful workspace with minimal inertia has been designed. There is no clear distinction between a parallel or serial nature, and it describes a truly unique hybrid structure. This is achieved by the use of a novel concentric gearbox, which is a complex mechanical component that allows actuation of 6 different DOFs by 6 motors attached to the fixed base of the machine. Currently there exists no satisfactory machine design that has all the characteristics that this novel machine would provide.

During that study it was necessary to build and test, mechanisms and linkages that comprise the robotic manipulator, this was accomplished using low cost Perspex. The complete design which has been described above was implemented on the same material to prove the concept. Thus far we were able to prove 4 working degrees of freedom, 3 DOFs to position the wrist and 1 to orient the wrist. The makeshift bearings for the concentric gearing systems then became problematic for the last 2 DOFs. However the physical model of the 3 DOF wrist does work and orients the end effector as desired.

The limitations on the mechanical properties of Perspex and the inaccuracy of the laser cutter used to cut out the parts, now mean that the next design iteration will have to use proper gearing and bearings, this will be achieved through 3D rapid prototyping (3D printing). A scaled version of the full 6 DOF concept is currently being designed and will be rapid prototyped to test functionality. Multiple configurations can be prototyped in this way at low cost to find the most suitable design option. This method will guarantee end of term full scale prototyping success. The Perspex model however did highlight structural problems, and the need for added motor axis support at the base. The laser inaccuracy also magnified backlash problems and this will have to be minimized in the next design.

The end goal is to build a full-scale prototype, which can then tested and compared to existing serial and parallel robots, and prove our claims of an improved design. We are currently in the process of acquiring sufficient funding to proceed with the research and development, and future research papers will focus on force transfer through the system, the effects of vibrations, the kinematics and dynamics of the machine, and other important metrics that will be used to then effectively compare the design to existing industrial robots.

The impact of this research will be realized if this technology can improve manufacturing quality, reduce product cost, increase production output rate and reduce the manufacturing carbon footprint. This will eventually yield higher profit margins for manufacturing companies, and will produce exports at lower cost increasing competitiveness.

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