Creating a distortion characterisation dataset for visual band cameras using fiducial markers.

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Abstract—**This paper presents two datasets for the purpose of calibrating, evaluating the calibration accuracy, and evaluating stereo vision accuracy of a pair of cameras. The authors provide a baseline that can be used as an initial comparison. This will allow other researchers to perform the same steps and create better algorithms to accurately locate fiducial markers and calibrate cameras. A second dataset that can be used to assess the accuracy of the stereo vision of two calibrated cameras is also provided.**

A fiducial marker was presented to a camera in a repeatable sequence of movements at different roll angles. Using the information captured during this stage it is possible to characterise the lens distortion of the camera. The calibrated cameras were then used with the stereo vision assessment dataset to triangulate the displacement between a pair of fiducial markers. The results show that it is indeed possible to use fiducial markers to calibrate visual band cameras but sub-pixel localisation would improve the results further.

All the data collected by the authors have been compiled and is available online at `http://prism.csir.co.za/fiducial/`.

I. INTRODUCTION

This paper investigates the suitability of fiducial markers for the task of distortion characterisation. Fiducial markers are typically used for augmented reality applications [1] due to their characteristics of being both uniquely identifiable and accurately locatable. These same properties make them attractive for camera calibration.

By presenting a known fiducial marker to a camera at a sequence of known positions it is possible to characterise the distortion of the camera. This paper aims to determine if the accuracy of the distortion characterisation is comparable to the method described by de Villiers and Cronje [2].

This paper provides two fiducial marker datasets, one for the calibration and one for the assessment of stereo vision accuracy. An initial analysis of the datasets are also provided. The first dataset allows for the calibration of the stereo cameras' internal parameters and their relative positions. This dataset contains thousands of images of a fiducial marker as it traverses the Field of View (FOV) of two cameras. These images are paired with accurate Three Dimensional (3D) robot arm positions which allows any researchers to perform their own camera calibration. The second dataset, again using fiducial markers, may be used to assess the accuracy of stereo triangulation. The dataset contains synchronised images of a pair of fiducial markers with known displacement which were statically mounted onto a rigid substrate. This will allow other researchers to compare the accuracy of their calibration and stereo vision algorithms by comparing the calculated displacement between the fiducial markers with the known ground truth displacement.

The rest of the paper is organised as follows: Section II provides an overview of the equipment used to capture the datasets. Section III presents and discusses the results. Section IV places the results in context and presents the final findings of the paper.

II. EXPERIMENT

This section describes the techniques and equipment used.

A. Fiducial Markers

The fiducial markers were generated, identified, and detected using the Chilitags [1] library. The fiducial markers generated by the Chilitags library are all distinct from one another and rotationally asymmetrical. Consequently there is little ambiguity when detecting and identifying a marker that has been presented to a camera.

After the marker has been identified the pixel coordinates of each of the four corners are determined. The usefulness of fiducial markers comes from the fact that they are both uniquely identifiable and accurately locatable. For example in augmented reality applications fiducial markers can be used to insert digital 3D models into live camera images [1].

Four example markers generated using the Chilitags library are shown in Figure 1. Each marker is composed of a square grid of cells and each cell is either black or white. A six by six cell grid containing white and black cells define the fiducial marker pattern. This pattern is surrounded by a black two cell border to provide contrast. The high contrast of the cells means that the markers can be identified even when they subtend a small angle in the FOV of a camera [1].

The datasets provide a full set of images that were captured during the robot movement sequence. When coupled with the accurate robot positions, these datasets will allow interested researchers to characterise the camera pair and compare their triangulation accuracy on the same data used in this paper.

B. Equipment

The equipment used for fiducial marker calibration is similar to that described by de Villiers and Cronje [2] and de Villiers et. al [3]. An ABB IRB 120 robotic arm with

(a) Marker with ID 1. (b) Marker with ID 2.

(c) Marker with ID 3. (d) Marker with ID 4.

Fig. 1: Four fiducial markers generated by the Chilitags library.

TABLE I: Camera specifications.

Manufacturer	Allied Vision	
Model	GE1600	
Sensitivity Spectrum	400-1000 nm	
Resolution	1600 × 1200	
Pixel size	5.5 μm	
Lens Name	Schneider Cinegon 1.8/4.8	Kowa LM5JCM
Nominal focal length	4.8 mm	5.0 mm
X (mm)	613.97	625.01
Y (mm)	-97.27	53.64
Z (mm)	444.66	450.94
Yaw (deg)	169.53	-178.70
Pitch (deg)	-0.21	-0.78
Roll (deg)	0.37	-0.09

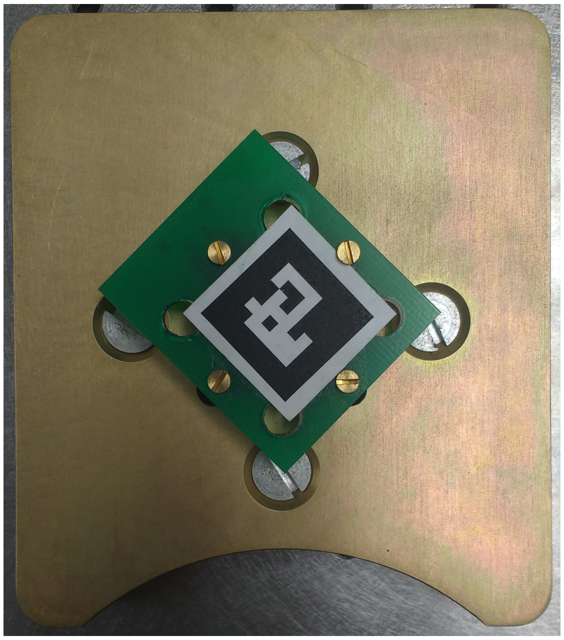


Fig. 2: Fiducial marker attached to the kinematic mount..

a stated 10 μm accuracy is used to present an identifiable object in a repeatable sequence of known poses to the camera being calibrated. The specifications of the cameras that were evaluated are given in Table I.

The primary difference between this new experiment and previous calibration techniques is that the energy source has been replaced with a fiducial marker. The fiducial marker is mounted on a NewPort M-BK-1A kinematic mount which in turn is mounted at an angle of 45° on a NewPort M-BKL-4 kinematic mount, shown in Figure 2, which is mounted on the robotic arm. The roll angles mentioned in this paper are the roll angles of the robotic arm meaning that a roll angle of 0° corresponds to a fiducial marker roll angle of approximately 45°.

There are some limitations to using a fiducial marker for calibration:

- This technique relies on reflected light for contrast. As such it is most applicable to shorter wavelengths of the optical part of the electromagnetic spectrum i.e. less than 2000 nm.
- Identifying a fiducial marker requires adequate contrast such that the blacks and white cells of the marker are distinct. This means that the calibration must be performed in a well lit environment and the exposure time of the camera increased. This drastically increases the time required to capture the dataset.
- Recognition of the fiducial marker requires sharp focus on the marker. To ensure such focus over the FOV the iris was stopped down, again increasing the dataset capture time.

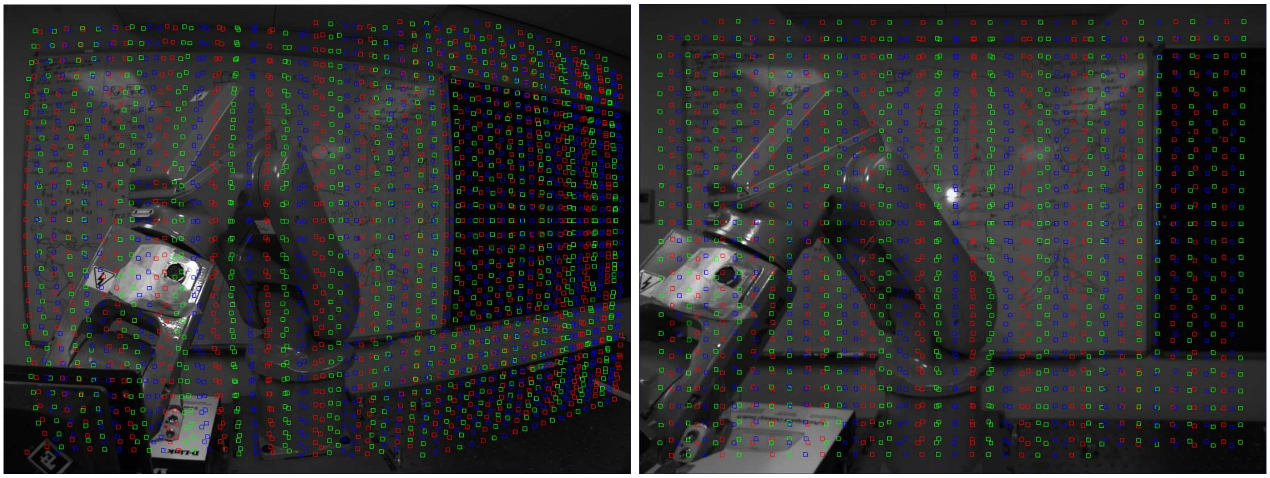
C. Experimental Design

This section serves to explain the full experimental design.

1) Calibration Dataset: A large movement sequence was used to move the robot across the full FOV of the camera. Each movement sequence was composed of a grid made up of 29 rows, 37 columns and two planes. Four full movement sequences were used with each sequence having a different roll of the fiducial marker. The captured positions of two of these completed sequences, overlayed on the camera images, are shown in Figure 3. The coloured blocks in the image represent the average centre of the fiducial marker at each robot position in the movement sequence.

For each position in the robot movement sequence the following steps occur:

1) Wait for the robot to reach the specified position.
2) Discard current image and next two images from the camera to ensure the exposure period did not include any robot movement.
3) Determine over several frames the average position of each corner of the fiducial marker.



(a) Roll angle 0° viewed by the Schneider Lens.

(b) Roll angle 45° viewed by the Kowa Lens.

Fig. 3: Example distortion grids captured using the fiducial marker with ID 1.

At each robot position the fiducial marker is located, identified, and the pixel positions of the four corners of the marker are located in the image plane. At each robot position multiple images of the fiducial marker are captured and the average corner pixel coordinates are saved to an output file.

Every saved image is 200 × 200 pixels with the fiducial marker centred, except for when the fiducial marker is touching the edges of the image. The output file contains a single line for each captured image which displays the offset from the top left (zero based) of the camera image in pixels as well as the X-, Y-, and Z positions of the robot arm in mm.

2) Assessment Dataset: The assessment dataset makes use of two fiducial markers attached to an aluminium block spaced approximately 100 mm apart as shown in Figure 4. The distances between the corners of the markers were measured with a set of Vernier callipers and are shown in Table II. The block was mounted onto the robot and placed in the approximate centre of the FOV of both of the cameras.

The robot was then commanded to move through 10 different roll angles evenly distributed between 360°. At each of these roll angles the robot was commanded to five further poses:

- 0° azimuth and elevation.
- 15° azimuth and 0° elevation.
- 0° azimuth and 15° elevation.
- $-15°$ azimuth and 0° elevation.
- 0° azimuth and $-15°$ elevation.

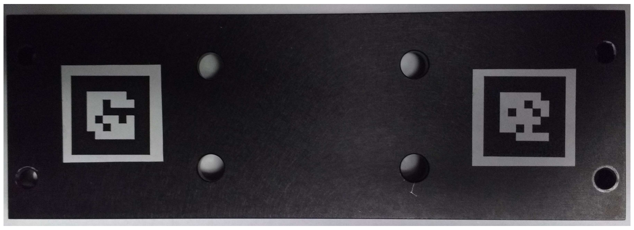


Fig. 4: Pair of fiducial markers used for stereo vision.

TABLE II: Distances between corners of fiducial markers.

Corner Pair	Distance (mm)
Top Left - Top Left	98.97
Top Right - Top Right	98.97
Bottom Right - Bottom Right	99.39
Bottom Left - Bottom Left	99.39

At each robot pose the markers are identified and located. An image of the pair of fiducial markers is captured and the pixel coordinates of the corners of each marker are saved to a file.

Stereo vision techniques were then used to compute the distance between the pair of fiducial markers. The experimental setup for the assessment dataset is shown in Figure 5(b).

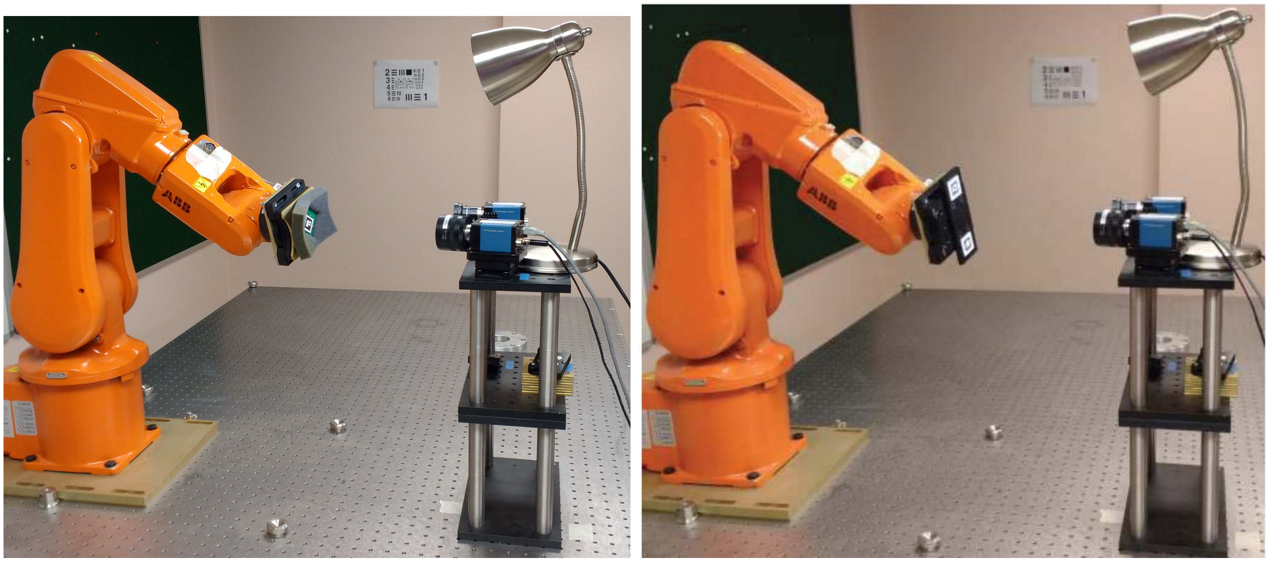
D. Data Analysis

Only the average positions of corner '1', the top left corner, of the markers was used in this preliminary analysis. Vectors were created using the image centre as the principal point and manufacturers' advertised focal lengths and pixel sizes.

The calibration technique used in this paper is based upon the work of de Villiers and Cronje [2]. The primary change that has been made is that the robot arm mounted energy source has been replaced with a fiducial marker. Brown's model [4], [5] is used to model the distortion of the camera and lens. Three tangential and five radial parameters are fitted to the captured data as described by de Villiers [6] to create an accurate mathematical model of the lens distortion.

The poses of the cameras relative to the robot were determined using vector bundle similarity as per [7].

Triangulation of the markers in the assessment dataset was performed using the distortion calibration and position



(a) Experimental setup for the distortion dataset.

(b) Experimental setup for the assessment dataset.

Fig. 5: Example distortion grids captured using the fiducial marker with ID 1.

characterisation described above to create a ray line in the robot reference system. Then performing the closest point of intersection of these ray lines.

III. RESULTS

This section presents the results of the experiment.

A. Distortion Calibration Results

Table III shows the results of the distortion calibration as well as position determination at the four different roll angles. The distortion error is the Root of the Mean Square (RMS) deviation of collinear points (in the real world) from the best fit straight line through them. The initial distortion values were 13.767 pixels RMS and 2.779 pixels RMS for the Schneider Cinegon 1.8/4.8 and Kowa LM5JCM respectively. The final position error is the RMS error in degrees between the corresponding vectors in the image based vector bundle and the hypothesised pose vector bundle [7].

These results show that while it is indeed feasible to perform camera calibration using fiducial markers instead of a Light Emitting Diode (LED), it is less accurate than the results reported by de Villiers *et al.* [3]. With errors in the order of one pixel RMS as opposed to less than half a pixel RMS. This degraded performance is due to corner positions reported by the fiducial marker corner detection not being sub-pixel accurate. The characterisations are robust to the angle of roll of the fiducial marker.

TABLE III: Distortion and position results

Lens	Roll Angle	Distortion Error (pix. RMS)	Position Error (pix. RMS)
Schneider Cinegon 1.8/4.8	0°	1.06042	0.31117
	30°	0.99687	0.30186
	45°	0.90994	0.22406
	70°	0.91149	0.25102
Kowa LM5JCM	0°	0.66428	0.24101
	30°	0.93907	0.25529
	45°	0.79221	0.18223
	70°	0.81938	0.19473

B. Stereo Vision Results

Table IV presents the stereo vision accuracy results based on the assessment dataset discussed in Section II-C2. It contains the stereo vision accuracy results for the pair of cameras calibrated using the distortion characterisation dataset with the roll angle specified. The robot arm was approximately 200 mm away from the cameras in the X direction.

From Table IV one can see that using the calibration results discussed in Section III-A it is possible to determine the displacement between the pair of fiducial markers to better than 4 mm, which is 2% of the distance of the markers from the camera and 4% the distance between them.

IV. CONCLUSION

This paper investigated the feasibility of using fiducial markers for the calibration of visual band cameras. This paper

TABLE IV: Stereo vision measurement of distance between top left corners of the fiducial marker.

Roll (deg)	Miss distance (mm RMS)		Displacement error (mm RMS)
	Marker 1	Marker 2	
0	0.3749	0.3897	1.8628
30	0.3058	0.4214	1.6413
45	0.5528	0.6189	3.7243
70	0.3054	0.4023	3.0830

presents a pair of datasets that can be used to characterise a stereo pair of cameras and then assess their triangulation accuracy.

The same fiducial marker was presented to two cameras by a robotic arm moving through a grid-like movement sequence at varying roll angles. The corners of the fiducial marker were detected using the Chilitags [1] library at each robot position. The position of the marker was captured multiple times at each robot position and the average marker position was stored. This information was then used to characterise the distortion of camera.

A preliminary analysis was performed to verify the correctness of the dataset and the results serve as an initial baseline for the reference of future researchers.

In this assessment it was found that the accuracy of the distortion model created using fiducial markers is slightly worse than that of a camera calibrated using a LED. The roll angles of the fiducial marker did not have a significant effect on the accuracy of the distortion characterisation but did have an effect on the resultant triangulation accuracy.

The preliminary analysis of the assessment dataset was used to verify the accuracy of the camera calibration by verifying the displacement between a pair of fiducial markers mounted onto a rigid aluminium substrate. The accuracy of the stereo vision was found to be within $3.8\ mm$ of the ground truth in the worst case, and $1.7\ mm$ in the best case.

This dataset will allow other computer vision researchers to use their own methods to locate the fiducial marker, characterise the photogrammetric properties of the camera, determine their triangulation accuracy, and compare their results to those presented in this paper. The dataset is available at `http://prism.csir.co.za/fiducial/`.

A. Future Work

To improve the efficiency of the dataset capture it is possible to mount multiple unique fiducial markers onto a single surface. At every robot position the camera will capture the image location of all the fiducial markers and thus fewer grid points will have to be visited to provide the type of dense grid required for distortion and position characterisation.

The method used to locate the fiducial markers could be improved to provide sub-pixel accurate positions which would further improve the accuracy of the distortion and position characterisation.

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