Accuracy of a 3D reconstruction system

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Abstract: - Despite of the needs, a calibrated 3D visual servoing has not fully matured as a technology yet. In order to widen its use in industrial applications its technological capability must be precisely known. The accuracy and repeatability are two of the crucial parameters in planning of any robotic task. In this paper we describe a procedure to evaluate the 2D the 3D accuracy of a robot stereo vision system consisted of two identical 1 megapixel cameras.

Key-Words: - Visual servoing, Robot vision, 3D reconstruction

1 Introduction

Advanced automation requires intelligent robots that are able to manipulate, grasp, inspect, weld, and machine objects in unstructured environments. In the past, a variety of sensors have been used for the purpose of real-time robot control, including force/torque tactile sensors, laser triangulation devices, proximity, sonar, and infrared phase or time-of-flight range sensors. For various reasons none of these sensors are wholly satisfactory and all have major weaknesses. Computer vision can provide powerful geometric cues to help guide and position robots and their tools. With respect to the sensors just mentioned, vision has several advantages: high resolution; increasingly lower cost, high reliability, low weight with low power consumption, large range of possible light wavelengths, it can operate over a substantial range, from 0.5 meters to tens of meters (with the same lens) and the bandwidth of a vision system is compatible with the robot controllers at the task level [1].

A key technique is visual servoing where the appearance of a target in the image is used to control the position of the end-effector and to move it to a desired position in the scene. More generally, visual servoing is an appealing technique which, with the increased speed of processing available today, enables the loop to be closed between sensing and action so that a robot's behaviour can be modified on-line according to what it sees [2].

In the last 15 years, there were many techniques developed using uncalibrated cameras for visual servoing purposes [3] [4] [5] and tested in the laboratory environments but due to many associated problems they never really found the way to the industrial robotic systems. The vast majority of the existing visual servoing methods in the industry use calibrated robots in conjunction with calibrated cameras. Among them, the 2D or mixed 2D/3D visual guidance still prevails over the pure 3D solutions. The later has not fully matured as a technology yet and is not widely used [6].

In order to use such a 3D robot vision system for visual servoing or any other metrological task its accuracy and repeatability must be precisely known. We investigated the procedure to evaluate the accuracy of a stereo vision system consisted of the two identical 1Mpixel cameras without very expensive metrological devices.

2 Methodology

Two types of tests were performed:
– the static 2D accuracy test and,
– the 3D accuracy test.

Within the static 2D test, we moved the array of infrared light emitting diodes (IR-LED) with the linear drive perpendicular to the camera optical axes and we measured the increments in the image. The purpose was to detect the smallest linear response in the image. The IR-LED centroids were determined in two ways: on binary images and on grey-level images as centers of mass. During the image grabbing the array did not move thus eliminating the dynamic effects. We averaged the movement of centroids in a sequence of 16 images and within the array of 10 IR-LEDs and calculated the standard deviation to get the idea of accuracy confidence intervals.

We performed the 3D accuracy evaluation with 2 fully calibrated cameras in a stereo setup. Using again the linear drive, the array of IR-LEDs was moved along the 3D line with different increments and the smallest movement producing a linear response in reconstructed 3D space was looked for.

3 Testing setup

The test environment consisted of:

– PhotonFocus MV-D1024-80-CL-8 camera with CMOS sensor and framerate of 75 fps at full resolution (1024x1024 pixels),
– Active Silicon Phoenix-DIG48 PCI frame grabber,
– Moving object (IR-LED array) at approximate distance of 2m. The IRLED array (standard deviation of IR-LED accuracy is below 0.007 pixel [7]) fixed to Festo linear guide (DGE-25-550-SP) with repetition accuracy of +/-0.02mm.

For static 2D test: a distance from camera to a moving object (in the middle position) that moves perpendicularly to optical axis was 195cm; camera field-of-view was 220cm, which gives pixel size of 2.148mm; Schneider-Kreuznach lens CINEGON 10mm/1,9F with IR filter; exposure time was 10.73ms, while frame time was 24.04ms.

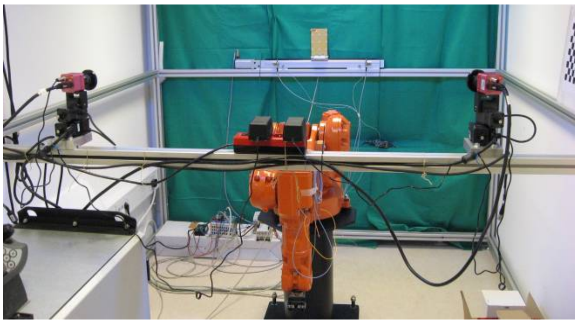

Fig. 1: The test environment consisted of two cameras, linear drive and industrial robot.

For 3D reconstruction test: left camera distance to IR-LED array and right camera distance to IR-LED array were about 205cm; baseline distance was 123cm; Schneider-Kreuznach lens CINEGON 10mm/1,9F with IR filter; Calibration region-of-interest (ROI): 342 x 333 pixels; Calibration pattern: 6 x 8 black/white squares; Calibration method [8]; Reconstruction method [9].

4 Results

4.1 2D accuracy test

Below are the results of the evaluation. Tests include the binary and grey-level centroids. For each lens type and tested movement increments the following figures are presented:

– Pixel difference between the starting image and the consecutive images (at consecutive positions) -for each position the value is calculated as the average move of all 10 markers, while their position is calculated as the average position in the sequence of the 16 images grabbed at each position in static conditions. The lines in these figures should be monotonically increasing and as straight as possible. See Fig. 2.

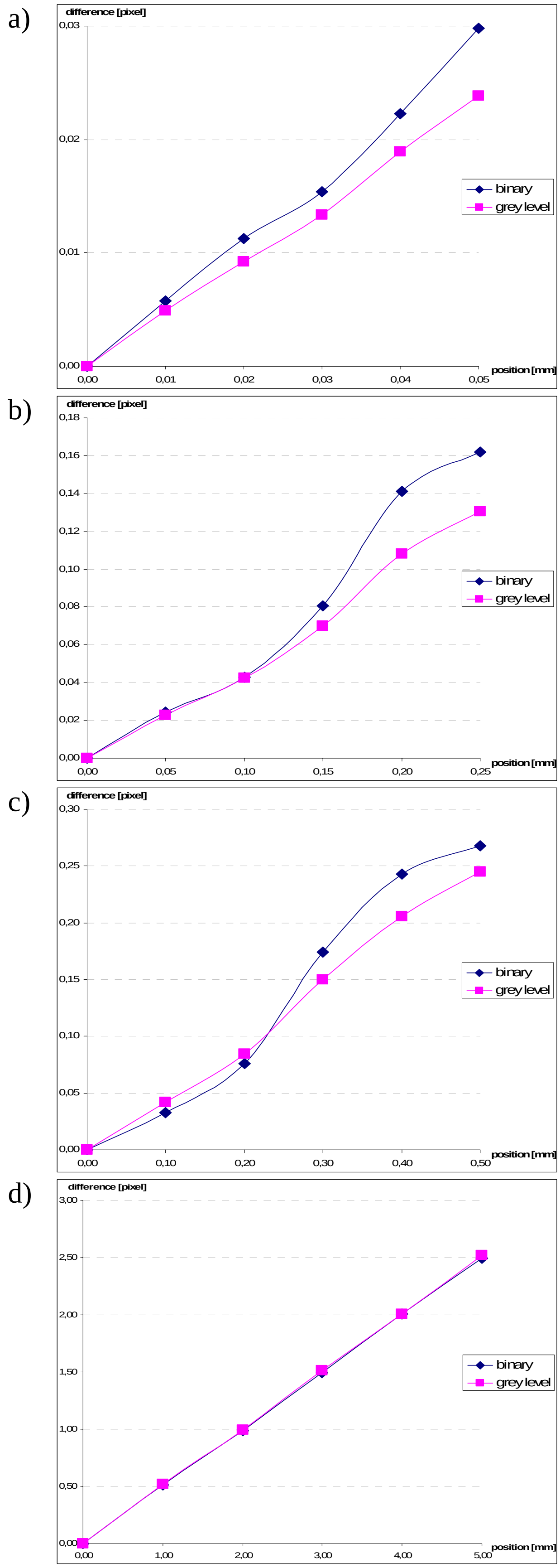

Fig. 2: pixel difference for binary and grey-level images in each position for different increments: a) 0.01mm, b) 0.05mm, c) 0.1mm, and d) 1mm.

– Standard deviation of center positions of all markers regarding their move according to the first image. The columns in these figures should be as low as possible. See Fig. 3.
– There are two additional figures to compare normalized movement increments (the lines in these figures should be monotonically increasing and as straight as possible): (1) pixel differences of the single marker when working with binary images, and (2) pixel differences of the single marker when working with grey-level images. See Fig. 4.

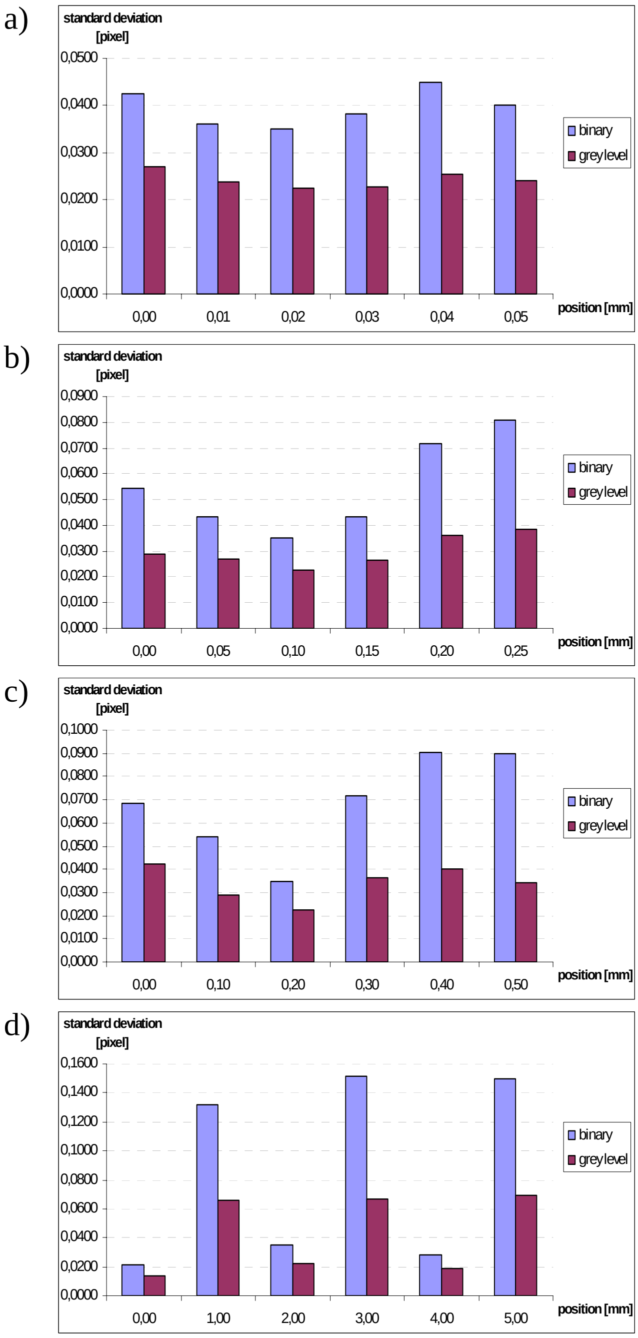

Fig. 3: standard deviation for binary and grey-level images in each position for different increments: a) 0.01mm, b) 0.05mm, c) 0.1mm, and d) 1mm.

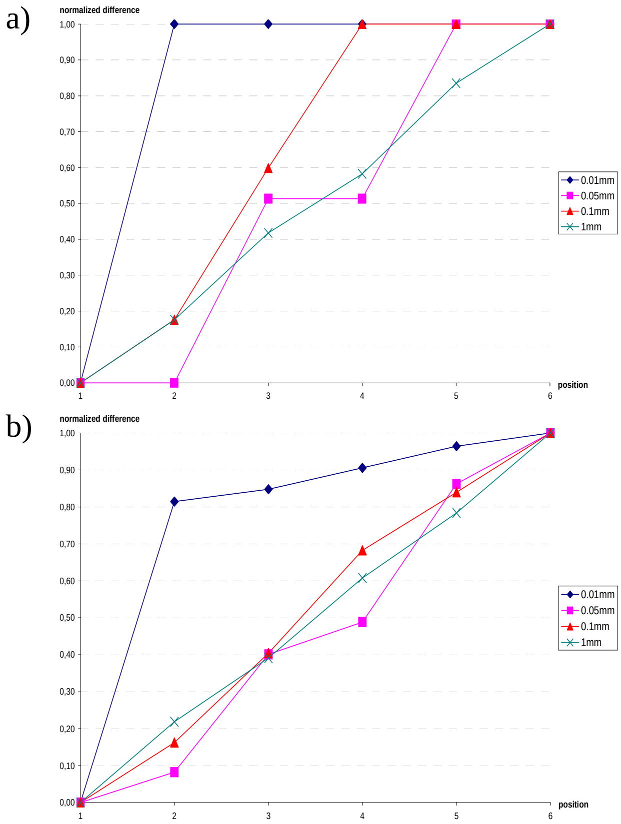

Fig. 4: normalized differences for each position comparing different increments: a) binary, b) grey-level images.

4.2 3D reconstruction test

We tested the static relative accuracy of the 3D reconstruction of the IR-LED array movements by linear drive. The test setup consisted of the two calibrated Photonfocus cameras gazing at the IR-LED array attached to the linear drive which exhibited precise movements of 0.01mm, 0.05mm, 0.1mm and 1mm. The mass center points of 10 LEDs were extracted in 3D after each movement and relative 3D paths were calculated and compared to the linear drive paths. Results are presented in Figs 5, and 6. Only grey-level images were considered, due to the better results obtained in 2D tests.

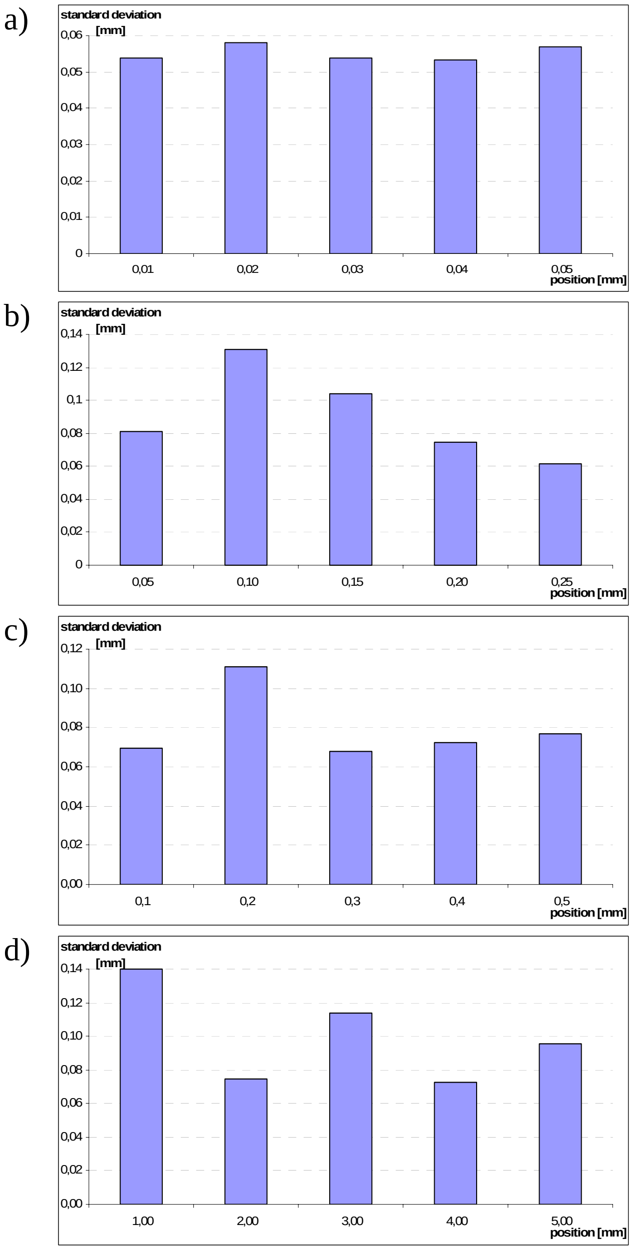

Fig. 5: standard deviation for 3D reconstruction with grey-level images in each position for different increments: a) 0.01mm, b) 0.05mm, c) 0.1mm, and d) 1mm.

We applied a linear regression model to measured data in Fig. 4, and we calculated the R^2 values to asses the fitting quality. The results are presented in the Table 1 for 2D tests and in Table 2 for 3D tests. The R^2 value can be interpreted as the proportion of the variance in y attributable to the variance in x (see Eqn. 1), where 1 stands for perfect matching (fitting) and a lower value denotes some deviations.

$$R^2 = \left(\frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 (y-\bar{y})^2}} \right)^2 \quad (1)$$

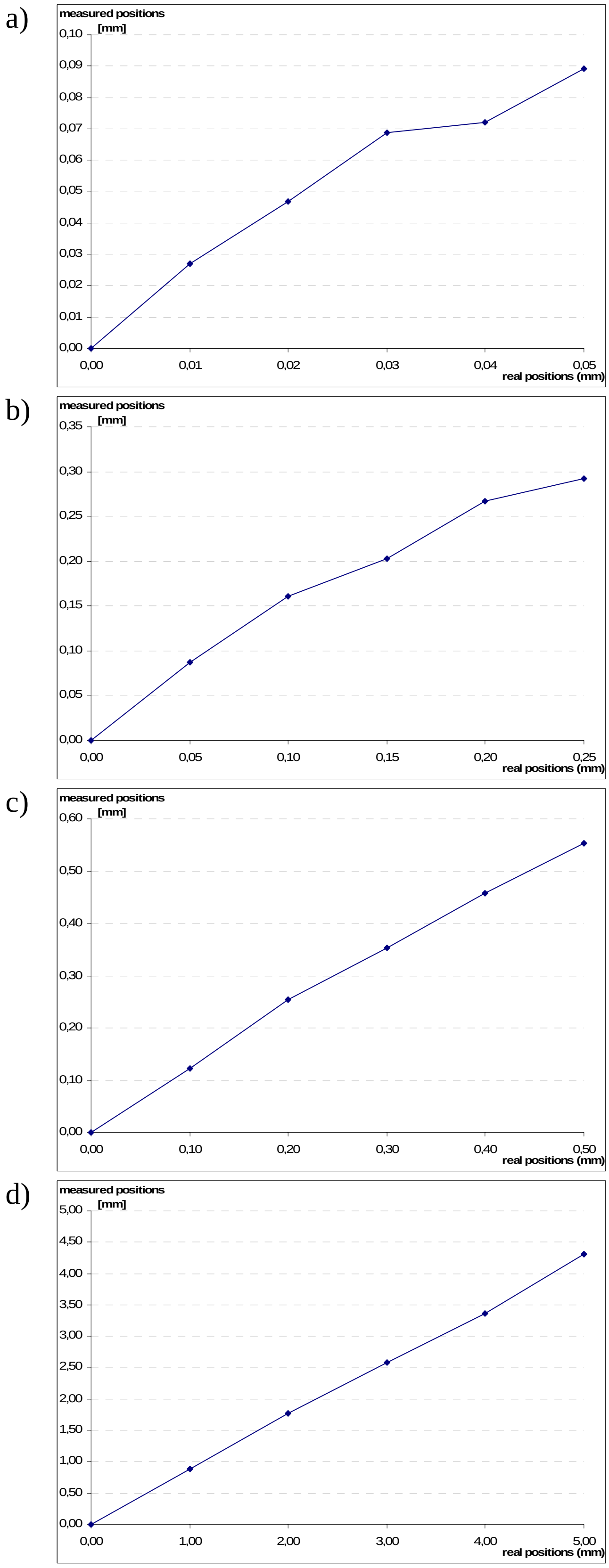

Fig. 6: pixel difference for 3D reconstruction with grey-level images in each position for different increments: a) 0.01mm, b) 0.05mm, c) 0.1mm, and d) 1mm.

Table 1
Comparison of standard deviations and R^2 values for different moving increments in 2D

increments [mm]	standard deviation		R^2	
	binary	grey-level	binary	grey-level
0.01	0.045	0.027	0.4286	0.6114
0.05	0.081	0.039	0.9141	0.9716
0.1	0.090	0.042	0.8727	0.9907
1	0.152	0.069	0.9971	0.9991

Table 2
Comparison of standard deviations and R^2 values for different moving increments in 3D

increments [mm]	standard deviation	R^2
0.01	0.058	0.7806
0.05	0.131	0.8695
0.1	0.111	0.9315
1	0.140	0.9974

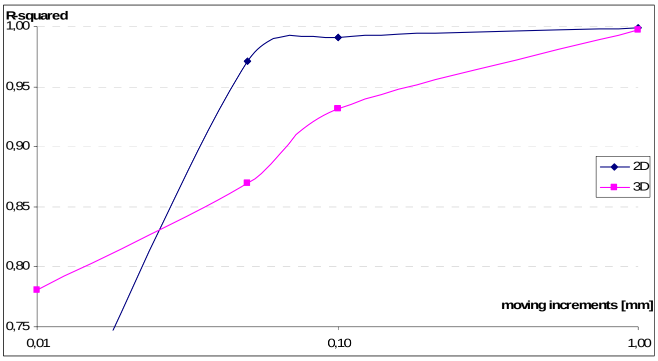

Fig. 7: R^2 values for 2D and 3D tests.

Fig. 7 presents the relationship between R^2 in 2D and 3D tests. Considering the R^2 threshold of 0.994 we were capable to detect increments of the moving object in the range of 1/5 of a pixel.
Accuracy in 3D is lower than in 2D case, due to the calibration and reconstruction errors, and according to tests performed it is approximately 1/2 of a pixel.

5 Conclusions
We performed the 2D and 3D accuracy evaluation of the 3D robot vision system consisting of 2 identical 1 megapixel cameras. The measurements showed that the raw 2D accuracy (without any subpixel processing approaches and lens distortion compensation) is confidently as good as 1/5 of a pixel. However, this is reduced to 1/2 of a pixel when image positions are reconstructed in 3D due to reconstruction errors.

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References:
[1] A. Ruf, R. Horaud, Visual servoing of robot manipulators, Part I: Projective kinematics, *INRIA technical report*, No. 3670, 1999).
[2] C. Samson, M. Le Borgne, B. Espiau, *Robot control, the task function approach*, Oxford science publications, Oxford, 1991.
[3] S. Hutchinson, G. Hager, P.I. Corke, A tutorial on visual servo control, *Yale University Technical Report*, RR-1068, 1995.
[4] N. Hollinghurst, R. Cipolla, Uncalibrated stereo hand-eye coordination, *Image and vision computing*, Vol. 12, No. 3, 1994, pp. 187-192.
[5] E. Grosso, G. Metta, A. Oddera, G. Sandini, Uncalibrated visual servoing in reaching tasks, *University of Genova Technical Report*, TR 3-95, 1995.
[6] D. Robson, Robots with eyes, *Imaging and machine vision-Europe*, Vol. 17, 2006, pp. 30-31.
[7] G. Papa, D. Torkar, Investigation of LEDs with good repeatability for robotic active marker systems, *Jožef Stefan Institute technical report*, No. 9368, 2006.
[8] Z. Zhang, A flexible new Technique for Camera Calibration, *Technical report*, MSRTR-98-71, 1998.
[9] O. Faugeras, *Three-Dimensional Computer Vision: A geometric Viewpoint*, The MIT Press, 1992.