REAL-TIME PHOTOGRAMMETRIC ALGORITHMS FOR ROBOT CALIBRATION

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Commission V, WG V/1

KEY WORDS: Industry, Robotics, Calibration, Measurement, Close Range

ABSTRACT

The aim of this project is to investigate a new photogrammetric approach to determine the pose of the robot end-effector in real-time for updating the robot model. Specifically, the two fundamental photogrammetric algorithms are investigated: intersection and resection. In both cases, cameras are mounted on the moving robot observing targets fixed on the floor. In the first approach the camera pose (exterior orientation) with respect to the target co-ordinate system can be measured directly by using the collinearity equation. In the second approach, the stereo-camera measures the position of the observed targets with respect to the camera co-ordinate system. If the target co-ordinates are available the camera position with respect to the target co-ordinate system can be determined. With a standard algorithm for hand-eye calibration the misalignment in-between camera and end-effector is computed. The paper compares the different set-ups with respect to ease of implementation, accuracy, and workspace size. These set-ups were simulated and verified in several investigations. In our test environment we use a industrial robot KUKA KR15/2 and digital CCD cameras with near infrared illumination.

1. INTRODUCTION

By ISO 8373 (International Standard Organization) industrial robots are defined as freely programmable appliances with a series of rigid components connected by joints. One end of the component chain is fixed while the other end (end-effector) can be moved by computer control. If there are for example six or more revolute joints, the industrial robot can reach every point of its working cell with every orientation. State-of-the-art industrial robots are able to move objects with weights up to 500 kg and with a repeatability of 0.3 mm or better. In most cases the joints are powered by electric motors whereas very heavy robots are powered hydraulically. Because of the maximum power at a relatively high speed of the electro motors, the speed must be geared down. Forward kinematic describes the relation between the motion of each joint and the motion of the end-effector and thereby the position and orientation (pose) of the end-effector in arbitrary coordinate systems can be computed. Therefore robot model parameters such as length of segments, distance between two adjacent segments and rotation angle for revolute joint between two segments have to be known. The rotation angle can be measured exactly by a position encoder between motor and gear unit. Other parameters are defined by the design plan of the robot. But due to manufacturing and other environmental influence they do not operate accurately.

The overall errors can be subdivided in geometric errors such as

- tolerance of the segment length,
- angle error,

and non-geometric such as

- gear elasticity
- segment elasticity
- temperature influence.

By a robot-calibration the influence of several errors can be eliminated (Whitney 1986, Heisel 1998, Wiest 2001), but there are still remaining time dependent errors such as temperature influence and tear and wear. These errors can only be reduced by the design of the robot in order to get it in accordance with the mathematical model. Nevertheless, the absolute accuracy of a robot is much lower composed to the repeatability and can be as large as several millimeters. The disadvantage of the approach of absolute calibration is obvious. Replacement of robot components requires a complete recalibration. In addition, the main disadvantage is that off-line programming is not possible, as the required accuracy cannot be reached. To remove the disadvantages an external measurement system for the direct measurement of the robots pose is required. There are several photogrammetric and non-photogrammetric measurement systems on the market (Wiest 2001). The main objective is that they cannot be used during production. Furthermore, the costs of these systems are very high, sometimes higher than the cost of a robot. Photogrammetry is certainly able to determine the robots pose very accurately by using industrial standard cameras at low cost (Maas 1997). Also, industry acceptance of camera-based systems has increased in the last few years. In the ideal case the frequency of the direct measurement of the robot pose and the frequency of the robot control loop are the same. For modern industrial robots the frequency of the control loop is between 200 and 1000 Hz. With inexpensive standard industrial camera this frequency is not possible, because of the high data rate. However, in our special case, only those parts of an image containing targets are necessary for measurement. In the near future CMOS-Cameras with direct access to the pixel will be available. With these cameras a measurement rate of 200 Hz and more is possible.

Nevertheless the problem of shadowing effects remains. For example, a robot moving into a car body to fix a new element does not have a direct view to targets fixed outside the car body. In this case, the robot pose cannot be determined. Therefore, it is easier to use direct pose measurement for updating the robot model than to correct the control loop directly.

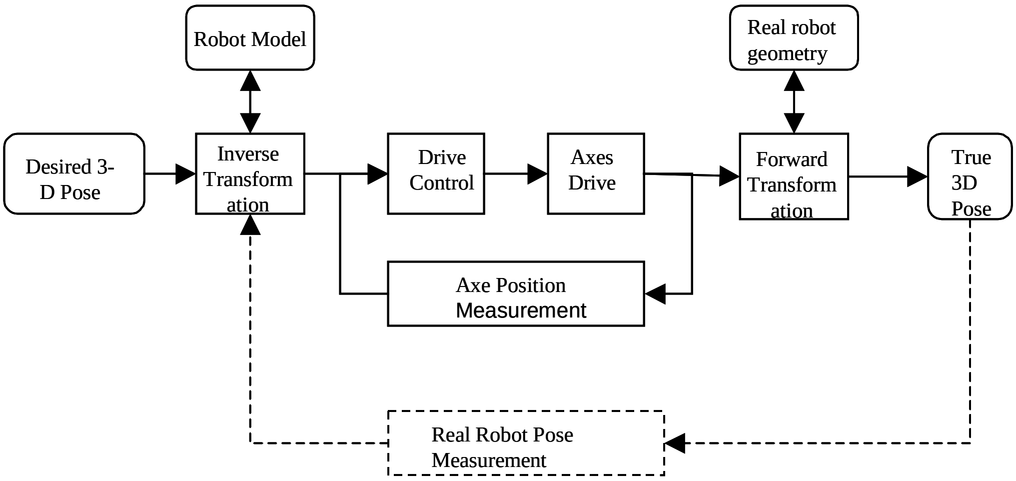

Figure 1 Robot Control Loop

The work flow for measuring the real robot pose by using the resection or the forward intersection process are nearly equal. Figure 2 gives an overview of this process. On the right side the work flow of the real-time process is displayed. The camera calibration (Chapter 4.1) and the hand-eye-calibration (Chapter 5) are done by the first start of the system. The hand-eye-calibration is obligatory for the coordinate transformation from the camera system to the robot system.

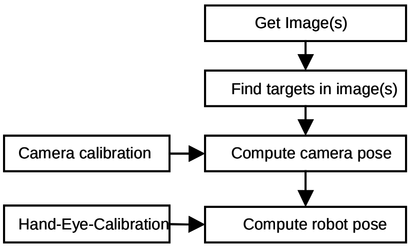

Figure 2 Work Flow

The real-time process starts with grabbing of the images. After getting the images from cameras, targets have to be identified as described in chapter 4.2. After transforming the measured image coordinates of the targets into the ideal image coordinate system (chapter 4.1) the resection process (chapter 4.3) or the forward intersection process (chapter 4.4) can be used to get the camera pose in relationship to the test field coordinate system. To get the camera pose in association to the robot system a normal coordinate transformation by using the parameter from the hand-eye-calibration is done.

Before exactly describing the work flow, some remarks concering robot control loop and some investigations in finding the absolute accuracy of the robot are necessary.

2. ROBOT CONTROL

Figure 1 shows typical components of a robot control unit. Starting from a given pose in 3-D space, the inverse transformation is used to compute values for all joints. In this transformation, a model of the real robot is used for all constants regarding translation and rotation offsets in the links and joints. Those constants are known from the robot design, however they are subject to manufacturing tolerances. The computed joint values are set and the forward transform is performed by the actual (real) robot. In order to control the movement of the robot, control loops exist which consist of axes measurement devices such as rotational encoders and a feedback to the drive control. Since these loops do not include the inverse or forward transform, they are not able to compensate for differences between the assumed and actual link and joint constants.

Using an additional measurement system in order to obtain the true 3-D pose of the robot end effector, an external control loop can be built (see Figure 1). The differences between required and actual pose can be used to estimate the constants of the robot model employed in the inverse transform. As there is usually quite a large number of constants, many robot poses have to be measured in order to obtain enough observations for a parameter estimation. This is done for example during a factory calibration of industrial robots. After calibration the obtained parameters are non-alterable. Erros which do not occur during calibration will be disregarded later.

3. ACCURACY OF A ROBOT

For this first experiment we used a KUKA KR 125/2 industrial robot which is able to handle loads of up to 125 kg and has a reach of 2410 millimetres. The manufacturer specifies a repeatability of better than ±0.2 mm. The robot is used mainly for automotive production and packing tasks.

The robot moves to six uniformly distributed positions in his working cell. After that the moves are repeated in the inverse order. In the table, the deviations of the position and orientation of the end effector are itemized. The second column contains the reached accuracy in the determination of the deviations. The statements of the deviations in x, y and z-direction are in mm. The deviation of the orientations are indicated in degree.

Pos	X [mm]	Y [mm]	Z [mm]	ω [DGR]	ϕ [DGR]	κ [DGR]
1	1.174	-0.284	-1.642	–0.008	–0.006	0.003
	0.114	0.111	0.096	0.002	0.002	0.002
2	-0.243	1.989	0.471	0.126	–0.052	–0.165
	0.112	0.108	0.084	0.002	0.002	0.002
3	-0.035	-0.189	-0.330	0.002	0.000	0.000
	0.110	0.109	0.084	0.002	0.002	0.001
4	0.172	-0.774	0.152	–0.010	0.004	0.0019
	0.113	0.139	0.106	0.002	0.005	0.002
5	-0.096	0.618	0.313	0.008	–0.003	–0.011
	0.193	0.187	0.147	0.004	0.004	0.003
6	0.386	0.854	1.459	–0.011	–0.028	0.000
	0.073	0.070	0.052	0.001	0.001	0.001

Table 1: Accuracy of a industrial robot

The result shows that the accuracy of this robot is much worse than 1 mm. The experiment shows not the absolute accuracy of the robot, it only shows the error for the repeatability using different paths. By changing other parameters like temperature, payload and acceleration the error will increase. In other words, the absolute accuracy for this robot will be much worse than 1 mm.

4. PHOTOGRAMMETRIC SYSTEM

4.1 Camera Model

While the basic camera model in photogrammetry is the pin-hole camera, additional parameters are used for a more complete description of the imaging device. The following parameters are based on the physical model of D. C. Brown (Brown 1971). The parameter follows the notation for digital cameras presented by C. S. Fraser (Fraser 1997). Three parameters K1, K2 and K3 are used to describe the radial distortion. Two parameters P1 and P2 describe the decentring distortions. And two parameter B1 and B2 describe the difference in scale between x- and y-axis of the sensor and the shearing. To obtain the corrected image coordinates (x, y) the parameters are applied to the distorted image coordinates (x', y') as follows:

$$\bar{x} = x' - x_0$$
$$\bar{y} = y' - y_0$$
$$\Delta x = \bar{x}r^2K_1 + \bar{x}r^4K_2 + \bar{x}r^6K_3 + (2\bar{x}^2 + r^2)P_1 + 2P_2\overline{xy} + B_1\bar{x} + B_2\bar{y}$$
$$\Delta y = \bar{y}r^2K_1 + \bar{y}r^4K_2 + \bar{y}r^6K_3 + 2P_1\overline{xy} + (2\bar{y}^2 + r^2)P_2$$
$$x = \bar{x} + \Delta x$$
$$y = \bar{y} + \Delta y$$

where (x_0,y_0) is the principal point and $r = \sqrt{\bar{x}^2 + \bar{y}^2}$ is the radial distance from the principal point. The camera parameters are determined in a bundle adjustment using a planar test field. The bundle adjustment process is carried out before-hand.

4.2 Target recognition

For the target array, we used a combination of coded and non-coded retro-reflective targets. In this case, the targets were fixed on a portable plate. They were arranged in such a way that for all intended robot positions at least four coded targets were visible in the camera image. During the measurement, coded targets are identified and measured first and an initial approximation for the camera pose is computed. Then, in a second step, all remaining (non-coded) targets are identified and measured based on this initial approximation.

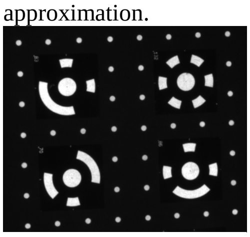

Figure 3 Targets

Regarding coded target design, there exist several possibilities. We used coded targets made of a central disk (used for measurement) and a concentric ring, which contains the code (for identification). Van den Heuvel and Kroon (1992) or Schneider and Sinnreich (1992) have suggested such a design for example. Of course, the design is invariant with respect to rotation, scale change and perspective distortion.

In order to achieve a robust target identification and precise image coordinate measurement, a very high contrast between targets and background is desirable. To achieve this, we use retro-reflective targets in combination with an illumination in the near infrared (IR) spectrum. IR light emitting diodes are placed in a concentric ring closely around the camera's lens. Additionally, the lens is covered with a daylight filter. This way, practically no objects are visible in the images except for the targets.

4.3 Resection

The problem of spatial resection involves the determination of the six parameters of the camera station's exterior orientation. To solve the resection problem a two-stage process is used. A closed-form solution using 4 points gives the initial values of for an iterative refinement using all control points.

Several alternatives for a closed form solution to the resection problem were given in the literature. In this approach the algorithm suggested by Fischler et. al (1981) is used. Named the "Perspective 4 Point Problem" their algorithm solves the three unknown coordinates of the projection centre when the coordinates of four points lying on a common plane are given. Because the control points are all located and a common plane the mapping in-between image and object points is a simple plane-to-plane transformation. The location of the projection centre can be extracted from this transformation T when the principal distance of the camera is known. The solution of this algorithm is not unique. There exist two possible solutions, one before the plane and one behind it. In this case the solution in front of the plane is used. For a detailed description of the formulas please refer to the original publication.

For the complete solution of the spatial resection problem the orientation of the camera must be also computed. The solution is based on the algorithm Kraus (1996) which gives a solution for the determining of the rotation angles when the coordinates of the projection center are already known.

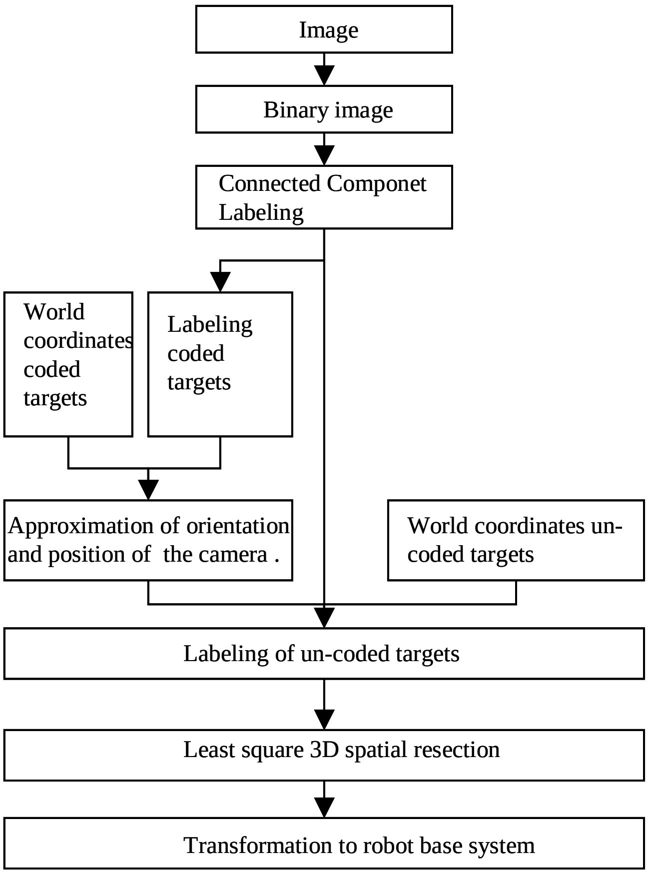

Figure 4 resection process

Figure 3 shows the complete operating sequence for the resection process. Of course the approximation of the camera orientation and position is not necessary, because the robot position and orientation can be used for the approximation. We can not use this approximation because there are no information available to get the robot pose in real-time from the robot control.

4.4 Forward Intersection

Forward intersection is another possibility for an accurate robot pose measurement. Two or more cameras observe the coded and un-coded targets fixed in the object space. The technique behind them is well known. By a beforehand calibration the relative position and orientation to a “master camera” is calculated. For identifying the un-coded target in one image the same algorithm used as described in 4.3. With the technique of epipolar geometry the homologous targets in all other images can be found. After this the 3D model coordinates of the observed coded and un coded targets are computed with process of forward intersection. The camera pose in relationship to the test field coordinates system is equivalent to the relationship between the test field system and the model system. For this a closed-form solution for computing the transformation is carried out.

5. HAND-EYE-CALIBRATION

The determined camera pose refers to an arbitrary coordinate system defined by the test field. But for the correction of the robot pose the data must be available in the robot coordinate system. To transfer the camera pose in the robot system a Hand-Eye-Calibration is necessary. It computes the offset of the fixed yet unknown position and orientation of the camera coordinate system with respect to the robot hand coordinate system. The robot hand coordinate system, also known as the end-effector frame or in some case the tool-centre-point (TCP), is the coordinate system that is often used within the robot control software. In this section only a short review of the implemented algorithm is given. For a fully description please refer to the paper of Tsai 1989.

The next table gives a short description of the involved coordinate systems for the computation of the hand-eye calibration.

R	Robot coordinate system. It is fixed in the robot station. The robot arm moves around it and the encoder output of all joints enables the system to tell where the TCP is relative to R
G	Hand coordinate system. Gives the position and orientation of the robot hand relative to R. The z-axis is coinciding to the last link of the robot. The x,y axes are parallel to the robot flange.
C	Camera coordinate system. Moves with the robot. The offset to the Hand coordinate system is constant. The z-Axis is coinciding with the optical axis and x,y axes are parallel to the image plane. The principal point is the origin
T	Test field coordinate system. Is arbitrarily to the robot system. Does not change the position and orientation during the hand-eye calibration

The next figure shows the relationship between the coordinate frames.

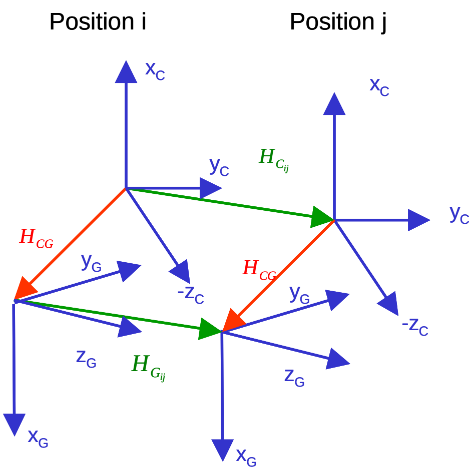

Figure 5 Relationchips between the different coordinate frames

From the figure following equation for the homogeneous transformation matrices can be extract:

$$H_{G_{ij}} H_{CG} = H_{CG} H_{C_{ij}}$$

The homogeneous matrices $H_{G_{ij}}$ and $H_{C_{ij}}$ are well known from the robot control and from direct measurement of the camera pose. One characteristic of the equation help out to solve this equation. The rotation angle of $H_{G_{ij}}$ and $H_{C_{ij}}$ is equal. Because of the six independent unknowns two or more robot displacements needed to obtain a unique solution under certain condition.

Figure 5 shows the accuracy for solving the above equation by using 2 or more robot movements. It illustrate that the increase of the measured robot pose has no influence on the accuracy of the hand-eye-calibration. The reason is the poor precision of the robot control in absolute positioning the tool centre point.

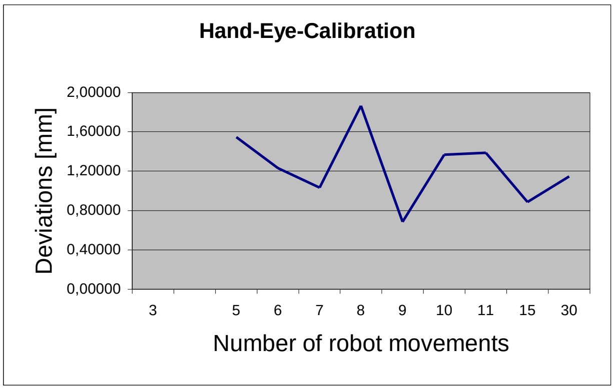

Figure 6 Hand-Eye-Calibration

6. RESULTS

For the experimental results a Basler A113 camera with a Sony CCD chip and a resolution of 1300 x 1030 pixels is used. The camera provides a digital output according to IEEE standard RS 644. A frame-grabber is integrated into a standard PC. With this combination Schneider-Kreuznach lenses with 12 mm focal length are mounted onto the camera. To maximize the signal intensity we use retro-reflective targets and a ring light on the camera described in 4.2.

The set-up for our experiments consisted of a Kuka KR15 robot. It is a six-axis robot with a maximum payload of 15 kg at a maximum range of 1570 mm. The robot is specified with a repeatability of ± 0.1mm. The absolute accuracy is not specified.

The sensor delivers a frame rate of about 12 frames per second. The implemented system is capable to process a single image in 420 ms. A typical image will contain 30 coded and about 200 un-coded targets. This gives a processing speed of 500 targets per second including all image processing steps and the resection process.

The following tables give you an idea about the absolute accuracy of the camera pose. View angle describes the angle between the optical axis and the plane of the targets. The assumed value of the precision of measurement of the targets is in this case 1/10 Pixel.

	Resection		Intersection	
View Angle	60 [Degree]	90 [Degree]	60 [Degree]	90 [Degree]
Resection in x	0.03 mm	0.5 mm	0.23	1.05
Resection in y	0.04 mm	0.6 mm	0.25	1.10
Resection in z	0.08 mm	0.05 mm	0.32	0.28

Table 2 Absolute accuracy of the camera position

The next table shows the interior accuracy of the resection process dependent on the accuracy of the image measurement. The Test-run column shows real obtained accuracy of the implemented system.

	Simulation		Test-run
Image measurement	1/5 Pixel	1/10 Pixel	1/10 – 1/20 Pixel
Resection in x	0.06 mm	0.03 mm	0.05 – 0.14 mm
Resection in y	0.06 mm	0.03 mm	0.05 – 0.14 mm
Resection in z	0.02 mm	0.009 mm	0.05 – 0.07 mm

Table 3 Standard deviation of resection

6.1 Circular Test

ISO 230-4 (ISO 1996) describes the “Circular test for numerical controlled machine tools”. While tests were originally designed for the simultaneous movement for only two axes, they also have valid implications for other machines. When the test is carried out the robot performs a circular motion and measurement system detects any deviation from the ideal path.

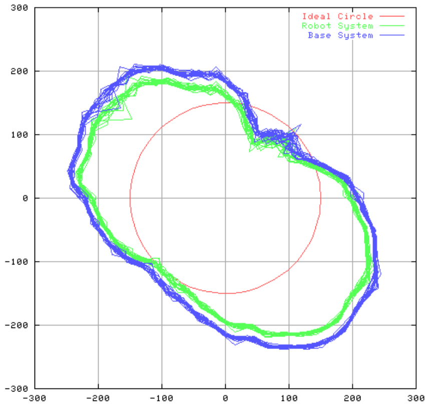

Figure 7 Circular test

Figure 6 shows the result of the circular test. The robot moves 10 times on a cricle path with a radius of 300 mm. The dark line shows the path computed in the robot base system, the light line computed in the camera system. The distance from the ideal path (inner circle) is 100 times excessive.

7. SUMMARY

The implemented system is an improvement of our off-line system published earlier (Hefele 2000). It has proven to be quite flexible and we believe it can be easily integrated into many applications in robotics, especially applications in optical measurement. The simulation showed, that by use the forward incision instead of the resection no increase of the precision is to be reached.

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