Calibration of a "Self-Viewing" Eye-on-Hand Configuration

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Abstract

We introduce a new calibration concept for eye-on-hand systems based on the self-viewing principle. A configuration where the camera directly observes the gripper offers new advantages to hand/eye calibration: a) decoupling the calibration process from the robot kinematics offers a great potential for accuracy, b) performing additional on-line calibration can significantly enhance reliability. We make use of both and propose a) a method which calibrates the gripper-to-camera transformation from camera calibration excluding the robot kinematics, and b) a method which monitors and updates the transform from the image of the gripper during operation. The methods are implemented and some experiments are performed to test the reliability of the on-line procedures.

1. Introduction

Eye-on-hand configurations are widely used in robotics since it is an easy way to supply robot manipulators with visual feedback information for fulfilling tasks requiring high flexibility and precision. Hand/Eye calibration is necessary in order to recover the spatial relationship between the manipulator and the wrist-mounted camera. This relation expressed explicitly as a mapping between robot end-effector/gripper frame and camera frame has to be determined by the calibration procedure which "logically" connects the two Cartesian spaces, i.e. measurements in one space can be referred to the other.

Many approaches have been proposed to find the corresponding transformation matrix, [7, 9, 1, 11, 4]. They all try to solve a transform equation of the form AX=XB, where A is a relative transform between two different end-effector frames known from the robots kinematic model and joint measurements, and B is the corresponding relative transform between the two camera frames known from camera calibration. At least two movements yielding two different equations are necessary to get a unique solution for the unknown camera-to-end-effector transform X. However, there are two major drawbacks of these approaches:

- Accuracy is limited to the precision of the robot kinematics. All measurement and modelling errors are propagated to the hand/eye calibration.
- The calibration procedure is strictly off-line. There is no practical way to cope with undesirable camera shifts relative to the end-effector during operation.

In this paper we introduce a new calibration concept based on partial visibility of the gripper by the camera. The so-called "self-viewing" approach eliminates the former restrictions since it

a) decouples hand/eye calibration from the robot kinematics and

b) provides on-line calibration to compensate for disturbances of the hand/eye geometry.

The main difference between the classical kinematic-based method and the new approach consists in the calibration reference frame. The first one calibrates the camera with respect to the end-effector frame of the kinematic chain while the latter one does so with respect to the gripper frame of the visible hand-geometry. So the self-viewing concept enables relative positioning of the gripper within a closed-loop control framework, which makes it superior to the classical one in that domain.

2. The Self-Viewing Approach

Generally speaking, a self-viewing configuration is the special case of a sensor-actuator configuration where the two subsystems are coupled by visual feedback such that the sensor directly observes the actuator. Self-viewing is an advanced invention of evolution, especially human hand/eye-coordination benefits from the "implementation" of this principle.

In robotic hand/eye-coordination, there are few approaches where visual feedback from separate cameras is used to control the motion of a visible manipulator [2, 3]. With eye-on-hand systems there are only first attempts to make use of this principle [10]. Although it should be easy to imagine that relative positioning can be done more reliably by controlling the gripper's motion in a closed loop fashion. Especially grasping tasks are performable with highest precision and repeatability. Once the uncertainties due to the invisibility of the gripper have been eliminated, its relative position keeps observable the whole duration until completition of the task. In that way eye-on-hand systems can perform best in grasping objects with unknown motion in 3D. To achieve the self-viewing capability, only an appropriate configuration has to be found

where the camera is forced to keep the gripper in its field of view without losing visual contact to the rest of the environment. Fig. 1 shows a self-viewing image from a wrist-mounted camera observing a parallel jaw gripper with fingers near the vertical edges of the image and a target object at the centre.

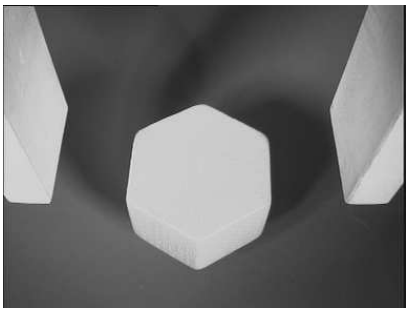

Figure 1: A typical self-viewing image during grasping

After a self-viewing configuration has been established, hand/eye calibration in principle reduces to camera calibration of extrinsic parameters with respect to the gripper frame. But the question still remains *how* to perform camera calibration in order to get a *reliable* estimation of the desired gripper-to-camera transform (${}^{C}\mathbf{H}_{G}$). In practice it would be rather difficult to get a sufficiently large number of suitable gripper calibration points (${}^{G}\mathbf{p}_{i}$) to directly apply a conventional camera calibration procedure since these points must

- be known by their location with respect to the grippers frame,
- be easily and accurately extractable from the grippers image and
- provide enough spatial information, i.e. their locations should be far away from singular configurations as they occur when the points are all collinear or concentrated in a small region.

So the calibration method has to take into account that there may be only a minimal set of gripper calibration points available. Therefore we divide the calibration procedure into two parts:

1. During *off-line calibration*, intrinsic and extrinsic camera parameters are fixed with respect to some special calibration object and ${}^{C}\mathbf{H}_{G}$ is derived from exterior camera orientation with some additional information of the ${}^{G}\mathbf{p}_{i}$.
2. During *on-line calibration*, the gripper calibration points are used exclusively to
   - monitor the transform and update ${}^{C}\mathbf{H}_{G}$ if changes are small and
   - recalibrate if a certain limit of change is exceeded.

Throughout the paper we refer only to points, the most general form of visible features. Although the results are derived more "directly" since the corresponding computations are simplified in some cases, similar results can be achieved by considering other features.

3. Off-line Calibration

The objectives of the off-line calibration procedure are twofold:

1. Camera calibration has to be performed, where essential parameters to be fixed are effective focal length f, radial lens distortion coefficient κ and world-to-camera transform ${}^{C}\mathbf{H}_{W}$. In the following we briefly introduce the chosen camera model. The image formation starts with a rigid-body coordinate transform from the world frame W, which is attached to some calibration object, to the camera frame C, with origin at the focal point, as illustrated in Fig. 2:

$$ {}^{C}\mathbf{p} = {}^{C}\mathbf{H}_{W}\,{}^{W}\mathbf{p} \tag{1} $$

with homogeneous transformation matrix

$$ {}^{C}\mathbf{H}_{W} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^{T} & 1 \end{bmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 & t_x \\ r_4 & r_5 & r_6 & t_y \\ r_7 & r_8 & r_9 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

where $\mathbf{R}$ is a rotation matrix.
The camera-to-image transform can be described by the well-known perspective equations:

$$ X = f\,\frac{{}^{C}x}{{}^{C}z}, \qquad Y = f\,\frac{{}^{C}y}{{}^{C}z} \tag{3} $$

where ${}^{C}\mathbf{p} = [{}^{C}x\ {}^{C}y\ {}^{C}z\ 1]^{T}$ are the camera coordinates and $[X\ Y]^{T}$ the corresponding undistorted image coordinates which are derived from the visible distorted ones $[\hat{X}\ \hat{Y}]^{T}$ by:

$$ X = \hat{X}\,(1+\kappa r^{2}), \quad Y = \hat{Y}\,(1+\kappa r^{2}) \tag{4} $$

where $r = (\hat{X}^{2}+\hat{Y}^{2})^{\frac{1}{2}}$. Making 3D measurements even with minimal point sets it is necessary to check for radial lens distortion, especially because the grippers image-points are normally located near the edges of the image where the effect of radial distortion is maximum. Considering only radial distortion by one coefficient κ as proposed will mostly suffice. We assume the principal point, the origin of the 2D image coordinate system, to be the centre of the image matrix and the aspect ratio to be the quotient of camera pixel-clock and frame-grabber sampling-rate. For discussion of these simplifications and further issues concerning camera calibration we refer to [8] where a suitable calibration algorithm is described. An accuracy of 1 part in 5000 is reported, which corresponds to a positional error of 0.02 mm at a distance of 100 mm, demonstrating the potential of CCD-cameras as measurement devices.

2. Initial Hand/Eye calibration has to be performed, where the gripper-to-camera transform ${}^{C}\mathbf{H}_{G}$ has to be calibrated with high accuracy.

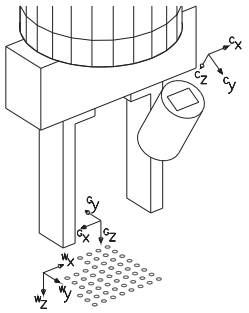

Figure 2: Coordinate systems of world, gripper and camera

Both goals would be easy to achieve at the same time if the gripper could be brought into a well defined pose with respect to the cameras calibration object. In practice this would only be achievable with a very special calibration plate exactly mounted to the gripper at some specified position. Since it would be difficult to realize such calibration-plate/gripper combinations, we developed a method based on what we call the "Plane Coincidence Constraint" (PCC). For the following explanations refer to Fig.2, where the three relevant coordinate frames are illustrated in general pose. The PCC can be expressed by the following relations:

$$(\mathbf{R}-\mathbf{I})\mathbf{m}=\mathbf{0} \;\wedge\; \mathbf{t}^{T}\mathbf{m}=0 \tag{5}$$

with

$$\mathbf{m}\in\{[1\,0\,0]^{T},[0\,1\,0]^{T},[0\,0\,1]^{T}\}$$

where $\mathbf{I}$ is the 3×3 identity-matrix. So the PCC simply constrains a rigid-body transform such that the axis of rotation is collinear to some coordinate axis and the translation vector is orthogonal to that axis. To impose the PCC physically on the hand/eye-calibration, the gripper with frame G has to be brought into contact with a planar calibration object with frame W such that a set of (at least three) coplanar gripper contact points coincide with the calibration x-y-plane; without loss of generality we assume $\mathbf{m}=[0\,0\,1]^{T}$. If the gripper frame can now be chosen such that the contact plane coincides with the x-y-plane of the gripper, then ${}^{C}\mathbf{H}_{G}$ is determined by ${}^{C}\mathbf{H}_{W}$ up to one rotational and two translational DOFs:

$${}^{C}\mathbf{H}_{G}={}^{C}\mathbf{H}_{W}\;{}^{W}\mathbf{H}_{G} \tag{6}$$

where ${}^{W}\mathbf{H}_{G}$ represents a rotation about the G-z-axis with parameters q_1, q_2 and a translation in the x-y-plane with parameters s_x, s_y corresponding to the remaining DOFs:

$${}^{W}\mathbf{H}_{G}=\begin{bmatrix} q_1 & -q_2 & 0 & s_x \\ q_2 & q_1 & 0 & s_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

with $q_1^2+q_2^2=1$. The meaning of the matrix-decomposition in (6) is that the PCC splits the determination of ${}^{C}\mathbf{H}_{G}$ into two subsequent tasks: First the orientation and the distance of the grippers x-y-plane is determined with respect to the camera frame by means of a calibration plate and a conventional camera calibration algorithm. Then, after the more critical depth-related parameters have been fixed, alignment of the corresponding x- and y-axis and coincidence of the origins has to be performed by relating the ${}^{G}\mathbf{p}_i$ to their undistorted image coordinates $[X_i\;Y_i]^{T}$.

To compute ${}^{W}\mathbf{H}_{G}$ we first perform back-projection in order to get the x- and y-coordinates of the ${}^{W}\mathbf{p}_i$. Combining (1) and (3) yields:

$$\begin{bmatrix} r_1 & r_2 & -X_i/f \\ r_4 & r_5 & -Y_i/f \\ r_7 & r_8 & -1 \end{bmatrix}\begin{bmatrix} {}^{W}x_i \\ {}^{W}y_i \\ {}^{C}z_i \end{bmatrix}=\begin{bmatrix} -r_3\,{}^{W}z_i-t_x \\ -r_6\,{}^{W}z_i-t_y \\ -r_9\,{}^{W}z_i-t_z \end{bmatrix} \tag{8}$$

As the ${}^{W}z_i={}^{G}z_i$ are known from the grippers model and the other parameters have been fixed during camera calibration, (8) can be solved for the unknowns ${}^{W}x_i$, ${}^{W}y_i$ and ${}^{C}z_i$ for every single gripper point.

Then expanding of

$${}^{W}\mathbf{p}_i={}^{W}\mathbf{H}_{G}\;{}^{G}\mathbf{p}_i \tag{9}$$

and rearranging terms yields two linear equations for each point:

$$\begin{bmatrix} {}^{G}x_i & -{}^{G}y_i & 1 & 0 \\ {}^{G}y_i & {}^{G}x_i & 0 & 1 \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ s_x \\ s_y \end{bmatrix}=\begin{bmatrix} {}^{W}x_i \\ {}^{W}y_i \end{bmatrix} \tag{10}$$

where $i=1,\ldots,n$ and $n\geq 2$. If there are more than two points available, we can solve for q_1, q_2, s_x, s_y by the least-squares method. To achieve orthogonality of the 2×2 submatrix of ${}^{W}\mathbf{H}_{G}$, q_1 and q_2 have to be scaled by $(q_1^2+q_2^2)^{-\frac{1}{2}}$. So with a minimum of only two gripper calibration points we can get a unique solution for ${}^{C}\mathbf{H}_{G}$ from (6).

Note that the coordinates of the ${}^{G}\mathbf{p}_i$ need not be known in advance if some geometric constraints can be utilised to infer them from their image locations. In the case of our gripper model the innermost four corner points of the two fingertips form a rectangle whose edges are parallel to the grippers x- respectively y-axis and whose centre coincides with the origin. Since the ${}^{G}\mathbf{p}_i$'s distances to the x-y-plane, i.e. their z-coordinates, are known from construction (to be zero), their image points can be back-projected into the calibration plane where their relative distances can be measured. From that distances and the above geometric relations the ${}^{G}\mathbf{p}_i$-coordinates are easy to obtain.

In practice it may be difficult to position the gripper in a way that the two corresponding x-y-planes of the gripper and the calibration plate coincide, but there is a simple trick to make the PCC work: If the calibration plate is posed on a flexible base such as a smooth foam rubber block and the gripper is pressed against the plate, the

resulting torque will tilt the plate as long as the two planes coincide (Fig. 3). The only condition is that the centre of the calibration plate must be located within the convex hull of the grippers outermost contact points.

Nevertheless there may be cases where the PCC cannot be applied due to the grippers special construction and other methods have to be found. But whenever the PCC is applicable it offers an efficient way to perform hand/eye calibration independently from the robot kinematics from one single view (Fig. 4) with a minimum of two visible gripper calibration points.

4. On-line Calibration

Once off-line calibration has been performed, for the moment we can assume to have a highly accurate estimation of ${}^{C}\mathbf{H}_{G}$, but as soon as the manipulator begins to move, we have to take into account that the relative pose of the camera might change to some degree. This is a consideration of the following real-world problem: if small cameras are used, the attachments will normally be small too and relatively flexible. This will cause the camera to rotate about some axis of the attachment if tensile stress to the cable connector occurs. In our configuration a rotational change of about 0.5 degrees already results in a 1 mm displacement of the Tool Center Point (TCP), the origin of the gripper frame. So it is of great interest to monitor the gripper-to-camera transform during operation and to compute reliable estimates of ${}^{C}\mathbf{H}_{G}$ if changes occur. We propose two methods:

1. Updating of ${}^{C}\mathbf{H}_{G}$ by some differential transformation will be the method of choice, if the changes keep below some specified limits.
2. Recalibration of ${}^{C}\mathbf{H}_{G}$ should be prefered, if the changes exeed the specified limits.

Both methods work well even with minimal sets of gripper calibration points under the following conditions:

- The effective focal length is fixed with some accuracy and
- image points are compensated for radial lens distortion.

The corresponding parameters f and κ are assumed to be known from off-line calibration.

Updating ${}^{C}\mathbf{H}_{G}$

A differential change/motion dT of a coordinate frame T can be expressed as in [6]:

$$\begin{aligned} T' &= T + dT \\ &= Trans(d_x, d_y, d_z)\ Rot(x, \delta_x)\ Rot(y, \delta_y)\ Rot(z, \delta_z)\ T \\ &= [I + \Delta]T \\ &= \Delta^{*}T \end{aligned} \tag{11}$$

where

$$\Delta^{*} = \begin{bmatrix} 1 & -\delta_z & \delta_y & d_x \\ \delta_z & 1 & -\delta_x & d_y \\ -\delta_y & \delta_x & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

The Matrix Δ^{*} can be derived from a homogenous transformation matrix with euler angle representation by replacing the trigonometric functions by their first-order taylor series expansion and neglecting all but the linear and constant terms. So for infinitesimal changes of camera frame C we can get an update ${}^{C'}\mathbf{H}_{G}$ from

$${}^{C'}\mathbf{H}_{G} = \Delta^{*}\ {}^{C}\mathbf{H}_{G} \tag{13}$$

For finite changes (13) becomes an approximative relation but if we can recover the unknown parameters δ_x, δ_y, δ_z, d_x, d_y, d_z from observation of the grippers image points, we will have a measure of the angular (δ) and positional (d) change of the camera frame:

$$\delta = (\delta_x^2 + \delta_y^2 + \delta_z^2)^{\frac{1}{2}}, \quad d = (d_x^2 + d_y^2 + d_z^2)^{\frac{1}{2}} \tag{14}$$

Assuming the ${}^{C}\mathbf{p}_i$ to be precalculated during off-line calibration:

$${}^{C}\mathbf{p}_i = {}^{C}\ \mathbf{H}_{G}\ {}^{G}\mathbf{p}_i \tag{15}$$

we can relate:

$${}^{C'}\mathbf{p}_i = \Delta^{*}\ {}^{C}\mathbf{p}_i \tag{16}$$

Insertion of the expanded coordinate equations of ${}^{C'}\mathbf{p}_i$ into perspective equations (3) and rearranging terms yields two linear equations for each point:

$$\begin{bmatrix} -X_i y_i & f z_i + X_i x_i & -f y_i & f & 0 & -X_i \\ -f z_i - Y_i y_i & Y_i x_i & f x_i & 0 & f & -Y_i \end{bmatrix} * [\delta_x\ \delta_y\ \delta_z\ d_x\ d_y\ d_z]^T = \begin{bmatrix} -f x_i + X_i z_i \\ -f y_i + Y_i z_i \end{bmatrix} \tag{17}$$

where $[X_i\ \ Y_i]^T$ are the corresponding image coordinates of ${}^{C'}\mathbf{p}_i$, $[x_i\ \ y_i\ \ z_i\ \ 1]^T$ the precalculated ${}^{C}\mathbf{p}_i$ and $i = 1, \ldots, n$. The unknown differential motion vector $[\delta_x\ \delta_y\ \delta_z\ d_x\ d_y\ d_z]^T$ can be solved for if $n \geq 3$ and if not all of the gripper points are collinear. If more than three point-correspondences are available, (17) can be solved by the least-squares method.

With the motion vector at hand we can

1. measure the amount of angular and positional change of the gripper-to-camera transform by (14) and
2. update ${}^{C}\mathbf{H}_{G}$ by (13). As a consequence of linearization the "rotational" part of the resulting matrix will not be orthogonal anymore and some error will be introduced to subsequent calculations using that matrix. But as long as the changes keep small the error will be tolerable in most applications.

We note that the above method could be easily extended to an iterative procedure which could improve accuracy of the motion-estimation, but we omit such an extension for realtime considerations. With the proposed method which consists of solving (17) the main computational effort is spent on inversion of a 6×6 matrix, which can be done within milliseconds on todays workstations.

Recalibrating ${}^{C}\mathbf{H}_{G}$

If changes increase, regarding them as differential ones as above will increase error too. Therefore, if some degree of change is reached the advantage of a reduced parameter set (in comparison to other linear techniques) and an accurate initial ${}^{C}\mathbf{H}_{G}$ diminish in consideration of the increasing modelling error. A possible limit of change based on the above motion vector measurements can be found experimentally. If this limit will be exeeded, recalibration has to be performed.

There are numerous approaches to calibrate the exterior orientation of a camera but it's beyond the scope of this paper to deal with the diverse techniques. In general the relative pose can be determined uniquely from a minimum of six calibration points and their corresponding image locations. If the points are coplanar the minimum number reduces to four.

5. Experimental Results

Our experimental set-up consists of a Panasonic industrial CCD camera of type WV-KS152 with 7.5 mm lens mounted to the end-effector of a PUMA 260 manipulator with pneumatic parallel jaw gripper and a force/torque sensor (Fig. 3). Frame-grabber and image-processing software run on a Sun Sparc 5. Images are CCIR 768×576 format. Our calibration plate is not very exact since we used a laser print of a 8×8-array of circular discs which is to expect to introduce some error to the measurements due to imprecise positioning of the printer.

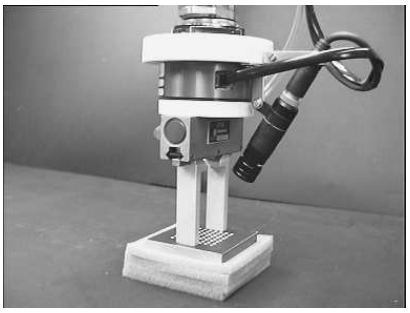

Figure 3: The calibration set-up

To achieve the self-viewing capability, the camera is tilted about 32 degrees and focus is adjusted to the depth of the grippers corner points at its fingertips. Because of the small distance the camera is a bit "short sighted" and needs to be supported by a separate camera with a more global view if distant objects are to be recognized and localized.

For the gripper calibration points we take the above mentioned corner points (Fig. 4). The corresponding subpixel image coordinates we get from intersecting the adjacent edges. There are six possible points but only the innermost four points are immune against disturbances of the camera orientation. One of the outermost points normally remains extractable too and can be used to improve accuracy.

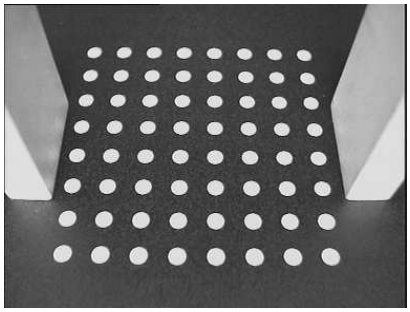

Figure 4: The off-line calibration image

During off-line calibration we use Tsai's algorithm [8] for coplanar points to solve for ${}^{C}\mathbf{H}_{W}$ and intrinsic parameters which are found to be: $f \approx 962\ pixel$ and $\kappa \approx 1.9 \times 10^{-7} pixel^{-2}$. However for recalibration from the ${}^{G}\mathbf{p}_{i}$ the algorithm is completely unusable. For that purpose we have implemented a widely known technique as described in [5], which calibrates from at least four coplanar points.

Evaluating the off-line calibration accuracy is complicated, since it would be difficult to measure the gripper-to-camera transform more accurately as with the proposed method itself. Using the robot kinematics as reference like the classical approaches do, would be contradictory since we have just decoupled hand/eye calibration from the kinematics in order to get a more accurate calibration. So it remains subject of future work to develop a reliable evaluation method. Nevertheless we have successfully used the results of the off-line calibration to perform grasping tasks based on visual servoing. We observed that the relative positioning of the gripper with respect to some object as seen in Fig. 1 could be done with high precision and repeatability.

In return, evaluation of the on-line calibration methods is straight-forward, since we can take the PCC-based measurements as reference. So we did in the following experiments:

First we "park" the gripper on the calibration plate and calibrate initial ${}^{C}\mathbf{H}_{G}$ as described in section 3, (Fig. 3). Then we disturb the cameras orientation by drawing the cable in a certain direction. Next we take a second image and apply the two proposed on-line methods. Finally we perform the off-line method on the second image and compare the result with the former measurements.

During the first series of 20 measurements (Table 1) we simulate realistic disturbances by drawing the cable to the right hand side of the camera inducing a displacement of the TCP, i.e. the grippers origin, with highest magnitude in ${}^{C}x$-direction of about 1.5 mm ± 0.3 mm. The second series (Table 2) was performed under unrealistic conditions, since we loosened the camera attachment and changed the tilt angle inducing a displacement of the TCP with highest magnitude in ${}^{C}y$-direction of about 4.5 mm ± 0.2 mm. The different on-line methods are abreviated as follows:

XP-U: differential update method with X points,

XP-R: recalibration method with X points.

	mean error (mm)			max. error (mm)		
	${}^{C}x$	${}^{C}y$	${}^{C}z$	${}^{C}x$	${}^{C}y$	${}^{C}z$
3P-U:	0.23	0.08	0.38	0.29	0.09	0.54
4P-U:	0.02	0.00	0.04	0.03	0.01	0.07
5P-U:	0.02	0.01	0.05	0.04	0.02	0.09
4P-R:	0.07	0.01	0.15	0.10	0.01	0.29
5P-R:	0.07	0.01	0.17	0.09	0.02	0.29

Table 1: TCP ${}^{C}x$-displacement: 1.5 mm

	mean error (mm)			max. error (mm)		
	${}^{C}x$	${}^{C}y$	${}^{C}z$	${}^{C}x$	${}^{C}y$	${}^{C}z$
3P-U:	0.22	0.08	0.54	0.26	0.09	0.64
4P-U:	0.02	0.01	0.21	0.03	0.02	0.27
5P-U:	0.02	0.01	0.24	0.04	0.02	0.31
4P-R:	0.09	0.02	0.07	0.13	0.03	0.13
5P-R:	0.09	0.02	0.09	0.10	0.03	0.17

Table 2: TCP ${}^{C}y$-displacement: 4.5 mm

Although the measurements are to be handled with care, due to the calibration plate as mentioned above, we think the following conclusions to be valid for our configuration:

- The 3P-U results are significant worse than the other ones. Taking a fourth point into account is highly recommendable.
- Taking a fifth outermost corner point into account does not improve the measurable accuracy.
- Under realistic conditions during operation the 4P-U method will completely suffice for both accuracy and robustness, there is no need for recalibration.

6. Conclusions

We have shown that there are good reasons for supplying eye-on-hand systems with self-viewing capability: Hand/eye calibration reduces to camera calibration from one single image and as in opposite to conventional approaches, it performs independently from the robot kinematics. The camera is calibrated with respect to the gripper frame which reduces uncertainty in visually guided relative positioning of the robot-hand. Furthermore, due to the continuous observability of the gripper the hand/eye relation can be monitored and updated or recalibrated if necessary. So on the one hand the gripper-to-camera transformation can be calibrated with high accuracy, on the other hand the achieved accuracy is immune against small disturbances which occur during operation. The experimental results confirm the validity of this new approach.

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