A FLEXIBLE MULTI-CAMERA SYSTEM FOR PRECISE TRACKING OF MOVING EFFECTORS

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ABSTRACT

This paper shows the potential to improve the absolute positional accuracy of a robot guided effector when applying photogrammetric strategies. First the need and aims of such a tracking process are explained, followed by a description of actual solutions and their restrictions. Then the potential of photogrammetric solutions for such purposes are outlined, followed by a detailed description of the system developed here. Finally, practical tests are shown, underlining that the design and realization are able to hold the challenging aims and improve the absolute accuracy of a robot by a factor of 20.

KEYWORDS

Optical tracking, absolute accuracy, robot guided measurement, industrial photogrammetry, quality control

1. Introduction

Robots are meanwhile one of the most important agents for production and effect many steps of a production process. A more extensive use is simply limited by their accuracy restrictions. When they should be used as platforms for optical sensors, for example, the absolute accuracy of the position resp. pose of the end-effectors has to be known more precisely then actually possible. The actual limit of an absolute position is in the range of 1 mm.

Existing solutions aiming at an improvement of this situation are not able to control the robot during his activity. They rely on prior calibration steps, which cannot assure to correctly improve each position of the work space at any time. On the other hand photogrammetric solutions are well known for their precision and flexibility, why is just strict to develop a photogrammetric solution allowing to control a robot and to extend his positional accuracy to at least a magnitude of 10.

2. Reason for Pose Determination of Moving Effectors

Geometrical features (edges, holes and bolts) and surfaces (shell, scratches, buckles, etc.) get increasing importance in industry because of the need of quality control. The aim is an automatic control of each component part simultaneously to the process of production, which offers direct elimination of parts showing too large deviation. This guarantees that all parts used for production lie within tolerances. Such systems can be found in many branches of industry.

Due to its flexibility and cost effectiveness industrial robots can be used as mounting platforms for optical sensors providing these desired geometrical features. The robot moves the sensor as “moving effector” into different positions, and the features are successively measured and recorded respectively. Therefore the position (the cartesian coordinates X, Y, and Z) as well as the orientation (the three solid angles A, B, and C) required for the absolute coordinate measurement have to be determined.

In general the determination of the pose of the end-effector is possible with the knowledge of the robot kinematics of a six-edge articulated arm robot and the measurement of the shaft angles of the particular setting. The standard for robots is to measure angles indirectly via the motor position, monitored by a resolver. This may lead to errors in the measurement due to the clearance in the transmission system. In addition the kinematics of a robot results in unfavorable error propagation. Another important factor is the temperature. Normally a robot is made of steel or aluminum, and after switching-on the metal warms up considerably on account of the heat of motor and gearing. Thus an industrial robot does not offer the very best conditions to realize a high quality measurement system.

Nevertheless robot manufacturers have succeeded in optimizing the repeatability accuracy of the robots. Nowadays a repeatability accuracy of 0.1 mm and 0.2 mm for the established bigger robots with a range of 2.5 m maximum can be achieved. But this accuracy cannot be guaranteed for long time periods in case of a standard robot. Therefore additional techniques are required to enhance the pose repeatability accuracy. In addition appropriate methods are necessary to determine the absolute pose (e.g. calibration with exterior measuring devices).

3. Solutions for Accuracy Enhancement of Robots

The limited absolute positional accuracy of robots is since a longer time subject of different investigations trying to improve this effect. First work was already carried out in the middle of the last decade. Improvements will be achieved introducing external physical measurements [4, 8, 9]. These activities are originated from and associated to the field of the manufacturer and consistently follow the idea to use different physical measurements, as are also essential part of a robot itself. In the context of a calibration, independent external control information is used, like length and straightness of a beam, for example, making positional inaccuracies visible. Based on such error measurements a correction model can be developed, which is introduced into the motion control and modifies each individual position according to the error function.

The quality of these calibration processes can be substantive and reach the magnitude of a factor of 10. However it only can be realized as a pre-processing step, which has to be performed offline. It's an additional time consuming action, which only holds, when the error model keeps invariant during the activities of the robot. Risks of temperature variation or other external factors changing the robot model can neither be respected in real time, nor be detected.

This only can be avoided, when the robot himself will be able to observe his erroneous position during his work activity. And as cameras are good instruments to observe spatial positions, research activities were directed towards photogrammetric concepts [6, 7, 10, 12]. Most developments followed the idea to equip the robot head with a set of cameras observing certain reference information. The reference can be introduced by the object itself or by special installations, like a field of target points, being distributed in space.

When the object provides the reference, the calibration is performed in relation to the object itself. This improves the positional accuracy at the object and increases the quality of processing and might be sufficient, when the robot has a repeating operating process. But it can not be seen as an absolute calibration. This will be the case, when the reference comes from an external point field, which is observed by a set of cameras on the robot head. However, such solutions have their limits in the degree of improvement and the practicability. Due to practical reasons, the arrangement of the cameras has to be kept in certain spatial limits, why the positional accuracy will be restricted from the geometrical relationships between cameras and point field. In addition, the reference points have to cover a large space, when the position has to be observed in any operational situation of the robot. This would need huge installations, which are not very practical.

Newer developments provide tracking concepts for the effector on the robot or the head itself. Different approaches have been presented or are element of commercial solutions [11, 13, 14, 15]. One idea uses the accuracy potential of laser tracker and extends the positional measurement coming from the tracker itself with optical solutions providing the orientation. This can be achieved observing reference points mounted on the object to be tracked. Such reference points can also act as single information, when a complete photogrammetric concept is realized. Then the target will be observed by a highly accurate calibrated camera installation, mostly consisting of two or three cameras.

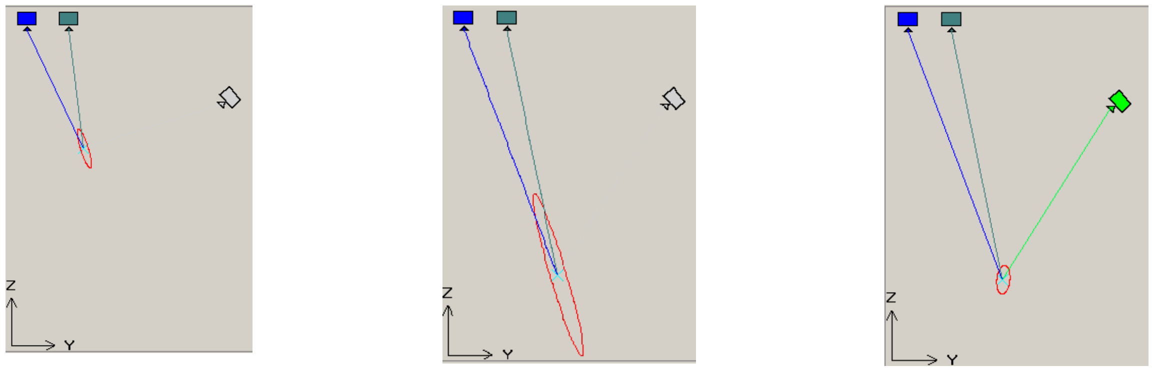
Both types of solution increase the positional accuracy of an instrument mounted on a robot head considerably. However, there are limits coming from the intersection geometry and from the dependence of the view direction of the tracking system. The accuracy is not homogeneous distributed over space and the head must be oriented to the cameras and cannot be observed in any operation state.

But in general, photogrammetric solutions have the potential to provide highest accuracy and the use of a photogrammetric conception should in principle solve the problem in a satisfying way. Already in an early stage suggestions were made to observe objects with a framework of appropriate arranged cameras [1]. And it could continuously be shown, that photogrammetric concepts are powerful to solve different problems in industrial applications [2, 5]. Although most applications aimed at the observation of an individual object by means of a set of images individually taken, it is also possible to precisely observe varying objects from a fixed set of cameras, which are mounted in a pre-defined way [3].

It's therefore logical to extend the idea of a general photogrammetric set up to the observation of an effector mounted on robot head. The success simply depends only on some well known rules, like a precise and stable internal and external set up of the cameras, an appropriate geometrical relationship between object and cameras to provide the accuracy requested and an object, which can be reliably observed in any position on the robot.

4. Photogrammetry based Tracking

Photogrammetry is characterized by its flexibility and adaptability to individual problems. Photogrammetric image bundles have many parameters which can be adjusted in order to get an optimum with respect to precision, cost, robustness and practical framework.



object at the front end of the measuring space

object at the back end of the measuring space

object at the front end of the measuring space supported by a third camera

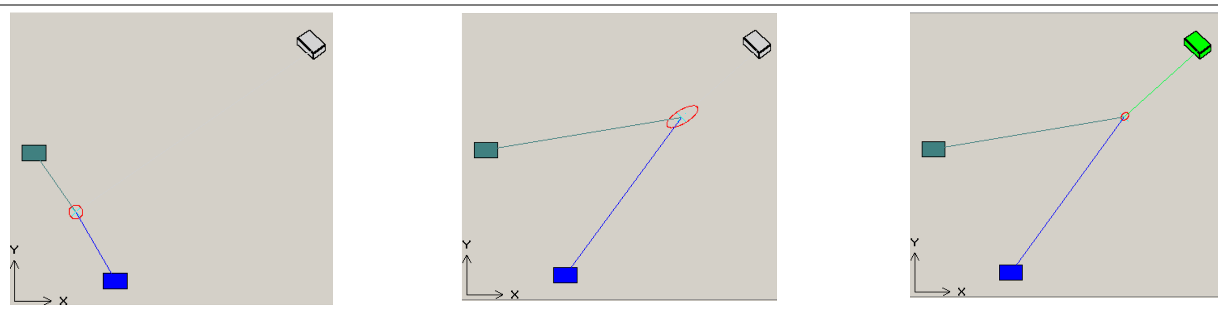
Figure 1: variation of point accuracy along line of sight

Consequently solutions can be investigated under several aspects like number and arrangement of cameras, field of view, size and resolution of image plane, number and distribution of target points, size and dimensions of the operation space of the robot together with possible variations in the orientation of the effector. Such a large number of influences only can be led to an optimum by means of numerical simulations with appropriate decisions which follow eventual practical and/or economical constraints.

But even without large simulations it is possible to show the impact of some major factors onto the quality. So it is

their distance to the supervising cameras varies significantly and is not an ideal precondition for a tracking solution. Some existing commercial systems [11, 13, 16] (cf. fig. 3) are designed in a similar way, why they suffer from a strong accuracy variation over the work space. This structural deficit can be eliminated with a more flexible arrangement of cameras, as by introduction of a third camera laterally observing the object space (right), for example.

Similar effects have to be observed concerning objects to be measured in positions largely apart from the baseline formed by the cameras (cf. fig. 2, left, middle). The



Object close to camera base line

object far outside base line

object far outside base line supported by third camera

Figure 2: variation of point accuracy across line of sight

Figure 3: optical tracking system (NDI Optotrack [16])

evident, that due to the inherent triangulation principle quality decreases with increasing distance between cameras and object. Figure 1 shows the point quality achieved by a two camera set up when observing an object in the foreground (left) and in the background (middle). A look onto the error ellipses shows a strong decline of accuracy along the line of sight. This gives a heterogeneous quality for calculated object points, when

coordinate component perpendicular to the base line direction is worse by a factor of 2 or more due to the geometry of the intersecting rays. This leads also to a heterogeneity of the point quality in a systematic and undesired manner and only can be compensated by more flexibility, as shown with a third camera at the side (cf. fig. 2 right).

These two simple considerations already show clearly, that there is a strong interrelation between point quality and design of a photogrammetric solution and that there is the need but also the possibility to adopt a set up to requirements of a tracking task. Other major aspects in such an adjustment process are size of the volume to be tracked, number of cameras and their distribution in space, field of view of a camera, size and resolution of the image space and the accuracy limit to be hold in the tracking process. As other factors exist also and have their impact onto the tracking quality an optimum can simplest been found by a numerical simulation.

Another aspect to be documented from table 1 is that limits for a positional accuracy are much simpler to hold than those for angular precision. From a geometrical point of view this is evident, because the angular accuracy is derived from a certain number of points and depends on

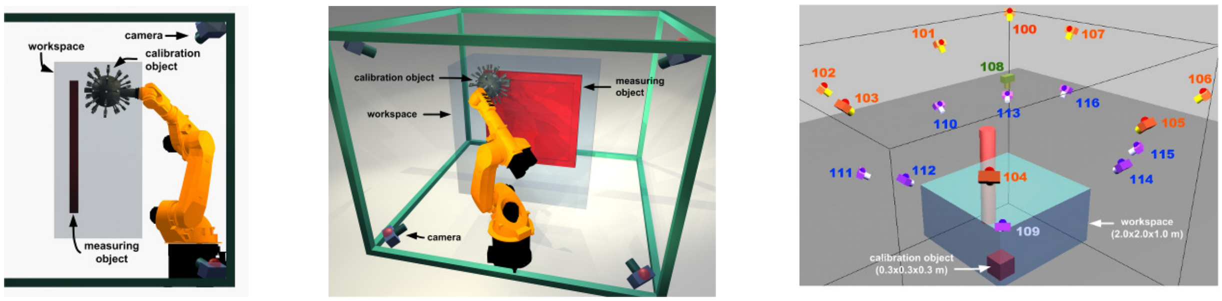
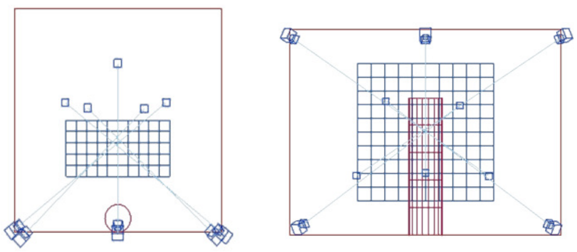


Figure 4: Schematic setup of the test measurement cell (left, middle) with possible camera arrangement (middle, right).



Top view

Front view

Figure 5: camera configuration

In order to demonstrate the potential of a photogrammetric design such a simulation has been performed for a work space of 4 m^3 (width 2 m; height: 2 m, depth: 1 m; cf. fig. 4). This space has been spatially designed together with the free space available for installation of all cameras and the object to be tracked (cf. fig. 4, right). Then, all main parameter e.g. number and positions of cameras, view angle, size of the reference body and so on have been optimized.

Targeted accuracy was 0.1 mm (at 2σ) for a tracked position of an effector and 0.2 mrad for the angular position of the effector. The latter one is of interest because of potential distances between the position of the manipulator and the location of targets to be observed on the effector itself. This distance has been assumed to be not larger than 500 mm and fits well to size and design of effectors like in-line sensors, for example.

One important first choice is number and type of cameras. Table gives some values for a smaller sensor chip (A1, A2) and a larger one (B1, B2). It can be seen, that all configurations are close to the angular accuracy required, but the amount of cameras used varies (A1: 7; A2: 5; B1: 5; B2: 4). This shows, that different configurations are exchangeable to a certain degree, but those with larger image frames are superior, what is evident due to the larger amount of image information available. Accordingly a camera arrangement as shown in fig. 5 gives a good base for a precise tracking.

Table 1: Change of accuracy in relation to type and number of cameras

	σ_x [mm]	σ_y [mm]	σ_z [mm]	σ_{rx} [mrad]	σ_{ry} [mrad]	σ_{rz} [mrad]
A1	0.026	0.017	0.017	0.163	0.232	0.206
A2	0.024	0.019	0.019	0.180	0.238	0.205
B1	0.021	0.020	0.020	0.201	0.223	0.186
B2	0.024	0.019	0.019	0.180	0.238	0.205

their spatial distribution and positional quality. This must be lower, than an individual point. The degree of reduction depends on number and arrangement of points on the target used to signalise the effector. Some other calculations clarify this relation.

Table 2: Change of accuracy in relation to number of object points being tracked

	σ_x [mm]	σ_y [mm]	σ_z [mm]	σ_{rx} [mrad]	σ_{ry} [mrad]	σ_{rz} [mrad]
A	0.156	0.200	0.153	2.003	1.545	2.041
B	0.112	0.145	0.114	1.552	1.184	1.581
C	0.078	0.093	0.076	1.058	0.797	1.077

Table 2 documents the influence of the number of object point mounted on a target to be tracked. Version A is calculated with 25 spatially distributed points, version B with 55 and version C with 151. The stabilization of the accuracy with an increasing number of signal points is visible; however it is achieved to the cost of a considerable cumulation of the number of signals. In addition there is no difference between positional and

Table 3: Change of accuracy in relation to distance between object points being tracked

	σ_x [mm]	σ_y [mm]	σ_z [mm]	σ_{rx} [mrad]	σ_{ry} [mrad]	σ_{rz} [mrad]
A	0.114	0.156	0.111	9.301	7.198	9.492
B	0.124	0.157	0.122	3.315	2.514	3.379
C	0.122	0.153	0.120	1.952	1.486	1.988
D	0.117	0.142	0.114	0.927	0.713	0.944
F	0.105	0.120	0.102	0.411	0.324	0.417

angular accuracy. For both factors the increase is the same.

This impression changes for the spatial distribution of the object points tracked. The larger the distance between the points to be tracked, the better the angular quality, what is similarly evident from the geometrical point of view. The configurations shown in table 3 vary from 5 cm distance (A) to 100 cm (F). Although this context is not surprising, a numerical simulation gives a reliable base for the practical design and avoids weak set ups.

As a consequence a reliable tracking needs not only a flexible arrangement of cameras, but also a tracking object of adequate size and with a sufficient number of object points to be determined. A geometrically ideal object serving for these purposes is formed by a sphere. It gives not only good preconditions for a homogeneous distribution of tracking points but also good geometrical frame work concerning the line of sight from the cameras onto the target object. Therefore a spherical object has been designed to house all necessary target points (cf. fig. 6). Size of this target object, the number and distribution of the signal points have been chosen according to the findings from the simulations.

Besides of those factors already considered there are other elements affecting the accuracy as shown in table 4:

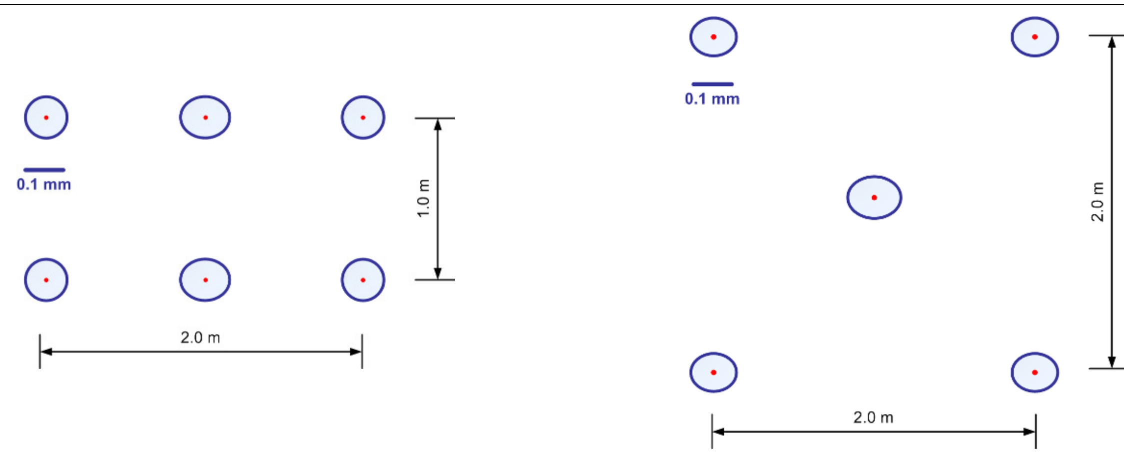


Figure 7: Error ellipses of theoretical accuracy for the effector position within the measuring volume. Left: Top view. Right: Front view

Table 4: Further factors with impact on the tracking accuracy

Pose parameter	Factor
Translation	Geometrical stability of the points Precision of the exterior orientation of the cameras Point detection precision within the images
Rotation	Precision of the exterior orientation of the cameras Point detection precision within the images

Taking all these factors into account our final simulations for a four camera configuration ended up with a theoretical accuracy of the effector position of 0.06 mm (one sigma). This result is based on a conservative assumption for the image accuracy (quality of image operators) of a 1/10 pixel. The accuracy is evenly kept over the whole work space, as shown in fig. 7. Other assumptions for this configuration are:

- std. dev. for the positional accuracy for the cameras: 0.15 mm and for the angular accuracy 0.06 mrad.
- std. dev. for a signal point on the target object: 0.05 mm.

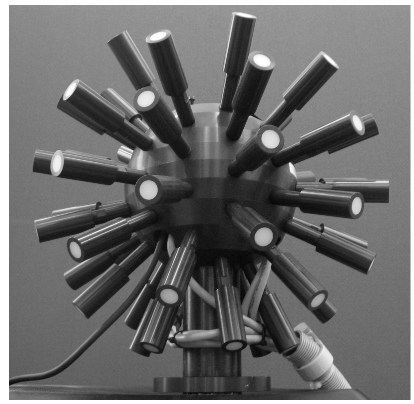


Figure 6: The active array of target points, completely loaded with LEDs and wiring.

These assumptions correspond very well to typical accuracies to be achieved in photogrammetric triangulations. Therefore these simulations should give a reliable assessment of the accuracy potential for such a photogrammetric solution and confirm that the desired level of accuracy is achievable. Practical tests then have to proof, that the assumptions underlying have not been too optimistic and that this quality for a pose determination will be hold in reality (see chapter 6).

5. Design of a test installation

As explained, the solution is based on a set of cameras observing an appropriate signalized reference and target object. Each set up can individually be adapted and scaled to the needs of the volume to be controlled. Simply the number of cameras and their distribution in space has to be changed. The cameras have to be arranged in a way that the target body installed on the robot head will be seen by a sufficient number of cameras for all used poses.

The target body was realized with the help of active, i.e. self-luminous, target points homogeneously distributed in space. Active targets have the advantage of being simply switchable, what helps to introduce point codes by a switching sequence. External illumination is not necessary, which largely extends the whole system's flexibility, as no special preparations have to be made in order to assure overall optimal lightning of the tracked body. Also, spurious daylight can be considerably suppressed by the use of infrared light.

For the actual test installation a measurement volume of 1.0 m x 2.0 m x 2.0 m (width, length, height) is assumed, which is a typical size for a robot's operational range in the automobile industry (see fig. 4). The volume will be observed by four cameras, arranged at the corners of a vertical square with four meters edge length, located about two meters behind the measurement volume. Four mega-pixel Firewire cameras were used in order to guarantee the required resolution in the pictures. Each camera is equipped with a lens with 12.5 mm focal length, resulting in a view angle of about 85 degree.

Figure 6 shows the realization of the active target body, which is installed on the robot head directly behind the effector. Each single target point is precisely fitted onto a stable support structure and contains an infrared LED (see fig. 8). An integrated diffuser assures together with the mechanical design a homogeneous illumination characteristic.

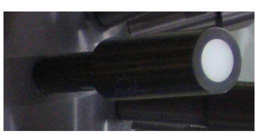


Figure 8: LED target

The support structure for the active targets, all in all up to 54 pieces, consists of two half-spherical shells made from aluminum. Its surface consists of 9 plane ring segments with six tapped holes each in an angle distance of 60°, where the targets bolt down. The ring segments have been designed in a way that all targets lie on a spherical shell, and are evenly distributed in space.

As the targets don't have an optical visible code, they will be distinguished by a switching device, when necessary. The point controller itself is connected to the control PC by a 100MBit Ethernet connection. The controller provides means to switch the targets via PC. It is possible to switch them individually, in groups or all together.

6. Test Results

The practical tests focus on the interior and exterior precision of the system.

Tests of the interior precision have been performed by the determination of 27 different head positions. For each position ten separate measurements where made. From these repetitions resulted a standard deviation of a position of 0.03_5 mm (one sigma), with a maximum out of all 27 positions of 0.10 mm.

Of greater interest and importance for the actual value of the positioning system is the exterior precision defining the system accuracy in the framework of an outer reference coordinate system (e.g. the measuring cell system).

In order to simplify set up and testing load we have chosen a reference system defined by a laser tracker. In general a laser tracker has a very high accuracy of about 0.02 mm for a single 3D point. This is about factor of 5 superior to our needs and therefore sufficient for our test purposes. The idea behind the test is to observe positions from the laser tracker and the cameras at the same time and to compare differences. The numerical evaluation will then be done based on distances between such observed positions. This avoids the necessity of datum transformations and simplifies the test.

Figure 9: Cross to be observed by a laser tracker

The spatial position of the robot head is represented by a reflector cross housing five reflectors for the laser tracker (see fig. 9). Its size is adapted to the spatial extend of the tracking object observed by the cameras, in order to get comparable situations for the determination of angular and spatial pose.

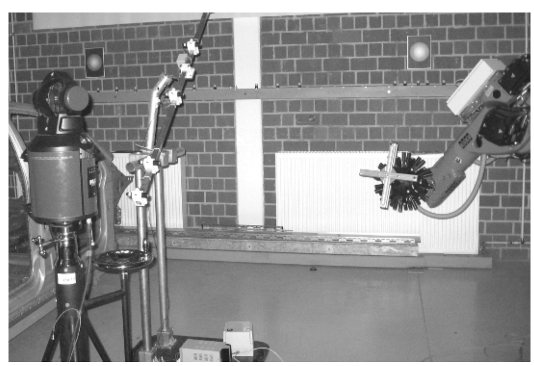


Figure 10: Results of the practical test: Reference differences compared to the tracked distances.

For the first tests the robot head was moved to six positions in the measurement volume and all pose data was collected (see fig. 10). This sequence was done eight times. For each sequence the residuals between reference distance and the photogrammetric calculated distance have been determined (cf. fig. 11). The results show a statistic average of the distance differences of 0.03_7 mm, a standard deviation over all differences of 0.07_0 mm with a maximum difference of 0.14_2 mm. Having in mind, that a distance is influenced by two points, a single coordinate has to be better by a factor of 1.41. Accordingly the absolute quality of the photogrammetric tracking is about 0.05mm for a single point, what is a factor of 2 better than the original targeted value.

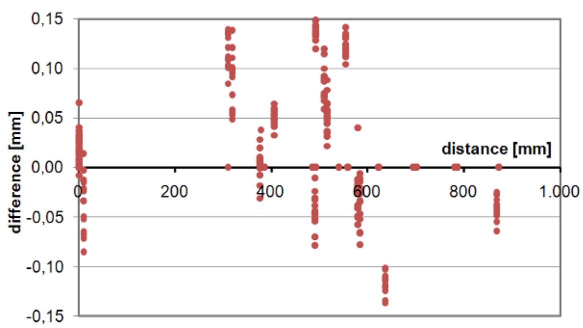


Figure 11: Results of the practical test: reference differences compared to the tracked distances.

The superior quality of a tracked position with respect to the coordinates provided by the robot itself will be visible, when the tracked distances are compared to those derived from the robot's own coordinate system. Here the standard deviation results in about 1.5 mm, what pretty much corresponds to the expectation of the absolute positional accuracy of a robot of about 1 mm per 3D-point and is largely worse, than with the new photogrammetry based tracking system.

7. Conclusion

As final conclusion it has to be stated, that this photogrammetric solution increases the absolute positional accuracy of a robot about a factor of 20. This opens new possibilities to use robots as precise device supporting measurement processes or other precision sensitive activities. Further advantages of this solution can be seen in the inline conception controlling the robot during his activity. This avoids expensive teaching and preparation steps and is free from any stability assumptions. Furthermore, this concept is scalable to other sizes or configurations of a volume to be surveyed.

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