Robot Pose Correction using Photogrammetric Tracking

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ABSTRACT

Traditionally, one of the driving forces behind the development of industry robots was the goal to replace tedious or hazardous manual work such as welding or varnishing. However, as robot prices are falling constantly, the use of robots becomes an economically sound solution in more and more applications – including areas which have nothing in common with the traditional "harsh environment" scenario. With the wider application scope, there also come more and tighter requirements, one of them certainly being accuracy.

The accuracy of a robot can be asserted by measuring the position and orientation of its end effector. For this purpose there exist a number of techniques, one of them being photogrammetric measurement. Robot manufacturers have used photogrammetry since several years in order to carry out a factory calibration. However, there is a growing need for systems which are able to calibrate and constantly monitor a robot on the factory floor.

This paper describes the possibilities which are offered by recent developments in sensors, image processing and close range photogrammetry. It then shows first results towards an on-line photogrammetric robot tracking system which have been obtained by a research group at the University of Stuttgart, Germany.

Keywords: Robot calibration, digital image processing, close range photogrammetry, industrial photogrammetry.

1. INTRODUCTION

Robot accuracy can be divided into two classes: absolute accuracy and repeatability. Today's industry robots are typically able to move to a position repeatedly with an accuracy of about 0.1 millimeters or better. In contrast, the absolute accuracy is much worse and can be as large as several millimeters. In order to achieve a better absolute accuracy, manufacturers usually offer an optional factory calibration.

Most often, however, the required accuracy can only be achieved by teach-in procedures. The disadvantages of this common approach in industry are obvious:

- Long term effects, for example caused by wear or temperature changes, lead to positioning errors.
- The replacement of robot components requires a complete recalibration.
- Off-line programming is not possible, since the required accuracy cannot be reached. Instead, off-line programs are modified interactively on the factory floor until all positions and orientations are correct.

Photogrammetry is certainly able to determine robot position and orientation (pose) very accurately. However, in the past, accurate measurement still required special and often expensive equipment, a certain amount of training, and typically involved processing huge amounts of image data. For these reasons, photogrammetric robot calibration today is usually limited to a factory calibration performed only once rather than a continuous photogrammetric tracking on the factory floor.

There has been substantial progress in several seemingly unrelated fields which allows to predict camera-guided robots in the foreseeable future:

- CMOS sensors started to replace CCD sensors. This is important since CMOS sensors are not only cheaper to manufacture, but also have a number of technical advantages. For example, since the pixels of a CMOS sensor can be addressed directly during readout, very high frame rates can be obtained when only parts of the image are needed. Also, CMOS sensors usually have almost no bloom and smear, which is especially useful in production environments, where bright light sources exist, for example close to welding arcs.

- Digital image processing has improved substantially. On the one hand, this is due to a general increase in computing power which makes it possible to run image processing algorithms in real time on (relatively inexpensive) general purpose PC hardware. On the other hand, algorithms themselves can be considered mature, and several image processing environments exist which allow to build applications using predefined operators in almost no time.
- Miniaturization has led to so-called "intelligent" cameras which combine the actual camera and a processing module in a single, small housing. This way, many practical problems arising in industrial environments can be avoided, such as the cabling between camera and frame grabber, and the placement of bulky processing hardware. Most intelligent cameras today are still limited with respect to computing power, but there are also systems based for example on Intel´s Pentium chip.
- Digital photogrammetry has made progress, especially towards faster, more accurate, more robust and fully automated systems. Today, coded targets and robust orientation procedures allow to carry out photogrammetric measurement without any human intervention.
- Instead of specialized hardware, robot control today is often based on standard PC´s. Thus, the integration of image processing, measurement algorithms and robot control running on a single processor is feasible.
- Due to the progress in digital image processing and close range photogrammetry, manifested also by a huge number of successful installations, industry acceptance of camera-based vision and measurement systems has generally increased in the last years.

With this background, a research project at the University of Stuttgart, Germany was started in order to investigate the possibilities for a fast, inexpensive photogrammetric robot tracking system. Participants of this project are the Institute for Photogrammetry (ifp) and the Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW). In detail, the project consists of three phases. First, different photogrammetric approaches are investigated and compared regarding their accuracy potential and realizability. Second, a fully automatic off-line procedure for robot calibration is set up. This will lead to a system able to correct long-term pose errors. In the third phase, first steps will be made towards a high frequency measurement system, which aims at the compensation of short-term pose errors.

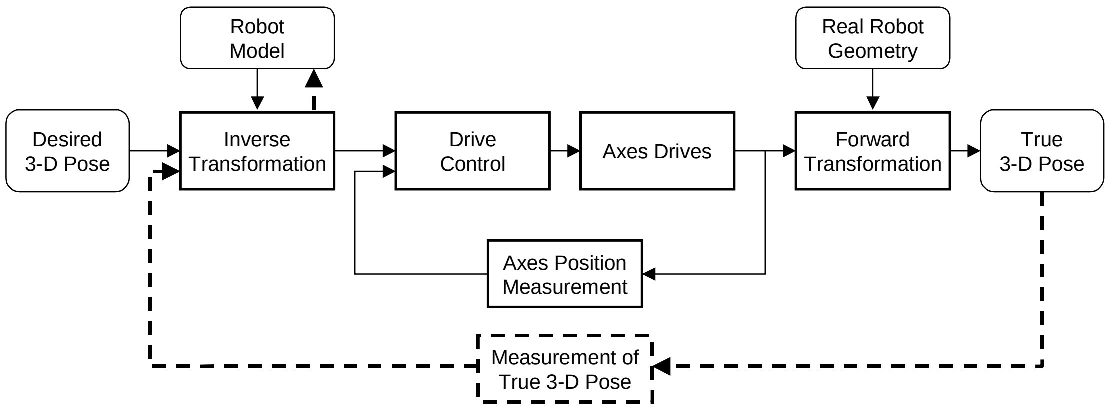

Figure 1: Typical robot control loop and extension by an external measurement loop (dashed).

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[2]. 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 desired and actual pose can be used to estimate the constants of the robot model employed in the inverse transform. Since 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. However, since in this case the obtained parameters are being fixed after calibration, any errors which are not present during the calibration process cannot be compensated for.

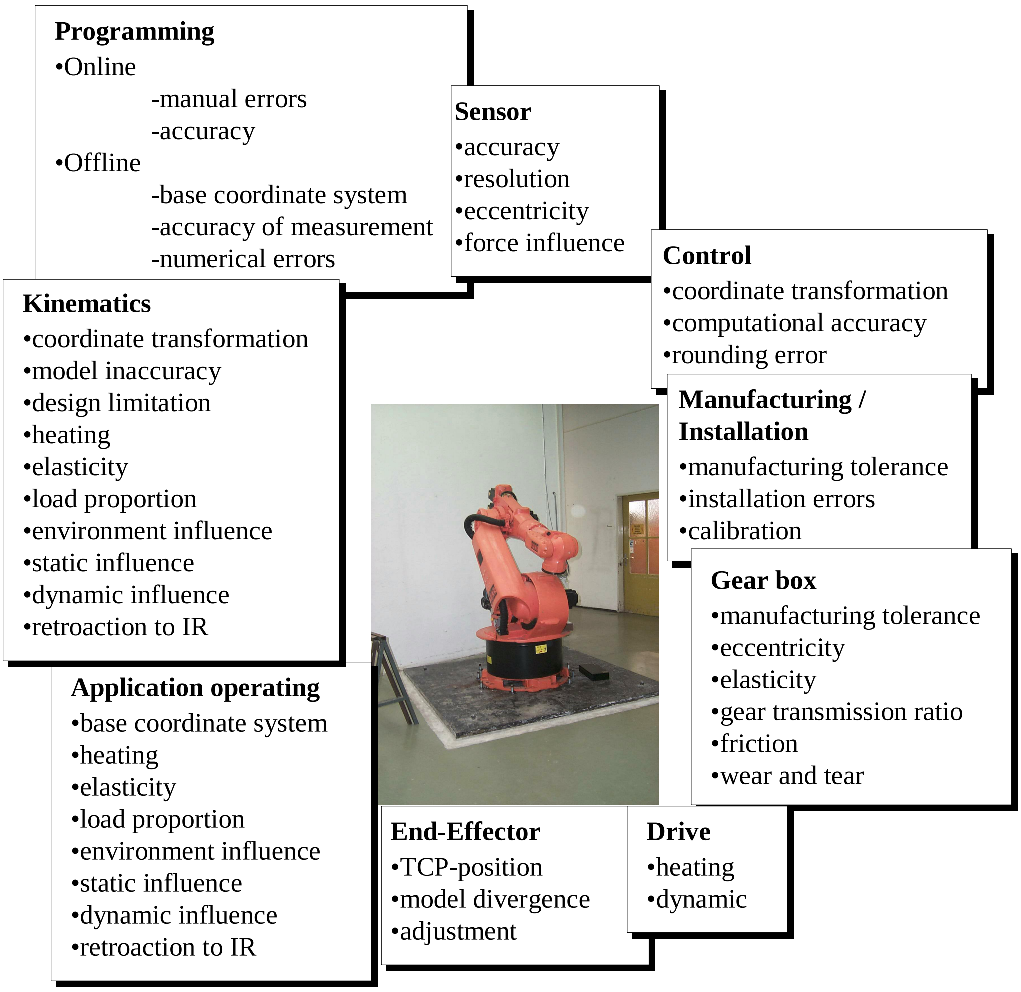

Figure 2: Possible errors for an industry robot[8].

3. ACCURACY OF INDUSTRIAL ROBOTS

There are two possibilities to program industrial robots, namely online programming (teach-in) and offline programming. In online programming, every required pose is defined manually. During teaching, the robot records the positions of all joints, which are later simply repeated during operation. In this case, the robot model shown in Figure 1 is not considered at all. This approach is used widely today, but since actually only the positions of the joints are repeated, any errors which are due to a change in the forward transformation result in deviations of the end effector pose from the originally taught pose. Still, the *repeatability* for industrial robots with six axes is usually specified between 0.05 and 0.25 mm, which is quite impressive compared to working volumes of several cubic meters and payloads up to several hundred kilograms. Nevertheless, concerning long term stability, a quick calculation shows us the effects of a change in temperature, for example due to warm-up or seasonal effects: An increase of 20 degrees Kelvin will lead to a length change of about 1 mm for a robot arm of 2 m length made of aluminum. There are many other possible error sources as shown in Figure 2.

With offline programming, *absolute accuracy* becomes important. Offline programming is desirable for several reasons. First of all, there are current developments towards simulating production lines in detail before building them. Programs then could be simply downloaded from the simulation to the actual robot on the factory floor. Secondly, failure of a robot means not only its replacement, but also requires a re-teaching of all poses – unless absolute accuracy is guaranteed. Since re-teaching has to be done in the robot´s final location, the production line has to be halted which may lead to huge production losses. In contrast to repeatability, absolute accuracy is hard to attain. The robot must be calibrated beforehand and mounted precisely.

Besides the distinction between absolute accuracy and repeatability, the German standard DIN EN 29283 differentiates between the cases where a position in 3-D space is reached through same or different paths[7]. However, even when a robot has a high accuracy using different paths, its long term stability is not guaranteed. This goal can only be reached with measurement devices which monitor the robot´s end effector pose constantly.

4. MEASUREMENT OF THE ROBOT END EFFECTOR

For the calibration of robots, many methods have been discussed in literature, among them tactile systems, acoustic time-of-flight measurement, interferometric laser trackers, theodolites, inertial measurement and photogrammetry[3,5]. For the evaluation of different approaches, several criteria are of importance, such as the required amount of work during calibration, price and mobility of the system, suitability for real-time measurement, and ability to recover all six pose parameters of the robot´s end effector.

Using photogrammetry, the location of several points in 3-D space can be measured simultaneously. Thus, photogrammetry is able to obtain the six pose parameters of a robot end effector. There are two fundamentally different approaches to do so. Either two or more cameras are fixed in 3-D space, observing target points which are mounted on the (moving) end effector. Alternatively, one or more cameras can be mounted on the end effector itself, observing (fixed) targets in 3-D space. The corresponding photogrammetric techniques are forward intersection and resection, respectively. Often, an approach known as photogrammetric bundle adjustment is taken, which can be seen as a combination of both and which is able to model all errors rigorously.

Nowadays, industrial photogrammetric systems are mostly used for off-line measurement of static 3-D points in space. Usually, the object is prepared by mounting targets which can later be identified and measured easily. Then, images are taken from a number of viewpoints. Finally, the images are processed, points are identified and measured automatically and photogrammetric algorithms determine 3-D points from measured 2-D image coordinates. Systems of that kind are commercially available and in regular use at automobile, shipbuilding, airplane, aerospace and chemical industries.

Moving from offline to online systems is mainly a matter of speeding up image processing. Image acquisition, transfer, target identification and measurement usually take by far the largest part of the processing time. A particular problem is the amount of data due to the images itself. For example, a 30 Hertz, stereo on-line setup using two cameras of 1k x 1k resolution and 8 bit digitization, produces data at a rate of 60 megabytes per second. However, since only the image parts containing targets are necessary for measurement, only a few percent of this data is actually needed.

A logical consequence would be to extract image regions containing targets as early as possible in the processing chain and to carry out all subsequent steps with this (largely reduced) data set. Even then, however, the maximum measurement frequency is limited by the readout of the CCD chip itself, which in turn depends on the maximum possible pixel clock frequency. For standard CCD chips, this is around 30 MHz, resulting in a maximum of 30 frames/s for a 1k x 1k image.

In the past few years, CMOS image sensors based on active pixel technology (APS) have made considerable progress. Since pixels of CMOS sensors can be addressed individually, it is possible to read out only parts of the image. Often, the time required is roughly proportional to the number of pixels being read out. Thus, frame rates of several hundred images per second can be reached.

In case of the robot tracking problem, the overall task of target and pose measurement can be assigned to different functional units as shown in Figure 3. The robot control software sends the current robot pose *(1)* to a photogrammetric module which computes approximate image coordinates for all cameras based on the known geometry. The coordinates *(2)* are sent to the cameras where a local CPU derives appropriate image windows *(3)*. The scan processor reads out the corresponding pixels from the image sensor *(4)* and sends them to the local CPU which performs the image measurement. The measured coordinates *(5)* are sent back to the PC where the 3-D robot pose is computed. From the differences to the assumed pose *(1)*, a correction *(6)* can be computed and sent to the robot control software, which in turn corrects the robot´s pose.

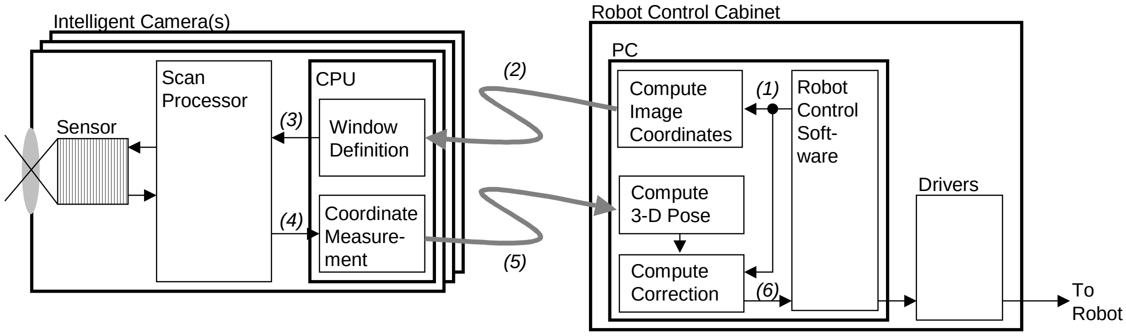

Figure 3: Proposed high speed photogrammetric tracking system.

This design has the advantage that the connection between camera and PC needs only a very low bandwidth, since only a few coordinates have to be transmitted. Also, typical image processing tasks are performed directly in the camera, where a scan processor or a dedicated signal processor can be used. On the other hand, photogrammetric routines which require floating point computations and are best programmed in high-level languages but are usually computationally inexpensive are run on the PC.

5. FIRST EXPERIMENTS

For our experiments, we have used CCD cameras, mainly because they offer a higher resolution and lower image noise than the CMOS cameras we have considered so far. In the first experiment, we have carried out an off-line robot calibration using a high resolution camera and targets mounted to the robot end effector. The second experiment is a first step towards and on-line procedure where the camera is mounted on the moving end effector, observing fixed targets.

5.1. OFF-LINE CALIBRATION

For this 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 millimeters (see e.g. Figure 2). The manufacturer specifies a repeatability of better than ±0.2 mm. The robot is used mainly for automobile production and packing tasks.

Camera	**Kodak DCS 460**
number of pixels	3072×2048
pixel size	9×9 μm^2
sensor size	27.6×18.4 mm
focal length	24 mm

For taking images, a Kodak DCS460 digital still video camera was used which has a CCD sensor resolution of 3072 x 2048 pixels and 8 bit digitization, leading to 6 Mbytes of data per image. We used a standard Nikon lens with 24 mm focal length and a standard flashlight. All points were signalized by retro-reflective targets with 10 mm radius. Most of the targets were placed stationary on a wall behind the robot. The remaining targets were located on an aluminum plate which was fixed to the robot end effector.

The robot was programmed to move to eight different locations which form the corners of a box in 3-D space of approximate size $600\times600\times300$ mm^3. At every location, the robot was halted and a total of 8 images were taken from two stations. The robot moved to the 8 locations in forward and reverse succession, yielding a total of 16 robot poses to be recorded. Figure 4 shows a sketch of the setup.

For the analysis we used the bundle adjustment program AUSTRALIS, a program from the University of Melbourne. We evaluated the positioning accuracy of the robot to be better than 3 mm. Figure 5 summarizes the project.

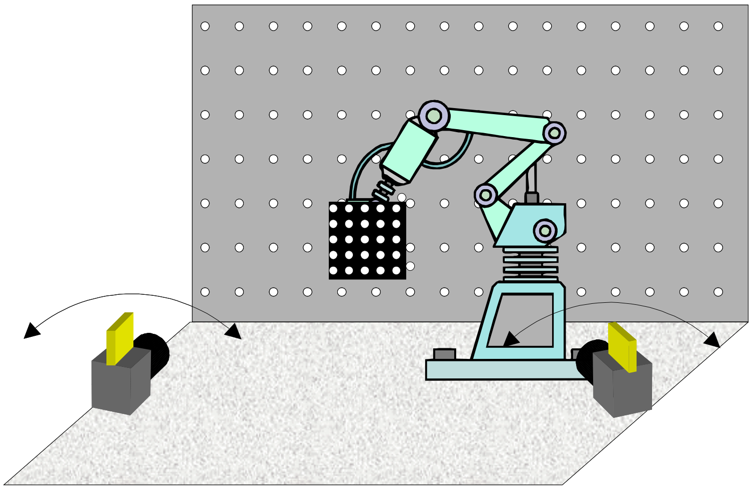

Figure 4: Setup for the off-line calibration experiment.

Total number of used images	97		
Camera base length	Approximately 5 m		
Time for taking pictures	6 hours		
Number of observations	17 764		
Number of robot position	8		
Number of rays	7 – 8 (min, max)		
Standard deviation of object points	X	Y	Z
	0.2407	0.1544	0.1607

Figure 5: Offline calibration project data.

5.2. ON-LINE MEASUREMENT SYSTEM

In this second experiment, a camera was mounted to the robot end effector (see Figure 6). In order to derive the end effectors pose, a fixed array of targets is placed in the scene and observed by the camera. Both the camera and the target array are calibrated beforehand.

During operation, the camera constantly takes images, which are grabbed and processed on-line. All labels are identified and measured fully automatically by digital image processing. The measured image coordinates are used together with the known 3-D target locations and the camera calibration data to derive the 6 parameters of the robot’s end effector using an algorithm known as spatial resection.

At a first sight, this arrangement may seem to be inferior compared to the forward intersection method used in section 5.1, because a pose measurement for all possible robot poses requires targets to be placed around the entire workspace. However, this method has a very practical background. Indeed, for example most handling tasks require a robot to be accurate only in certain locations, for example where an object is picked or placed. This means that the accuracy is not needed in the entire workspace, which usually encloses several cubic meters, but rather only in a few, relatively small areas, which are not necessarily related. Thus, a higher (local) accuracy can be obtained from the same measurement system.

For the target array, we used a combination of coded and non-coded retroreflective targets. In this case, the targets were fixed to a concrete factory floor. 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.

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). Such a design has been suggested for example by van den Heuvel and Kroon[9] or Schneider and Sinnreich[11]. 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 retroreflective targets in combination with an illumination in the near infrared (IR) range. 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.

Figure 6: Robot with moving camera (at end effector) and stationary targets (on the ground).

Camera	**Sony XC-75-CE**
number of pixels	752 × 582
pixel size	8.6 × 8.3 μm^2
sensor size	7.95 × 6.45 mm
focal length	8 mm

For the experiment, we used a standard CCD video camera from SONY (see table on the left). In the future, this will be replaced by a digital high resolution camera. The 3-D coordinates of the target field are determined by a bundle adjustment. Since additional camera parameters are included, the adjustment also delivers all camera calibration parameters. The bundle adjustment indicates target coordinate RMS values of 0.03 mm in the plane and 0.06 mm in depth.

During operation, the resection works in two phases. First, a minimum number of four coded targets is selected and an initial resection is computed using the approach described by Fischler and Bolles[4]. In a second step, all remaining coded and non-coded targets are identified and measured and a conventional resection is computed[12]. This yields the final values for the pose of the robot end-effector.

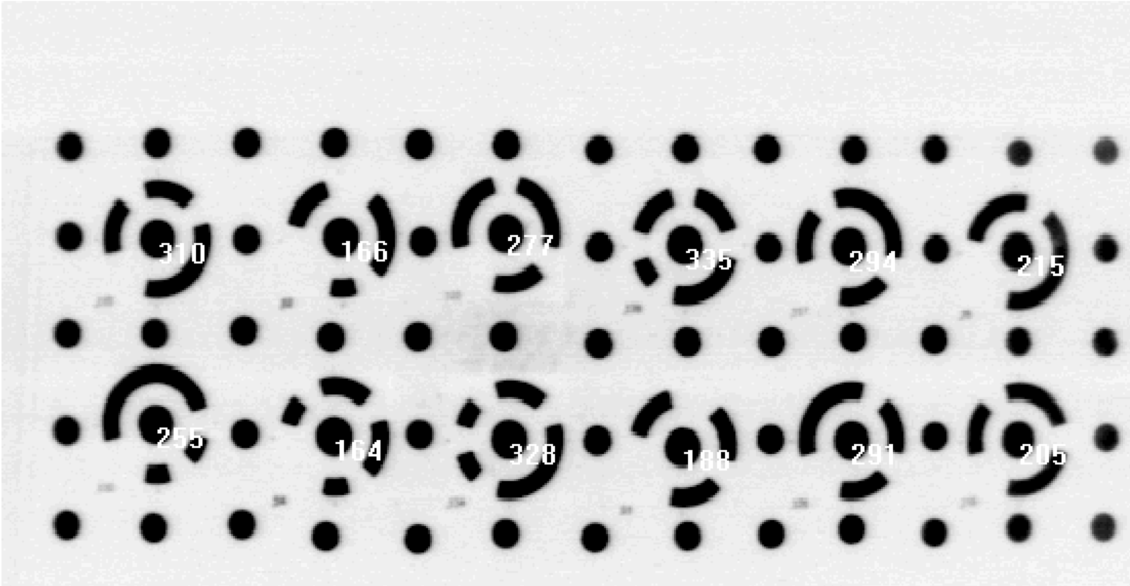

Figure 7: coded targets with labels

6. CONCLUSION AND OUTLOOK

In this paper, we have outlined our approach for setting up an inexpensive photogrammetric tracking system. We have described two different realizations, consisting of a forward intersection and a resection method, using a fixed or moving camera, respectively. For both approaches we have made experiments using an industrial robot and CCD cameras.

As being initial experiments, the full potential regarding accuracy and computation time has not been reached yet. For example, in the second experiment, the robot's drives interfered with the video signal, leading to disturbed images. Also, the resolution of the video camera was too low. In our next experiments we will use a high resolution digital camera which should solve both problems. We also will investigate using a stereo setup at the robot's end effector rather than only a single camera.

Regarding processing speed, the current implementation of the image processing and photogrammetric routines runs on a standard PC in about 20 milliseconds, which corresponds to over 50 frames per second. Thus, much higher frame rates can be expected when image processing and point determination are separated as shown in Figure 3.

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