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Robot calibration using a portable photogrammetry system

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A R T I C L E I N F O

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A B S T R A C T

This work investigates the potential use of a commercially-available portable photogrammetry system (the MaxSHOT 3D) in industrial robot calibration. To demonstrate the effectiveness of this system, we take the approach of comparing the device with a laser tracker (the FARO laser tracker) by calibrating an industrial robot, with each device in turn, then comparing the obtained robot position accuracy after calibration.

As the use of a portable photogrammetry system in robot calibration is uncommon, this paper presents how to proceed. It will cover the theory of robot calibration: the robot's forward and inverse kinematics, the elastogeometrical model of the robot, the generation and ultimate selection of robot configurations to be measured, and the parameter identification. Furthermore, an experimental comparison of the laser tracker and the MaxSHOT 3D is described.

The obtained results show that the FARO laser tracker ION performs slightly better: The absolute positional accuracy obtained with the laser tracker is 0.365 mm and 0.147 mm for the maximum and the mean position errors, respectively. Nevertheless, the results obtained by using the MaxSHOT 3D are almost as good as those obtained by using the laser tracker: 0.469 mm and 0.197 mm for the maximum and the mean position errors, respectively. Performances in distance accuracy, after calibration (i.e. maximum errors), are respectively 0.329 mm and 0.352 mm, for the laser tracker and the MaxSHOT 3D. However, as the validation measurements were acquired with the laser tracker, bias favors this device. Thus, we may conclude that the calibration performances of the two measurement devices are very similar.

1. Introduction

The principal metrology characteristic in industrial robots—presented in technical documentation—is repeatability: the ability of the robot to reproduce the same movement over and over again. To achieve it, the desired end-effector poses (i.e. position and orientation) can be obtained by the so-called on-line programming method, through which the operator teaches the poses directly to the physical robot. However, there is another frequently used method, off-line programming, in which the robot poses are not taught but computed. The goal of such computation is to find the joint configurations of the robot to enable its end-effector to reach the desired pose. Hence, this computation needs ample knowledge of the robot's mathematical model, which is usually affected by unknown errors due to factors such as manufacturing and assembly tolerances and flexibility.

The kinematic model is computed by using the nominal dimensions of the robot, essentially the nominal kinematic parameters. However differences between the nominal and actual values of the robot's parameters (e.g. link lengths and joint offsets) lead to pose errors. Furthermore, the robot's structure and joints are non-rigid components. This flexibility implies that the end-effector's position will be affected by the deflection of the robot's components especially when external forces are applied. These differences are known as non-kinematic errors. As a result, the reached poses of the end-effector might differ from the desired poses. The sources of such errors have been studied in many works over the last decade [1,2].

To compensate for kinematic and non-kinematic errors, the robot should be calibrated. To that end, three categories of calibration are presented in the literature [3,4]. The first is joint calibration, also called level-1 calibration or mastering, where the only errors considered are the joint offsets. Level-2 calibration, which includes level-1, considers all kinematic errors. Level-3 includes the two lower levels and adds the consideration of the non- kinematic errors.

Robot calibration is usually based on minimizing the forward kinematic errors (i.e. the position errors). The end-effector's position is measured in certain chosen robot configurations, which are selected from a large random set based on an observability analysis. Then, an optimization algorithm is used for parameter identification. Subsequently, it is

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possible to validate the identified parameters by evaluating the improvement of the robot position accuracy inside its workspace.

Obviously, the choice of a measurement system is of utmost importance in robot calibration. While several papers present custom-designed measurement tools, others use commercially-available devices. In the early works, several measurement devices were used, such as a ballbar [5] or a LVDT ballbar combined with an inclinometer [6]. More recent works show the use of theodolites [7], acoustic sensors [8], and, of course, laser trackers [9,10]. After the year 2000, calibration studies using optical devices were very frequent [11–18].These studies showed that vision-based measurement systems are accurate enough to produce a significant improvement in the position accuracy of industrial robots. Recent developments and applications of digital photogrammetry in industrial measurement are summarized in [19].

Using a camera is very promising, as this technology is far more affordable in comparison to many others such as the CMM and the laser tracker. Hence, studies that use cameras for estimating the 6 degree-of-freedom (DOF) poses needed in robot calibration are presented in [16]. Cameras are used primarily in two ways: in *Eye-In-Hand mode* (i.e. mounted on the robot's end-effector), or in *stationary mode* (i.e. fixed in the robot's work cell). The first method, also known as camera-in-hand, is presented in [12,17]. The second approach, also called a non-mounted approach, is often restrictive because only one point of view is used. Given that a camera is a two dimensional measuring device, when a third dimension is needed, either a dual camera sensor (stereo camera) can be employed or a portable photogrammetric system. In both methods, the information from multiple points of view can be merged to acquire 3D data. Examples of suitable commercial stereo cameras are Creaform's C-Track [11] and NDI's Optotrak [18]. However, a portable photogrammetry system can equally be used for gathering 3D data. Consequently, the present work analyzes the use of one such portable photogrammetric system in industrial robot calibration. The device used in this study is the MaxSHOT 3D system provided by Creaform. For comparative purposes, the calibration procedure is also carried out with a second device, the FARO laser tracker ION. The comparison will be based on the full calibration (level-3) of a six-axis FANUC LR Mate 200*i*C serial robot. The dataset for the robot configurations is generated through a pseudo-random algorithm, taking into consideration the limitations of both measurement devices. This step is followed by an observability analysis, allowing the selecting of the most appropriate robot configurations for identifying the robot's parameters. The least-squares method is then used. Finally, the models identified with the use of each measurement device are presented and the two devices' performance is analyzed.

2. Experimental devices

The devices used in this experiment are described and analyzed in the sections that follow.

2.1. Description of experimental devices

The main device in this study is a portable photogrammetry system from Creaform, named the MaxSHOT 3D. To the best of our knowledge, this is a previously unseen application of this type of device. Portable photogrammetry devices, unlike other CMM devices, can be moved freely in space without losing their reference, thereby providing new possibilities (i.e. a complete modeling of the measured object). The accuracy of the MaxSHOT 3D is 0.025 mm/m. It is affordable, easy to use, and allows the observation of a scene (hundreds of 3D points). However, it requires that the measured objects be stationary, it calls for a large number of manipulations, and is difficult to use in an automated manner.

Using this system involves adding certain references (Fig. 1) regarding the robot and its surroundings. This system can measure only special passive reflective targets. These targets can be either non-coded or coded. Non-coded targets are self-adhesive retro-reflective dots. Nine such non-coded targets can be seen in Fig. 2. Note that we also use as non-coded targets three Hubbs Machine & Manufacturing retro-reflective photogrammetry targets. These consist of a retro-reflective dot centered on a 0.5-inch half sphere made of steel (labeled 3 in Fig. 2) and can be mounted on a special magnetic nest (labeled 1 in Fig. 2). The coded targets are located on a small magnetic square containing seven reflective dots (i.e. targets). The pattern of these dots is unique and can be recognized by the MaxSHOT 3D system. The coded targets can be seen in Fig. 1. Furthermore, a reference frame (Fig. 1) is included in the scene. This frame is a large "L" shaped magnetic plate with three coded targets. It is used as a reference frame (i.e. X-Y-Z origin) for all measurements to be taken. Finally, the use of two calibrated scale bars (Fig. 1) is mandatory. The scale bars are approximately one meter long carbon-fiber bars with magnetic feet at each end.

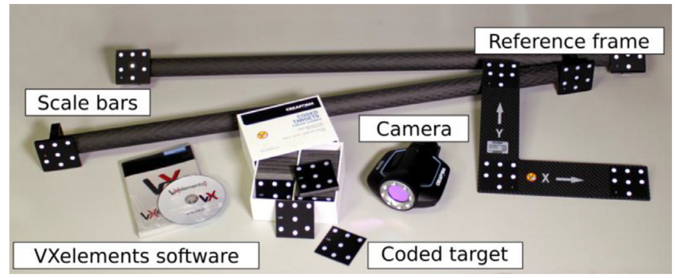

Fig. 1. The MaxSHOT 3D photogrammetry system.

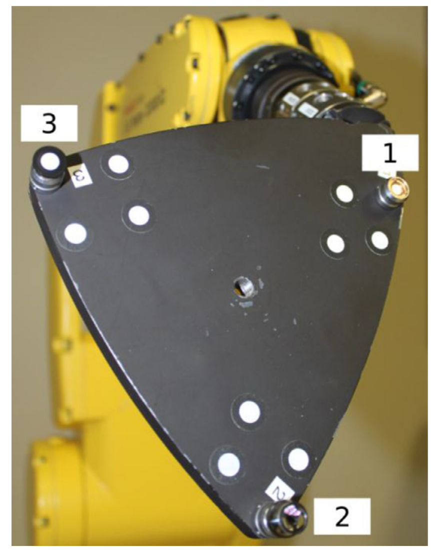

Fig. 2. The end-effector tool.

This system's core consists of Creaform's VXelements software suite. It contains several modules, including VXshot, which facilitates picture acquisition from the MaxSHOT3D. The software suite also assembles these pictures into a 3D model containing every target of the scene. The process is well-guided and a color theme provides evidence of the moment at which the number of pictures is enough to create an accurate model. As soon as the model has been created, the software provides several standard metrology features for analyzing it. Additionally, the results can be easily extracted for use by third party software (e.g. MATLAB) for calibration purposes.

For comparative purposes, we also used a second measuring device, the FARO laser tracker ION. The laser tracker's accuracy is similar to that of the MaxSHOT 3D (0.025 mm/m). However, it can measure continuous trajectories and allows full automation of the measurement process. Yet, it is very expensive, allows the measurement of only one 3D point