# Repeatability measurement and kinematic identification of LBR iiwa 7 R800 using monocular camera

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## ABSTRACT

In this paper, we have performed the kinematic identification and repeatability analysis of LBR iiwa 7 R800 (7 axis serial link robot) using monocular camera mounted at the end-effector of the robot. We started the process with the camera calibration process to identify intrinsic and extrinsic parameters of the camera used. In order to determine the pose of the end-effector using camera for repeatability analysis, we have used a 9x6 checkerboard for the repeatability experiment and for kinematic identification we have used ArUco markers. For repeatability analysis, we have used poses from ISO 9283 standards. Also we have used dispersion as a statistical means for quantifying the repeatability analysis. Subsequently, we have compared the results of kinematic identification with those from laser sensors and the theoretical CAD data sheet provided for the robot. Also in this paper, the algorithm has been introduced for measuring repeatability under force control mode and consequently, a single point repeatabilty has been evaluated.

## CCS CONCEPTS

• **Reliability, Maintainability and maintenance, Camera Calibration, Vision for robotics, Modelling and Parameter extraction**;

## KEYWORDS

Industrial robot, Camera, Kinematic Identification, Repeatability

## 1 INTRODUCTION

In recent years, industrial robots are often used to perform high precision tasks such as medical operations [1] and product inspections in assembly lines. There is a need for them to work precisely even after performing the same task repeatedly. The inaccuracy of robot positioning is a major problem being faced in the robotic industries [2]. A method is required in order to check how accurately the industrial arm is operating after a period of time so that we can correct these uncertainties accordingly. The standard method of measuring the accuracy of a robotic arm is done using equipment such as Theodolite, CMM, Laser interferometry, etc [3]. Since many industrial arms are already equipped with a camera attached to the end-effector for visualising and positioning tasks, reconfiguring the same camera to measure robot accuracy and repeatability is a feasible solution. It is also possible to use a laser tracker determine the accuracy of motion of industrial robotics arms [4]. Although a laser tracker is highly accurate, it comes with a number of drawbacks such as high maintenance cost, requirement of additional setup space and capital cost. Instead, we are proposing a simpler method that uses a monocular camera mounted on robot end-effector to measure the accuracy of robot movement. In fact, in many industrial arms a camera is also present as an end-effector extension, this can easily be configured for use in our experimentation. Since we are using different hardware for pose tracking, the point of comparison also comes into account. We have also made a comparison between the laser tracker data and the data from the monocular camera.

The method of repeatability we are using is very similar to what's been discussed in [5]. The repeatability experiments are done based on the ISO standards [6]. We have tested out the repeatability of the industrial arm using monocular camera and also done kinematic identification of the same. The data obtained is then used to determine the D-H parameters of the arm experimentally.

## 2 EXPERIMENTAL SETUP

KUKA lbr iiwa 7 R800 is a seven degree of freedom (DOF) manipulator. This manipulator is widely used in industries as a collaborative robot (cobot) in workspace involving human-robot interaction. The compliance control and position control of LBR iiwa handles the work piece with care, and the joint torque sensor feedback enables human beings to perform tasks in the close vicinity of the manipulator. Pose repeatability of LBR iiwa is (ISO 9283) ± 0.1 mm [7]. OpenCV based modules are used for the image processing. We have used computer vision to determine the end-effector position with precision [8].

Figure 2 shows the setup established. We have used a Basler acA2440-20gm monocular camera which has a resolution of 2048 pixels × 2048 pixels mounted on the end-effector of LBR iiwa 7 R800 to take images of a 9x6 checkerboard from different positions. We are using these images to determine the reference pose of the camera with respect to the checkerboard. To identify the position of the end-effector, we are using a checkerboard [9] and ArUco markers [10]. A checkerboard refers to a single image of black and white squares arranged alternatively similar to that on a chess board. Calibration of a monocular camera using a checkerboard is a common practice. On the other hand, ArUco markers refers to a whole dictionary of images of binary matrix based markers that are used to identify the position of the camera.

Two different test beds as shown in Figures 1 and 3 were setup for the purpose of our experimentation. The first test bed (Figure 1) is used for camera calibration and repeatability experiments while the second one is used to perform kinematic identification and D-H parameter extraction. One should ensure that there is no slack while

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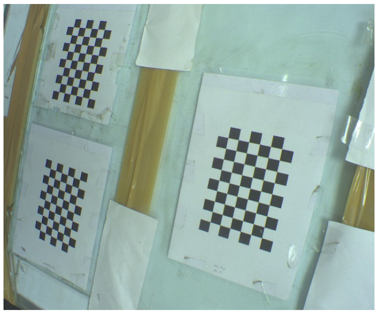


Figure 1: 9x6 checkerboard for Camera calibration and repeatability experiments

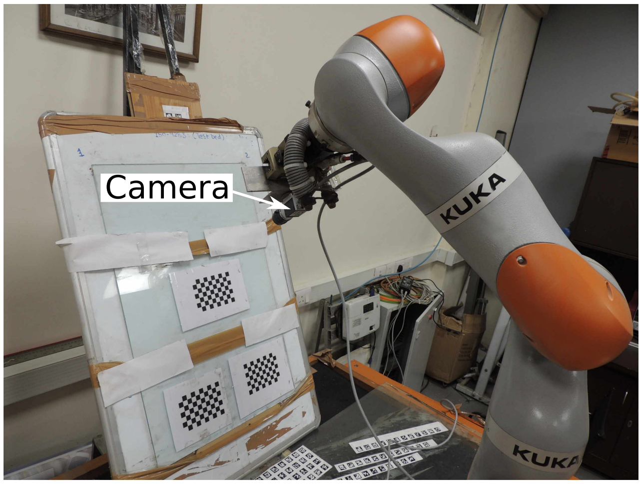


Figure 2: Setup for identification of Kinematic parameters

fixing the markers on the test bed, this can result in the algorithm not being able to recognise the markers correctly and provide us with inaccurate data.

## 3 REPEATABILITY

Repeatability, as stated by the *International Vocabulary of Basic and General Terms in Meteorology*, refers to the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement [11]. It could be quantitatively expressed as the dispersion characteristics of the results. The repeatability analysis requires experimental conditions to be constant which includes methodology, procedure, apparatus, environment such as lighting conditions and time duration of the experiment [11]. Most of the industrial serial arm manipulators are used for a repetitive task on a factory floor. The continuous and extensive use of manipulator leads to friction non-linearities and backlash and hence, industrial manipulators tend to lose their repeatability. Therefore, it is necessary for an operator to check the robots' repeatability in regular cycles. We have used a vision-based method using a monocular camera mounted on the end-effector of the industrial arm for the purpose. Additionally, to make sure that all the joints of LBR iiwa are used,

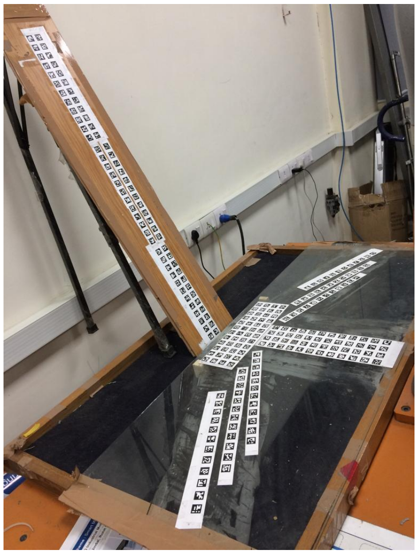


Figure 3: ArUco markermap bed consisting of 216 6x6 bit ArUco markers

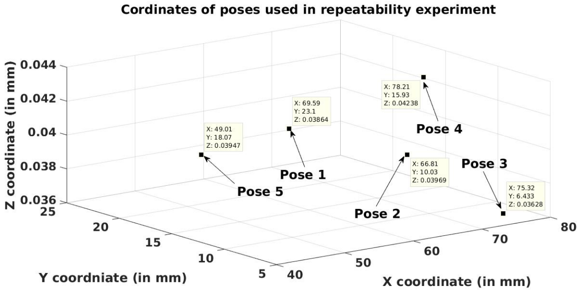


Figure 4: Coordinates of poses used in repeatability experiment under no-load condition

we followed ISO 9283 standards for choosing the poses at which repeatability is measured [6]. For determining the repeatability, we took a set of images for 5 different poses (2). From the images taken, the pose of the end-effector is extracted using a C++ script based on OpenCV module. The experiments were performed for the motion of the end effector at two different speeds. Repeatability has been measured at 100% and 50% speed of motion of the robot under no-load conditions where 100% refers to the maximum speed at which robot end effector can move. The formulations used for calculating the repeatability are mentioned below:

$$\overline{x} = \frac{1}{n}\sum_{j=1}^{n} x_j \quad \overline{y} = \frac{1}{n}\sum_{j=1}^{n} y_j \quad \overline{z} = \frac{1}{n}\sum_{j=1}^{n} z_j \tag{1}$$

where $x$ = X coordinate of pose, $y$ = Y coordinate of pose, $z$ = Z coordinate of pose, $\overline{x}$ = mean of X coordinate of pose, $\overline{y}$ = mean of Y coordinate of pose and $\overline{z}$ = mean of Z coordinate of pose

$$l_j = \sqrt{(x_j - \overline{x})^2 + (y_j - \overline{y})^2 + (z_j - \overline{z})^2} \tag{2}$$

where $l_j$ = Distance of each point from the mean position

| Repeatability (in mm) | 50% speed (Camera) | 100% speed (Camera) | 100% speed (Laser Tracker) |
|---|---|---|---|
| **Pose 1** | 0.0447 | 0.0460 | 0.0220 |
| **Pose 2** | 0.0339 | 0.0275 | 0.0151 |
| **Pose 3** | 0.0319 | 0.0396 | 0.0217 |
| **Pose 4** | 0.0329 | 0.0326 | 0.0290 |
| **Pose 5** | 0.0411 | 0.0492 | 0.0306 |

**Table 1: Experimental values of repeatability obtained for 5 different poses**

$$\bar{l} = \frac{1}{n} \sum_{j=1}^{n} l_j \tag{3}$$

where $\bar{l}$ = mean of $l_j \forall j \in \{1, n\}$

$$S_l = \sqrt{\frac{\sum_{j=1}^{n} (l_j - \bar{l})^2}{n - 1}} \tag{4}$$

where $S_l$ = Sample standard deviation of $l_j \forall j \in \{1, n\}$ As mentioned in equation above, we have used the sample standard deviation for quantifying the repeatability of the robot at different poses.

The values of repeatability obtained (in millimeters) for all the 5 poses have been illustrated in Table 1. From the Table 1, we can conclude that the values obtained using the camera as not as good as the laser tracker but well within the region of 0.1 mm as recorded in the KUKA lbr documentation. [7]. Although the laser tracker produces more accurate results it is also expensive, requires a much larger setup and the experimentation and data processing part takes more time.

Although the values obtained from the Laser tracker are much more accurate as compared to the use of a camera as observed from the Table 1, the lazer tracker requires bigger setup and is comparatively more expensive than our suggested setup using camera. Therefore, even though using a camera is less accurate in comparison to the lazer setup but the former can be implemented in real time while the arm is performing an industrial operation.

## 4 REPEATABILITY IN FORCE CONTROL MODE

A different class of industrial robots that involves human assistance also known as Cobots (Collaborative Robots), high repeatability is required for operations involving precision based manufacturing such as reducing errors in sensitive tasks like mobile phone assembly or during medical surgeries. In the experimental setup, the robot was assigned to move continuously between three predefined points in it's workspace. Over the course of this motion, external forces were applied to the robot to simulate human interaction with the robot. If the applied external force exceeds a certain limit (specified by the user), the robot moves to a preallocated point to check its position and orientation based repeatability. The limit for external force applied on the arm is decided on the basis of the work requirement. If the achieved position is within the acceptable force limits, the robot will continue the task otherwise the robot will stop for re-calibration. Single pose based repeatability test allows simple and fast repeatability test without any major change in the setup.

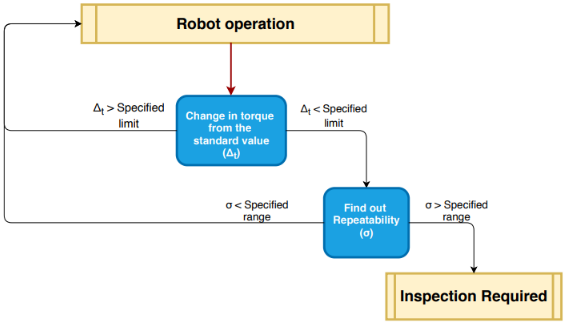


**Figure 5: Flow chart depicting repeatability under force control mode**

We have performed the experiment on LBR Kuka iiwa. External forces on the robot were constantly measured to identify interaction with the environment. Flow chart of the process is illustrated in Figure 5.

$$Repeatability\ of\ pose = 0.0520281mm$$

As compared to the values recorded in Table 1, we can observe that the repeatability obtained is slightly higher when external forces were applied on the robot which is to be expected.

## 5 KINEMATIC IDENTIFICATION

Kinematic identification refers to the mapping of joints positions for a robotic manipulator. We are using this method to find out the error associated with each joint individually. To perform Kinematic Identification, we have used ArUco markers [10]. ArUco markers are synthetic square markers consisting of binary matrices in the form of images. Their black border allows for a much faster detection in the image while their small size and less amount of information makes them less accurate as compared to a checker board. To add further, different ArUco markers can be placed on different objects which is not feasible in case of a checkerboard, hence ArUco markers easily allow relative positioning of different objects with respect to each other. The methodology used for kinematic identification is similar to the approach used in [3], [12] and[13] to extract the D-H parameters based on the pose data of end-effector configuration. First, each joint was actuated individually and images were taken at an interval of 1-1.5°. The order of actuation of joints is from joint A1 to A7 as shown in Fig. 6. Corresponding to each image, the pose of the end-effector was extracted. For each individual joint actuation, the poses will lie on a circular arc since all the joints of LBR iiwa are revolute. Then Singular Value Decomposition (SVD) is done on a given set of pose coordinates for each joint motion individually and then the poses are projected onto a plane whose normal direction is determined using SVD. The projected points obtained are then used to determine the centre of the circular arc using least square solution based on inverse matrix approach (Moore-Penrose inverse matrix). The normal to the projection plane and the centre of the circle form a dual vector, this dual vector is then used to extract the D-H parameter of each joint individually as shown by green arrows in Figures ( 9, 10, 11, 12, 13, 14 and 15). The path followed by the end-effector for each joint is represented via a Point Cloud Distribution as shown in Figure 7. Before actuating any joint, lets say A3, we can adjust the values of A4, A5 and A6 initially such that the maximum workspace could be defined for a manipulator. The reason behind this is that the transformation matrix of lower joint angles (A1 and A2 in this case) is now fixed and hence, any change in initialization of their values will lead to misleading results of D-H parameters for the A3 joint.

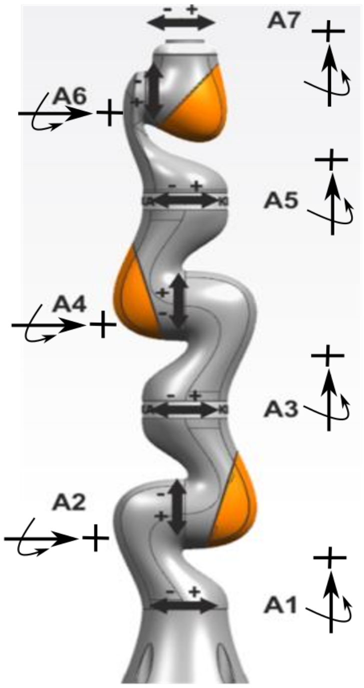


Figure 6: Joints of LBR iiwa labelled A1 to A7[14]

Before actuating each joint angle, the robot is brought back to its home position. This is a common practice to ensure that we could have range of motion for each joint angle. In fact, we could have chosen another point for actuation also. The reference point should be such that it lies in the path of the joint angle before being actuated. This can be explained using an example, suppose you want to get data for A3. Now instead of home position of robot, we could have chosen any other point following the condition that it lied in the path of A2 when joint angle 2 was actuated. This ensures that there is a definite relationship between A2 and A1 otherwise choosing a point curtailing to satisfy these conditions would lead to error as there would not be an exact relation between A2 and A1 available. A similar argument holds for other joint pair angles too.

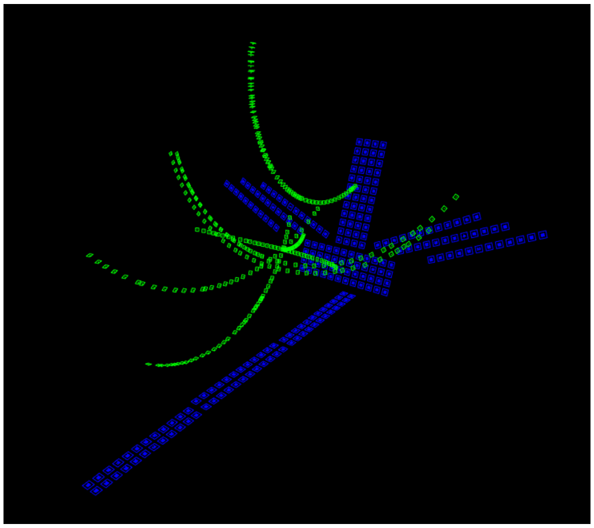


Figure 7: Plot of end-effector poses along circular arcs (green color) and ArUco marker bed setup (blue color)

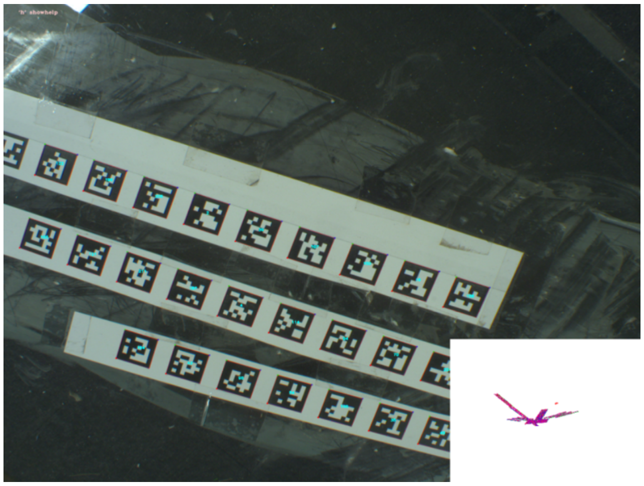


Figure 8: Detection of ArUco markers during pose estimation

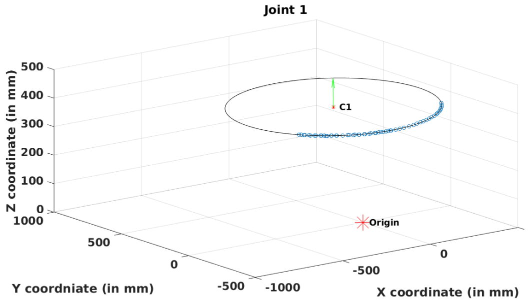


**Figure 9: Dual vector extraction from the poses corresponding to Joint A1**

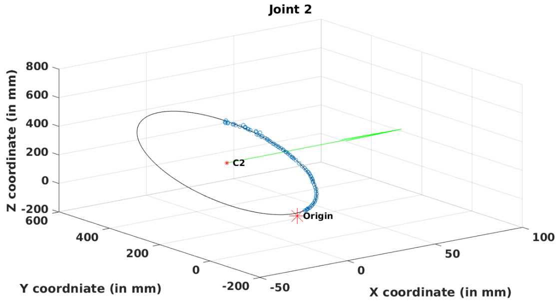


**Figure 10: Dual vector extraction from the poses corresponding to Joint A2**

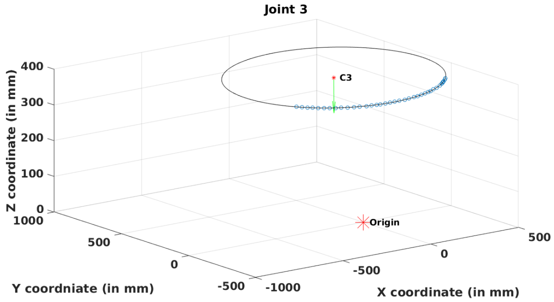


**Figure 11: Dual vector extraction from the poses corresponding to Joint A3**

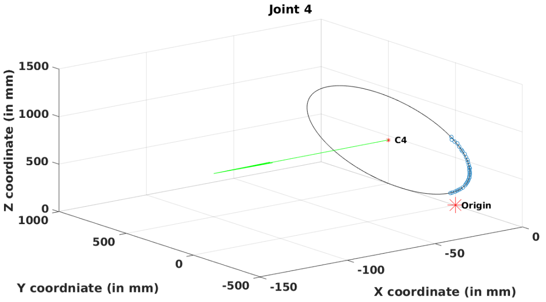


**Figure 12: Dual vector extraction from the poses corresponding to Joint A4**

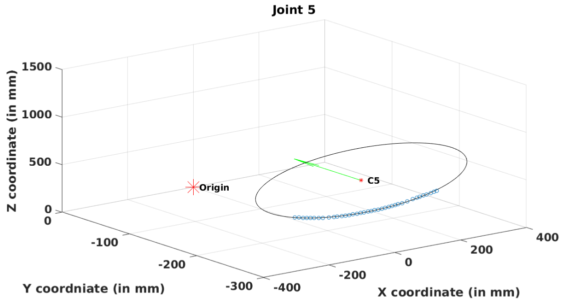


**Figure 13: Dual vector extraction from the poses corresponding to Joint A5**

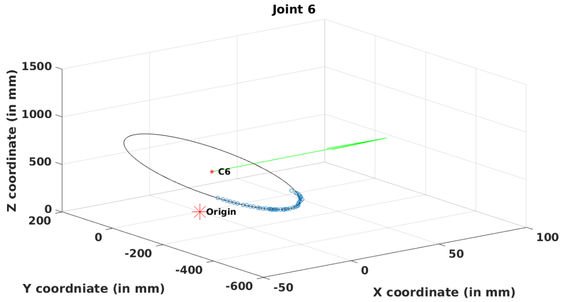


**Figure 14: Dual vector extraction from the poses corresponding to Joint A6**

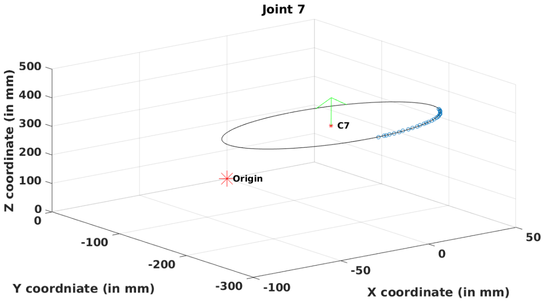
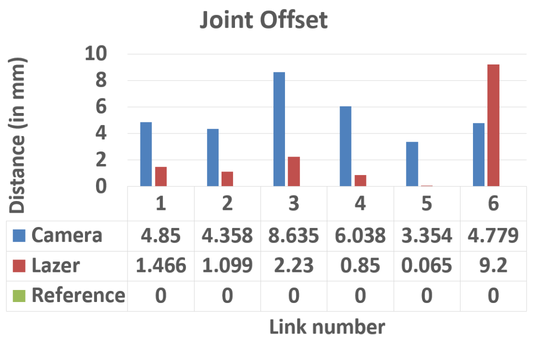


**Figure 15: Dual vector extraction from the poses corresponding to Joint A7**

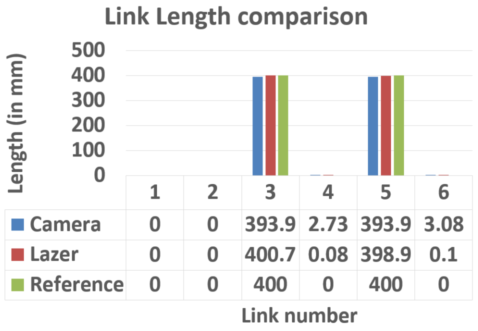
## 6 COMPARISON WITH LASER TRACKER

Repeatability experiment was also performed using a laser tracker. The results of which are shown in table 1. We extracted the D-H parameters of Kuka LBR iiwa using a laser tracker. Figures 16, 17 and 18 shows the comparison of joint angles, link length and twist angle respectively from the laser tracker data, monocular camera and the theoretical data of the parameters obtained from CAD drawings of LBR iiwa. A future possibility is modeling of repeatability using a different statistical approach.



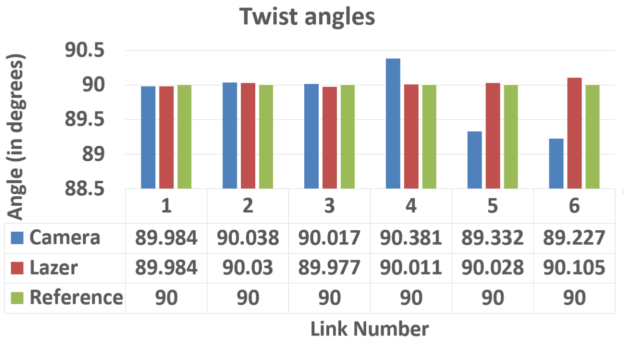
| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 🟦 Camera | 4.85 | 4.358 | 8.635 | 6.038 | 3.354 | 4.779 |
| 🟥 Lazer | 1.466 | 1.099 | 2.23 | 0.85 | 0.065 | 9.2 |
| 🟩 Reference | 0 | 0 | 0 | 0 | 0 | 0 |

**Figure 16: Comparison of Joint offset for joints 1 to 6 of LBR iiwa**



| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 🟦 Camera | 0 | 0 | 393.9 | 2.73 | 393.9 | 3.08 |
| 🟥 Lazer | 0 | 0 | 400.7 | 0.08 | 398.9 | 0.1 |
| 🟩 Reference | 0 | 0 | 400 | 0 | 400 | 0 |

**Figure 17: Comparison of Link length for joints 1 to 6 of LBR iiwa**



| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 🟦 Camera | 89.984 | 90.038 | 90.017 | 90.381 | 89.332 | 89.227 |
| 🟥 Lazer | 89.984 | 90.03 | 89.977 | 90.011 | 90.028 | 90.105 |
| 🟩 Reference | 90 | 90 | 90 | 90 | 90 | 90 |

**Figure 18: Comparison of Twist angle for joints 1 to 6 of LBR iiwa**

## 7 CONCLUSIONS/ FUTURE WORK

A standard algorithm has been created in order to test the repeatability and kinematic identification of an industrial robotic arm using a monocular camera mounted on the end-effector of the robot. We have tested out our algorithm on Kuka LBR iiwa. For the first time a method has been proposed to evaluate repeatability of a robot under force control conditions. The results from the repeatability can be used to check the accuracy of robot operations from time to time. The kinematic identification experiment can be used to find out the D-H parameters of the robot experimentally.

## 8 ACKNOWLEDGEMENT

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