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A CONTACTLESS ROBOT KINEMATIC CALIBRATION METHOD BY DIGITAL PHOTOGRAMMETRY

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ABSTRACT

A technique to obtain the kinematic calibration of multilink systems is presented. The technique that is based on a digital photogrammetry vision system and the D-H based kinematic equations, can be considered as a reverse engineering aspect. The most important aspects of this technique consist in that no information on the kinematics chain is needed, it is fast, low cost, non invasive and also friendly for the operator. Tests of the technique on a revolute robot are also reported, showing a good reliability of the technique itself.

Keywords: Kinematic calibration; digital photogrammetry; Robot mechanics; Reverse engineering

1 INTRODUCTION

Kinematic Calibration

Because of the manufacturing and assembly tolerance, the actual kinematic parameters of a robot differ from their design values; these differences represent the kinematic errors. Because of these kinematic errors the robot end-effector will reach a position that is different from the one that was expected if the nominal kinematic parameters were considered. Especially when the lowering of the costs is required, the kinematic calibration is an effective way to improve the absolute accuracy of robots without the need of a high accurate tooling during the link manufacturing. The kinematic calibration process of an articulated mechanism has different implications in all areas where they are present. This often implies that the presence of such a procedure is also required in applications where the need of the procedure is not so evident. An example can be represented by all the devices that are used as simulators [1].

A relatively recent trend is to use optical equipment based on artificial vision techniques for the measurement instrumentation that is necessary to measure the data used in the calibration of the kinematic chain. Studies were implemented on the use of stereoscopic vision system to obtain the tri-dimensional data necessary to a kinematic calibration procedure [2, 3].

It must be also said that nowadays, calibration tasks need a lot of measurement techniques [4].

The need for an increasingly automated techniques for kinematic calibration of robots, has always pushed toward greater use of vision as a measure of the environment. Different visual feedback motion control methods of the robots was studied in the last few years, to achieve accurate measurement in the industrial robot [5]. At the same time, many algorithms have been developed for the environmental recognition and the motion detection in robot applications, with the aim to promote the integration of vision systems in robotics, especially in mobile and autonomous robots, and to promote and to improve the possibilities of control in robotic applications [6].

The applications based on main sensor with one camera installed in the robot hand, are always more and more numerous, and by means of them the positions of the end effector are related to the positions of the robot joints, and so it is possible to implement a kinematic calibration of the robot, using a kinematic model based on the Denavit-Hartenberg parameters [7, 8].

In this paper is presented a kinematic calibration technique based on a vision system measurement, in particular the position data of some points of the robot are detected by means of digital photogrammetry. The technique uses a kinematic model of the robot based on the Denavit-Hartenberg convention, and the relative displacements between the points “observed” with the vision system.

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The main purpose of this work was to develop a kinematics calibration procedure that could be applied without knowing any information on the kinematic chain under investigation and therefore without having to do any measure on it.
The main goals were also represented by the possibility of obtaining a fast, low cost, non-invasive and also friendly for the operator technique

Digital Photogrammetry

Today Reverse Engineering (RE) systems make it possible to solve the problem of the digital reconstruction of objects, even of complex shapes, through principles codified in complete sets of procedures, specific to various applications.
Among the RE systems, the digital photogrammetry – low cost non-contact passive technique – was chosen for this research.
Photogrammetrical methods are as old as photography and can be dated to the Mid-nineteenth century.
Photogrammetry was used for the first time in 1851 by the French officer Aimé Laussedat, referred to as the "Father of Photogrammetry", who developed the first photogrammetrical devices and methods, using terrestrial photographs for topographic map compilation.
The process was called iconometry (from the Greek words icon meaning image and –metry measurement) [9].
Digital Photogrammetry instead was born in the 80's, having as a great innovation the use of digital images as a primary data source.
The extraction of 3D information from digital images is a complex task requiring a mathematical formulation between the images (at least two) and the object. It uses methods from many disciplines, including optics and projective geometry, in particular, the fundamental principle is that of triangulation (Fig. 1): taking photos from at least two different locations, so-called "lines of sight" can be developed from each camera to points on the object. These lines of sight, the viewing ray (i.e. a ray from the optical centre of the camera through the projection of the feature on the image plane), are mathematically intersected to produce the 3-dimensional coordinates of the points of interest. It is what our brain does all the time in conjunction with our eyes' retinas. Algorithms for photogrammetry typically express the problem as that of minimizing the sum of the squares of a set of errors, known as bundle adjustment [10].
Due to the fact that the 3D reconstruction is performed through the identification of common natural features in the image set, the accuracy of the reconstruction depends on the quality of images and textures.
Digital photogrammetry is characterized by the following main phases:

- analysis of the shape of the object and planning of the photos to be taken;
- calibration of the camera;
- processing of the photos with specific software to generate a point cloud;
- transfer of the point cloud to CAD software to create a 3D CAD model.

The advances in computing speed, parallel processing, high camera resolution and the availability of several photogrammetry software packages, that work in ordinary computers without any specialized hardware systems that were required in the past, has made photogrammetry much more feasible and affordable in many applications [11-14].
Currently, photogrammetry is used in several applications such as: Topography (e.g. GIS, Map production), Civil Engineering & Historical Preservation (e.g. 3D CAD reconstruction of buildings or historic objects for preservation or restoration purposes [15]), Quality Control (e.g. quality control tool for piping manufacturers), Aerospace (e.g. tooling inspection, Reverse Engineering of parts by aftermarket fabricators), Automotive (e.g. measuring the effect of crash-tests), Shipbuilding & Repair (it represents the main industrial application [16]. Most shipyards have adopted an advanced measurement technology in an effort to contain costs and further cut down the production cycle) and also Medicine (e.g. in Dentistry to record the location and orientation of multiple implants [17]).

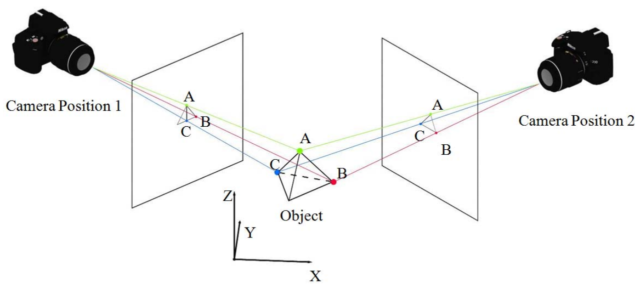

Figure 1 Triangulation Principle used to produce 3-dimensional point measurements.

By mathematically intersecting converging lines in space, the precise location of the point can be determined. It is the two-dimensional (x, y) location of the point on the image that is measured to produce this line. By taking pictures from at least two different locations and measuring the same point in each picture a line of sight is developed from each camera location to the point.

2 THE CALIBRATION TECHNIQUE

If the coordinates in the working space and the joint parameters are known, it is possible to write the direct kinematics equations by means of the Denavit-Hartenberg convention. With this method, each degree of freedom of the robot is characterized by four parameters that describe also the type of joint. As shown in Figure 2, the four

parameters are sufficient to describe any geometric transformation associated to a generic kinematic joint.
A matrix transformation (homogeneous coordinates), associated to a generic geometric transformation between the coordinates in the frame "i" and the coordinates in the frame "i-1",can be obtained as the product of the four basic transformations described by four parameters:

$$^{i-1}A_i = \begin{bmatrix} \cos(\vartheta_i) & -\cos(\alpha_i)\cdot\sin(\vartheta_i) & \sin(\alpha_i)\cdot\sin(\vartheta_i) & a_i\cdot\cos(\vartheta_i) \\ \sin(\vartheta_i) & \cos(\alpha_i)\cdot\cos(\vartheta_i) & -\sin(\alpha_i)\cdot\cos(\vartheta_i) & a_i\cdot\sin(\vartheta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

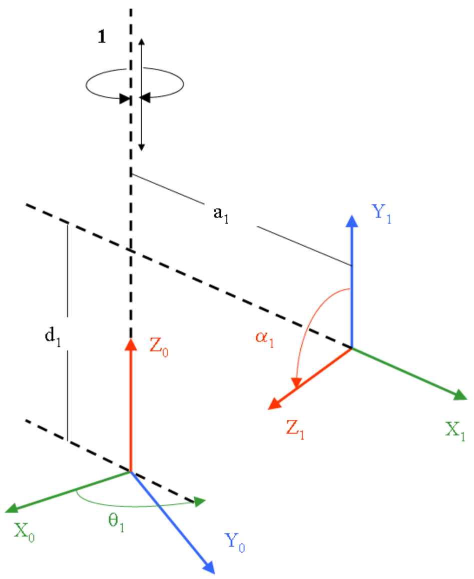

Figure 2 Denavit-Hartenberg parameters of a generic kinematic joint transformation.

The four parameters θ_i, d_i, a_i and α_i of matrix (1), describe the type of joint, so if the joint is rotational the joint variable is θ_i, while if the joint is translational the joint variable is d_i.
By means of such matrixes it is possible to calculate the transform matrix that allows to obtain the coordinates in the frame 0 (the fixed one) of the robot, from those in frame n, that is the one of the last link of the robot: $^0T_n = {}^0A_1 \cdot {}^1A_2 \cdot \ldots \cdot {}^{n-1}A_n$.

$$\{P_0\} = {}^0T_n \cdot \{P_n\} \quad (2)$$

The equation (2) contains all Denavit-Hartenberg parameters, which describe the kinematic chain of the robot, among these there are the joint variables that describe the configurations of the robot.
The kinematic calibration consists of an inversion of the equation (2), by means of whose it is possible to calculate the Denavit-Hartenberg parameters, other than the variables of the joints.
To do this it is necessary to know $\{P_0\}$, $\{P_n\}$ and the joint variables, but in general it is not possible to calculate more unknowns with only one equation, so (2) must be estimate for a sufficient number of robot configurations.
The developed procedure, consists of measuring the position of the robot with a photogrammetric technology. In particular, by means of this technique it is possible to know the position of some targets, that are placed on a revolute robot with three rotational joints, figure 3.
The photogrammetric measure allows to calculate the position of the targets in its reference system, $\{P_v\}_i$.
In order to use the equation (2) to estimate the Denavit-Hartenberg parameters, it is necessary to know the positions of the target in the reference of the robot. This operation is possible if the relation between the reference of the robot and the reference of the photogrammetric system is known, but this relationship is not easy to know or to measure.
This proposed and developed calibration procedure is based on the measures of distances, instead of the absolute positions of the target points, so it is not necessary to know the relation between the robot and the photogrammetric system.

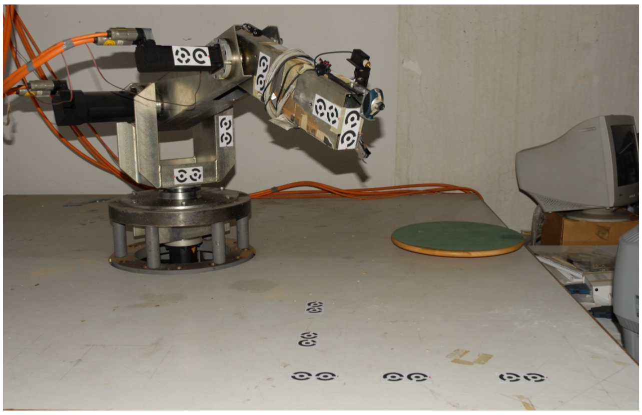

Figure 3 Robot and target.

If $[d_{ij}]_{kt}$ is the distance between the target point "i" in the robot configuration "k" and the target point "j" in the robot configuration "t", it is possible to write the following relation:

$$[d_{ij}]_{kt} = \left\| \left[\{P_0\}_i\right]_k - \left[\{P_0\}_j\right]_t \right\| = \left\| \left[\{P_v\}_i\right]_k - \left[\{P_v\}_j\right]_t \right\| = \left\| \left[{}^0T_n\right]_k \cdot \{P_n\}_i - \left[{}^0T_n\right]_t \cdot \{P_n\}_j \right\| \quad (3)$$

where:
i, j = target points;
k,t = robot configurations;

$[\{P_0\}_i]_k$ = position of target "i" in the robot base system and for the robot configuration "k";
$[\{P_0\}_j]_t$ = position of target "j" in the robot base system and for the robot configuration "t";
$[\{P_v\}_i]_k$ = position of target "i" in the photogrammetric reference system and for the robot configuration "k";
$[\{P_v\}_j]_t$ = position of target "j" in the photogrammetric reference system and for the robot configuration "t";
$[{}^0T_n]_k$ = robot transform matrix between frame "n" and frame "0" and for robot configuration "k";
$[{}^0T_n]_t$ = robot transform matrix between frame "n" and frame "0" and for robot configuration "t"
$\{P_n\}_i, \{P_n\}_j$ = coordinates of the target points "i" and "j" in the reference system "n" of the robot.
In equation (3) there is no dependency from the relationship between the reference of the robot and the reference of the photogrammetric system, and the unknown are the Denavit-Hartenberg parameters, other than the coordinates of the target point in the reference "n" of the robot, while the variables of the joints and the distance d_{ij} are known.
The kinematic calibration problem can be expressed as following:

$$d_{ij} = F\left(\{\Theta\}_k, \{\Theta\}_t, \pi_{DH}, \{P_n\}_i, \{P_n\}_j\right) \tag{4}$$

where:
$\{\Theta\}_k$ = vector of the variables of the joints in the robot configuration "k";
$\{\Theta\}_t$ = vector of the variables of the joints in the robot configuration "t";
π_{DH} = vector of unknown parameters of the Denavit-Hartenberg convention;
$\{P_n\}_i, \{P_n\}_j$ = coordinates of the target points in the reference system "n" of the robot.
The problem described by equation (4), obviously, can not be resolved to find the unknown Θ, $\{P_n\}_i$ and $\{P_n\}_j$ with only one distance d_{ij}, so it is necessary to write it for a sufficient number of times, and then it is possible to invert the equations (4) to estimate the unknowns.
The proposed procedure estimates the equation (4) for some target points, applied on the last link of the robot and for some different configurations of the robot. In this way it is possible to write a lot of equations (4) because it is possible to compute the distances between each target point and the others in all the different configurations of the robot.
If N_T is the number of target point and N_C is the number of robot configurations, all the possible distances, N'_d, that it is possible to compute is the number of combinations of $N_T x N_C$ points taken two at a time.

$$N'_d = \left(N_T \cdot N_C\right)! \Big/ \left(\left(N_T \cdot N_C - 2\right)! \cdot 2\,!\right) \tag{5}$$

In addition to these distances, it is possible to calculate the mutual distances between the target points, also in the coordinate reference system "n" of the robot. The number of these last distances N''_d, is the number of combinations of N_T points taken two at a time. In the calculation of these distances the parameters of Denavit-Hartenberg convention and the vector of the variables of the joints, but only the coordinates of the target points in the reference system "n" of the robot.

$$N''_d = \left(N_T\right)! \Big/ \left(\left(N_T - 2\right)! \cdot 2\,!\right) \tag{6}$$

In conclusion the total number of distances that is to possible to evaluate and so the number of equation (4) that is possible to compute, N_d, is the following:

$$N_d = N'_d + N''_d \tag{7}$$

3 THE EXPERIMENTAL PROCEDURE

The proposed procedure was applied to a revolute robot with three degree of freedom, figure 4.
The reference systems hypothesized according the convention of Denavit-Hartenberg are shown in Figure 4.
In particular the photogrammetric analysis, was performed using 50 targets to define the three-dimensional coordinates. Some of these were fixed and identified the reference system, the others were attached to the robot and were moved with it.

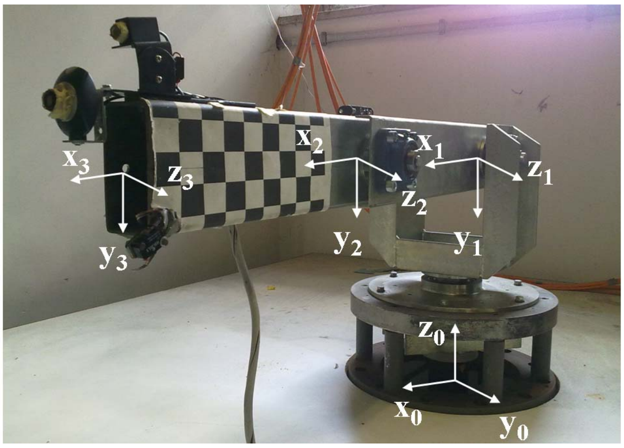

Figure 4 Revolute robot and the Denavit-Hartemberg reference system.

3.1 3D POINT ACQUISITION

A photogrammetry software package, RhinoPhoto by Qualup SAS (France) and a Nikon D200 camera were used for 3D points acquisition.
The following two main phases were performed:

- calibration of the camera;
- processing of the images.

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3.2 CAMERA CALIBRATION

Camera calibration plays a fundamental role in Photogrammetry, in order to obtain accurate digitizing, as confirmed in literature [18, 19].

During the process of camera calibration, that is obtained by RhinoPhoto with 4 photos taken with the camera rotated 90°of a calibration grid (Fig. 5) fixed on a perfectly flat area, the metric characteristics of the camera are determined.

This phase is essential for determining:

- the real focal length of the camera, not exactly the same as the focal length indicated by the manufacturer;
- the real position of the Principal Point of the CDD sensor essential in order to calculate the exact 3D positions of the camera;
- the Lens Distortion in order to compensate for this error.

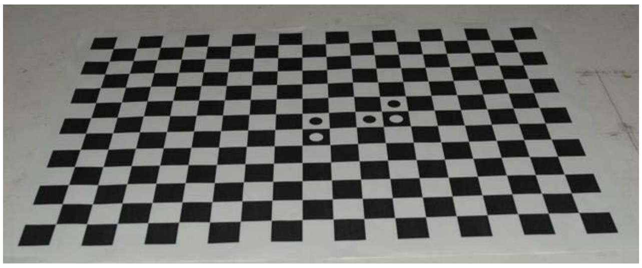


Figure 5 Camera calibration grid.

3.3 IMAGE PROCESSING

After the camera calibration phase, coded targets, similar to circular barcodes were defined and positioned on the points to acquire and various photos were taken at different angles (Fig. 6).

To each one of the target corresponds a number (Fig. 7a). These numbers are automatically read from the images and 2D points on the images are created at the center of the target (Fig. 7b).

The 3D positions of the camera, not known when the photos were taken, then were computed from 2D points on each image (the centers of targets) and finally, the 3D points were created (Fig. 8).

4 EXPERIMENTAL RESULTS: ROBOT PARAMETERS IDENTIFICATION

To perceive all the robot degree of freedom, three coded markers were placed on the end of the third link, like it is shown in Figure 9. Each of these markers is composed of two calibrated target points and of a third target on the side of the marker.

The tests were carried out by analyzing five configurations of the robot and seven target points, shown in Figure 9.

For each of the five configurations of the robot there is a vector of the variables of the joints Θ, as reported in Table I.

In this case $N_T = 7$ and $N_C = 5$, so all the possible distances, $N'_{d,}$ that are possible to compute with (5), are 595, while the distances N''_d, that it is possible to compute with (6) are 21. So, the total number of equations that can be used to the identification of unknown parameters, is 616.

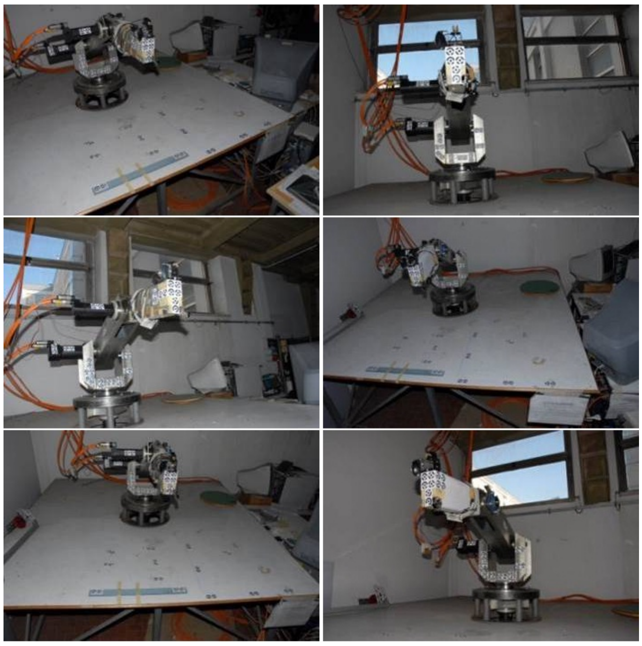
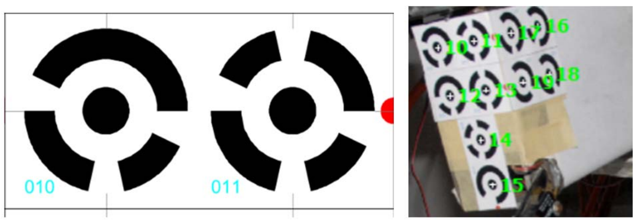


Figure 6 Photos of the points to be acquired taken at different angles.



a) b)

Figure 7 Coded targets.

The kinematic calibration problem (4) has been inverted with an optimization procedure, as said, it is possible to evaluate the parameters of the Denavit-Hartenberg convention and the coordinates of the seven target points in the reference system "3" of the robot.

In particular the problem (4) is written as a scalar function of several variables, and constrained nonlinear optimization attempts to find a constrained minimum of this function starting at an initial estimate.

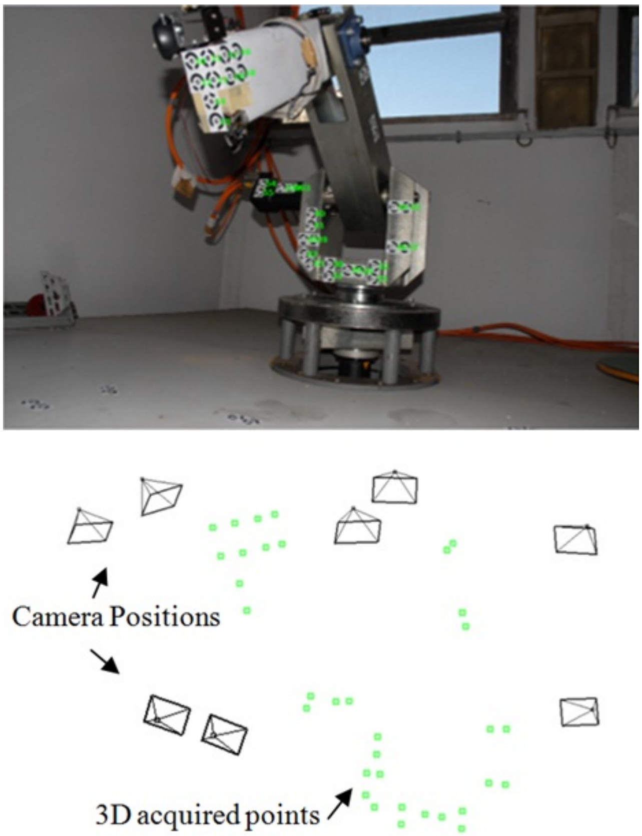


Figure 8 3D acquired points in a CAD environment.

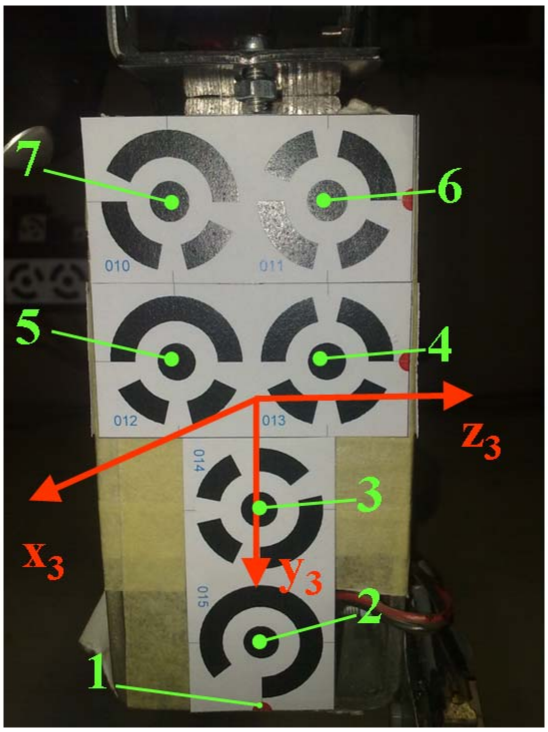


Figure 9 Target points used for robot parameters identification.

Table I – Value of variables of joint in five robot configuration

Robot configuration	θ_1 (rad)	θ_2 (rad)	θ_3 (rad)
1	0	-0,4443	1,1709
2	0	-0,6487	1,5995
3	0	-0,2674	1,0974
4	0,1419	-0,4265	1,1342
5	0,0082	-0,4389	1,1430

The vector of unknown parameters of the Denavit-Hartenberg convention, π_{DH}, consists of 9 elements, while the coordinates of the target points in the reference system “3” of the robot, are 3x7=21.

In Table II the identified parameters of problem (4) are reported.

Table II – Identified parameters

	Identified value (mm)		Identified value (mm)
a_1	-1,41	X_3	1,01
a_2	398,76	Y_3	15,40
a_3	404,06	Z_3	0,83
d_1	449,00	X_4	0,3
d_2	4,2	Y_4	-14,35
d_3	4,33	Z_4	14,31
α_1	-1,56	X_5	0,84
α_2	0,00	Y_5	-14,52
α_3	0,00	Z_5	-14,44
X_1	1,07	X_6	0,32
Y_1	59,95	Y_6	-44,37
Z_1	0,64	Z_6	14,44
X_2	1,01	X_7	0,66
Y_2	44,35	Y_7	-44,48
Z_2	0,73	Z_7	-14,36

In Figure 10, the residual values of the distances calculated with the identified parameters, compared to those measured with the photogrammetric system, are shown. It is possible to see that the mean value of the residual is 0.32 mm with the identified parameters and target points coordinates, while the same value is 1.68 mm with the nominal parameters and the measured coordinates of the target points.

A verification of the results is obtained by measuring the displacement of point 1 with photogrammetric system, planning the robot motion with nominal and identified parameters of the Denavit-Hartenberg convention.

Three sets of coordinates, in the reference system 0 of the robot, are taken in to account for point 1 and these are shown in Table III.

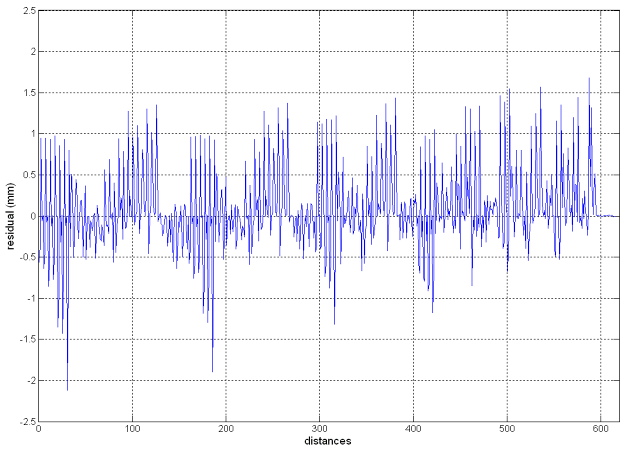


Figure 10 Residual values in mm of the distances calculated with the identified parameters.

The motion of the robot is planned to move point 1 of the reference system 3 of the robot, indicated in Table II, in the three positions indicated by the Table III. The inverse kinematics was applied with the nominal parameters of the Denavit-Hartenberg convention and with those identified with the kinematic calibration.

Table III – Sets of coordinates for point 1.

Point 1 pos.	x mm	y mm	z mm	Distance	d (mm)
1	700	0	450	$d_{1,2}$	100
2	600	0	450	$d_{1,3}$	100
3	700+100/e3	100/e3	450+100/e3	$d_{2,3}$	177,6148

The photogrammetric system made it possible to measure the distances between the positions, whose nominal values are shown in the last column of the Table III.

In Table IV the obtained results are shown:

Table IV – Measured distances with nominal and identified robot parameters.

Distances	NOMINAL PARAMETERS			
	d (mm)	error		
		(mm)	%	% mean
$d_{1,2}$	99,7678	0,2322	0,2322	1,1551
$d_{1,3}$	101,9261	1,9261	1,9261	
$d_{2,3}$	179,9363	2,3215	1,307	

Table IV – cont.

Distances	IDENTIFIED PARAMETERS			
	d (mm)	error		
		(mm)	%	% mean
$d_{1,2}$	100,6948	0,6948	0,6948	0,878
$d_{1,3}$	98,6149	1,3851	1,3851	
$d_{2,3}$	176,6305	0,9843	0.5541	

The data reported in Table IV show the measurements of movements performed by the robot planned with the two sets of D-H parameters, and the relative percentage errors with respect to the nominal displacements. With the identified parameters a lower average percentage error is obtained.

5 CONCLUSIONS

A method for the kinematic calibration of almost any multilink system was presented. The method was then experimentally tested on a low cost revolute robot prototype that was designed and built in our laboratory.

Mainly the technique presents the following peculiarities:

- the technique is non-invasive for the mechanism;
- no measures from an operator are required; this drastically reduces the possibility of errors and, hence it is friendly for the operator;
- the procedure is simple and requires a very short time to obtain the full calibration data;
- the computational efforts are very low;
- once the test rig is acquired, the procedure is a very low cost one. Hence it can be used for a mass production;
- no information is necessary on the kinematics chain.

The presented test results clearly show that the technique permits to obtain accurate values of the kinematic parameters.

Further developments will concern deeper investigations on the error sources in order to obtain a further increase in the accuracy of the calibration proposed technique.

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