A Calibration Procedure For The Parallel Robot Delta 4

P. Maurine, E. Dombre

L.I.R.M.M., U.M.-9928 CNRS-Université Montpellier II
161, rue Ada, 34392 Montpellier Cedex 5, France

Abstract

A two stage calibration method for the parallel robot Delta 4 is presented. It allows one to identify the offsets on the three first joints and the absolute location of the robot base. It involves a cheap displacement sensor and dedicated targets which can be easily moved on the work area. Intensive simulations show the robustness of the protocol and experimental results validate this procedure.

1 Introduction

Many comprehensive studies and works have been made in the area of parallel robots [12], [17], [15]. This is due to their interesting features by comparison with serial robots: great dynamic capabilities and rigidity, a high positioning repeatability, and so a high positioning accuracy if the actual parameter values are known.

The loss of accuracy of such structures is mainly due to the joint offsets, the manufacturing tolerances and the errors of the robot registration in the environment. The solution to compensate this loss of accuracy is known as robot calibration. This allows one to identify the real robot kinematic parameters to compensate the nominal geometric model.

Several papers can be found about the calibration of serial robots [8], [19], [13]. Nevertheless, few papers have been published about the calibration of parallel robots. Bennett and Hollerbach, [1] use the approach they have developed about the autonomous calibration of single closed loop kinematic chain to calibrate the RSI-6DOF wrist. The offsets and the gain of this structure are identified. Using the same approach Nahvi, Hollerbach and Hayward [14] identify the joint offsets and three other kinematic parameters of a 3 degree of freedom (d.o.f.) platform. Like in the previous work, experimental results are given and compared to those identified using an external calibration device.

Other works have been carried out on the calibration of the Stewart platform. Zhuang and Roth [21] propose a new solution but they conclude that the main drawback of their method is that its parameters can not be identified globally. Masory, Wang and Zhuang [10] develop a more robust method to identify the platform parameters. No experimental studies are performed but extensive simulations including measurement noise show that the positioning error of the platform can be reduced by one order of magnitude at least. Geng and Haynes [7] simulate a two stage calibration procedure of the Stewart platform. Recently Olivers and Mayer [16] propose and simulate a method to identify the platform parameters globally. They use the singular value decomposition to eliminate the redundant parameters of the model.

None of these methods takes into account the registration of the robot in the environment. So the location errors of the robot base which occur when the robot is first installed or is moved on its work area cannot be compensated. Moreover no experimental results are given about the three last methods.

We have developed a method to calibrate the robot Delta 4. This method is efficient and can be easily carried out in real environment. It allows to identify the robot location in the work area and the joint offsets. These parameters are subject to change after each maintenance operation and when the robot is moved on the line.

The other kinematic parameters whose influence on the robot accuracy is less important, are not taken into account. Therefore, in our approach the robot is supposed to have been calibrated before (the leg lengths and the angles between two successive axes may be considered as stationary along the robot life).

The used measurement device is an inexpensive laser displacement sensor. It operates in a range finder mode or in a detection mode in both cases on dedicated targets. These targets are easily placed and moved in the work area due to their small dimensions.

The first section of this paper describes the delta robot and the used kinematic modeling. The specifications of the procedure are then developed. Simulation studies which are presented next have been performed to analyze the sensitivity of the procedure to parameters such as sensor location and orientation, target setup and number, and measurement noise. They allow us to validate modeling approximations. Experimental validation on the robot Delta 4 is presented in the last part.

2 The robot Delta 4

The Delta 4 is a very fast parallel robot with 4 d.o.f. suitable to pick and place works. It can move and place small weight objects with high speed along trajectories about 200 mm long.

Its fully parallel structure [18] complies with this kind of applications. Mechanism specifications are given in [4][5]. A simplified view is given in figure 1. The robot consists of a base plate, a traveling plate and three identical kinematic chains made of two parts:

- the arm actuated by one of the three motors secured on the top plate and distributed on a circle at 120 degrees mutually.
- the lower parallelogram, which drives the traveling plate.

Thus the traveling plate always remains parallel to the base plate and the translational motions result from the combined motions of the three actuators.

The end effector is secured on the mobile plate and it is connected with a fourth actuator secured either on the top plate or directly on the traveling plate.

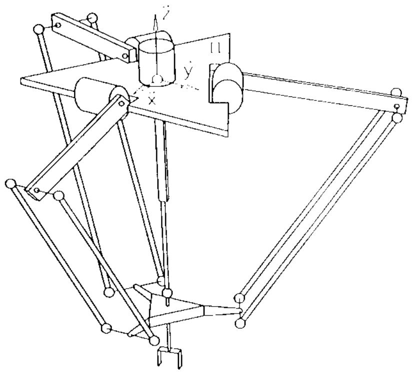


Fig. 1: the robot Delta 4

3 Modelization

Several approaches have been developed to establish direct and inverse kinematic models [20] [6]. We will use here the model proposed by Pierrot [18].

4 Calibration procedure

As in our previous works [3] [11], the idea is to identify a restricted set of parameters at the time instead of identifying all the parameters globally.

In this section we present the procedures used to identify the three offsets θ_{1off}, θ_{2off}, θ_{3off} of the three first joints, the position errors d_x, d_y, d_z and the orientation errors δ_x, δ_y, δ_z of the robot base with respect to the environment. These errors are assumed to be small. Two procedures allow one to identify two sets of parameters: (1) δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off} and (2) d_x, d_y, δ_z. Note that the offsets can also be identified with the second set of parameters. The offset on the fourth joint θ_{4off} is not identified since it has no influence on the end effector position and a negligible influence on its orientation along z_4 axis.

The frames defined to present the procedures are (figure 2):

R_w: the reference frame associated to the work cell,

R_b: the base plate frame tied to its center O_b,

R_t: the mobile plate frame tied to its center O_t,

R_c: the sensor frame associated to the point O_c, the z_c axis is on the sensor optical axis.

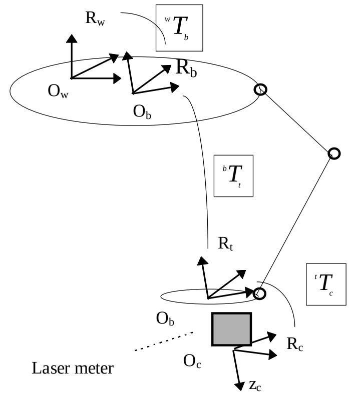


Fig. 2: The different transformations used

Using homogeneous transformations matrix ${}^iT_j$ [2] to describe in the frame R_i the coordinates of a vector given in the frame R_j we can define ${}^wT_b$, ${}^bT_t$, ${}^tT_c$:

$$ {}^wT_b = \begin{bmatrix} 1 & -\delta_z & \delta_y & X_0+d_x \\ \delta_z & 1 & -\delta_x & Y_0+d_y \\ -\delta_y & \delta_x & 1 & Z_0+d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^bT_t = \begin{bmatrix} 1 & 0 & 0 & X_t \\ 0 & 1 & 0 & Y_t \\ 0 & 0 & 1 & Z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$[X_0\ Y_0\ Z_0]^T$ are the nominal coordinates of O_b in R_w.

The coordinates of $[X_t\ Y_t\ Z_t]^T$ are computed using the direct kinematic equations (DKE) taking into account the offsets θ_{1off}, θ_{2off}, θ_{3off}:

$$ \begin{bmatrix} X_t & Y_t & Z_t \end{bmatrix}^T = DKE\left(\theta_1+\theta_{1off}, \theta_2+\theta_{2off}, \theta_3+\theta_{3off},\ \theta_4\right) $$

θ_i is the i^th joint variable.

If $[X_c\ Y_c\ Z_c]^T$ are the O_c coordinates in R_t then:

$$ {}^tT_c = \begin{bmatrix} 1 & 0 & 0 & X_c \\ 0 & 1 & 0 & Y_c \\ 0 & 0 & 1 & Z_c \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$X_c=0$, $Y_c=0$, Z_c are the nominal coordinates of O_c; the sensor optical axis is aligned with the z_t axis of R_t.

4.1 Identification of δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off}

P is an horizontal support plane accurately positioned in the work area. Its altitude in R_w is h_P. The robot is driven to reach the knots N_i of a virtual horizontal pattern grid whose altitude in R_w is h_μ (figure 3).

For each knot N_i the distance d_i between the sensor head O_c and the plane P is recorded

Using the previous definitions of ${}^wT_b$, ${}^bT_t$, ${}^tT_c$, the matrix ${}^wT_t$ is computed:

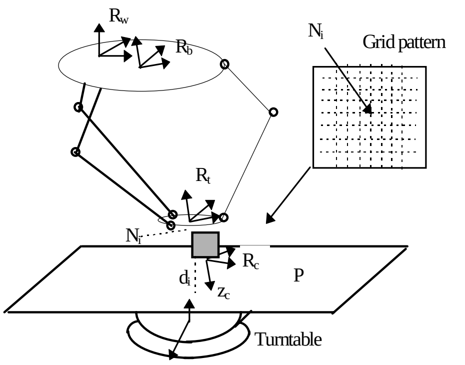


Fig. 3: Identification of δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off}

$$^{w}T_t = \begin{bmatrix} 1 & -\delta_z & \delta_y & X_0 + X_t + \delta_y\cdot\left(Z_t + Z_c\right) - \delta_z\cdot Y_t + d_x \\ \delta_z & 1 & -\delta_x & Y_0 + Y_t - \delta_x\cdot\left(Z_t + Z_c\right) + \delta_z\cdot X_t + d_y \\ -\delta_y & \delta_x & 1 & Z_0 + Z_t + Z_c + \delta_x\cdot Y_t - \delta_y\cdot X_t + d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & -\delta_z & \delta_y & X' \\ \delta_z & 1 & -\delta_x & Y' \\ -\delta_y & \delta_x & 1 & Z' \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

If the sensor optical axis is aligned with the z_c axis of R_c frame, one can calculate the theoretical distance d_i between O_c $[X'\ Y'\ Z']^T$ and the plane P along the z_c direction whose components in R_w are $[\delta_y\ -\delta_x\ 1]^T$.

$$d_i' = \left(Z' - h_P\right)\cdot\sqrt{\left(\delta_y^2 + \left(-\delta_x\right)^2 + 1^2\right)}$$

neglecting the second order terms leads to:

$$d_i' = \left(Z' - h_P\right)$$

The vector of parameters $p_1=[\delta_x\ \delta_y\ d_z\ \theta_{1off}\ \theta_{2off}\ \theta_{3off}]^T$ that has to be identified is the one that minimizes for all the number M of measurement points N_i:

$$\sum_{i=1}^{M}\varepsilon_i^2 = \sum_{i=1}^{M}\left(d_i' - d_i\right)^2$$

$$\varepsilon_i = \left[Z_0 + Z_{ti} + Z_c + \delta_x\cdot Y_{ti} - \delta_y\cdot X_{ti} + d_z - h_P\right] - d_i$$

$$\begin{bmatrix} X_{ti} & Y_{ti} & Z_{ti} \end{bmatrix}^T = DKE\left(\theta_{1i} + \theta_{1off}, \theta_{2i} + \theta_{2off}, \theta_{3i} + \theta_{3off}, \theta_{4i}\right)$$

$[\theta_{1i}, \theta_{2i}, \theta_{3i}, \theta_{4i}]^T$ is the nominal configuration given to the robot controller to reach N_i (no location errors and no offsets are taken into account).

The non linear minimization problem is solved using MATLAB library.

4.2 Identification of d_x, d_y, δ_z, (θ_{1off}, θ_{2off}, θ_{3off})

A number I of cylinders are plugged on the plane P. The positions are uniformly distributed on a circle C_k (figure 4). So the position and the orientation of each cylinder are accurately known in R_w. The robot is moved so the center of the traveling plate O_t describes a circle C_k' above the cylinders.

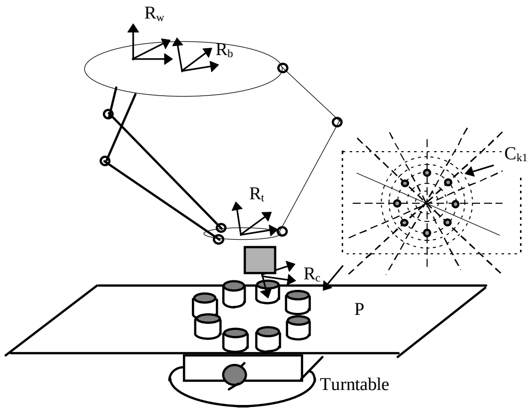


Fig. 4: Identification of d_x, d_y, δ_z, (θ_{1off}, θ_{2off}, θ_{3off})

The laser sensor secured on the mobile plate detects the first edge B_{1j} of the cylinder j. Then the robot moves to detect the second one B_{2j} and so on for each cylinder. The configurations θ_{1ij}, θ_{2ij}, θ_{3ij} (i=1, 2 ; j=1, ..., I) are stored. Using the definition of $^{w}T_c$, B_{ij} coordinates are:

$$X_{ij} = X_0 + X_{tij} + \delta_y\cdot\left(Z_{tij} + Z_c\right) - \delta_z\cdot Y_{tij} + d_x$$

$$Y_{ij} = Y_0 + Y_{tij} + \delta_x\cdot\left(Z_{tij} + Z_c\right) - \delta_z\cdot X_{tij} + d_y$$

$$\begin{bmatrix} X_{ti} & Y_{ti} & Z_{ti} \end{bmatrix}^T = DKE\left(\theta_{1i} + \theta_{1off}, \theta_{2i} + \theta_{2off}, \theta_{3i} + \theta_{3off}, \theta_{4i}\right)$$

Using δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off} values identified with the first procedure, the parameter vector $p_2=[d_x\ d_y\ \delta_z]$ to be identified is the one that minimizes for all cylinders:

$$\sum_{i,j}\left(r_i - \sqrt{\left(X_{ij} - x_{ci}\right)^2 + \left(Y_{ij} - y_{ci}\right)^2}\right) \text{(i=1, ..., I ; j=1,2)}$$

x_{ci}, y_{ci} are the coordinates of the i^{th} cylinder center in R_w.

As in the previous procedure, this non linear problem is solved using MATLAB library.

Note that the offsets can also be included in the vector $p_2=[d_x\ d_y\ \delta_z\ \theta_{1off}\ \theta_{2off}\ \theta_{3off}]^T$ to be identified with d_x d_y δ_z. This allows one to verify the results given by the first procedure.

5 Discussion

In the previous section, the location errors of the sensor on the mobile plate are not taken into account. Practically the laser sensor is roughly secured on the plate in order to save time and to reduce the cost of fixturing. Thus, the sensor head is placed with d_{xc}, d_{yc}, d_{zc} position errors and with δ_{xc}, δ_{yc}, δ_{zc} orientation errors.

Therefore, neglecting second order terms, the matrix $^{w}T_c$ becomes:

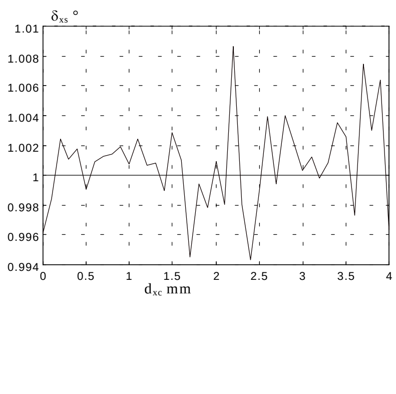
$$^{w}T_c = \begin{bmatrix} 1 & -\delta_z - \delta_{zc} & \delta_y + \delta_{yc} & X_0 + X_t + \delta_y\cdot\left(Z_t + Z_c\right) - \delta_z\cdot Y_t + d_x + d_{xc} \\ \delta_z + \delta_{zc} & 1 & -\delta_x - \delta_{xc} & Y_0 + Y_t - \delta_x\cdot\left(Z_t + Z_c\right) + \delta_z\cdot X_t + d_y + d_{yc} \\ -\delta_y - \delta_{yc} & \delta_x + \delta_{xc} & 1 & Z_0 + Z_t + Z_c + \delta_x\cdot Y_t - \delta_y\cdot X_t + d_z + d_{zc} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The direction of the laser optical axis along z_c and the coordinates of the sensor center O_c are modified so that

the sensor optical axis is not aligned with z_t. This introduces a bias on the coordinates of the measured points on P and on the cylinder edge coordinates.
To compensate these errors [11], for each point N_i and for each edge B_{ij} two measurements are performed respectively at the position θ_4 and $\theta_4+\pi$ of the mobile plate with respect to z_4 axis. The value of d_i and θ_{1off}, θ_{2off}, θ_{3off} used in the minimization algorithm is the mean value of the measurements performed respectively at the θ_4 and $\theta_4+\pi$ sensor position.
In the next part we validate these hypotheses. We show that the identification procedure of δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off} is robust to location errors of the sensor on the end effector. We also discuss the choice of the number of measurements M. We finally analyze the parameter sensitivity to the measurement noise.

6 Simulations

a) Influence of the sensor location on the end effector
The purpose of this simulation is to evaluate the sensitivity of the parameters δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off} to the variations of the location errors of the sensor on the end effector. For example, figure 5 shows the variations of simulated parameters δ_{xs}, θ_{1offs} when d_{xc} or δ_{xc} vary. Each figure corresponds to two measurements of d_i at θ_4 and $\theta_4+\pi$. The nominal values of simulated parameters are $\delta_{xn}=1°$, $\delta_{yn}=-1.5°$, $d_{zn}=-1$ mm, $\theta_{1offn}=-1°$, $\theta_{2offn}=1.5°$, $\theta_{3offn}=-1°$. The parameters of the experimental setup used in this simulation are $h_P=-650$ mm, M=100 (grid pattern dimensions: 200x200 mm), $h_\mu=-530$mm, $Z_c=-90$ mm.
The noise introduced on each computation of d_i is a randomly distributed and non biased noise which range is ±0.1 mm. The simulation shows the robustness of the procedure for parameters δ_x, δ_y, θ_{1off}, θ_{2off}, θ_{3off} when two measurements are performed at θ_4 and $\theta_4+\pi$. Nevertheless the location error of the sensor d_z is not compensated.



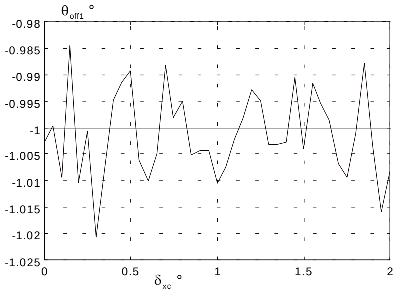
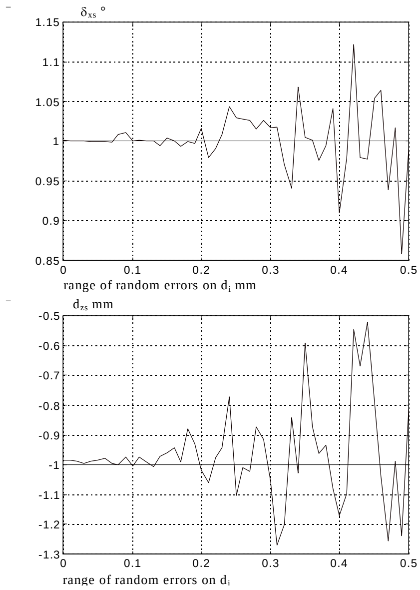


Fig 5: Influence of d_{xc} and δ_{xc} errors

b) Influence of the number of measurements
The noise features are the same as in the previous simulation. No error is introduced on the sensor location. Simulations run for M=9, ..., 256. Simulations show that the accuracy of the simulated parameters is not really sensitive to the number of measurements. Nevertheless the grid patterns with 64 and 100 points seem to be more accurate.

c) Influence of the measurement noise
The previous simulations have been carried out introducing random errors on parameter d_i whose range is ±0.1 mm. The purpose of this simulation is to analyze the sensitivity of the parameters to the measurement noise. Random errors on parameter d_i are introduced in the process. Figure 6 shows the sensibility of parameters δ_{xs}, d_z, θ_{1off} when the range of the random errors on d_i varies from 0 to 0.5 mm. This simulation shows that the random errors should be less than 0.3 mm to have the parameters accuracy about ±0.1 mm for the d_z error and ±0.1° for the orientation and the offsets errors. The resolution of the sensor (2 μm) is very good but the surface state on the plane P has to be carefully checked since it may have a non negligible influence on the parameters.



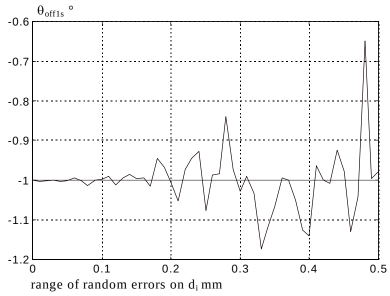


Fig 6: Influence of the noise on δ_{xs}, d_z, θ_{1off}

d) Conclusion

These simulations show that the protocol for the identification of δ_x, δ_y, θ_{1off}, θ_{2off}, θ_{3off} is robust to the sensor location errors on the end effector and to the number of measurements. Besides, the noise sensitivity studies show that the procedure is robust if the random errors on d_i are less than ±0.3 mm.

Similar simulations have been performed for the identification of d_x, d_y, δ_z, (θ_{1off}, θ_{2off}, θ_{3off}). They show that the procedure is robust as well. Simulations about the noise sensitivity have shown that the procedure is robust if the random errors on the measurements of θ_{1i}, θ_{2i}, θ_{3i} relative to the detection of the cylinder edges are less than ±0.25°.

7 Experimental validation

a) Experimental set up

The experimental setup is shown in figures 1 and 2. A rigid plate is used as the measurement plane P. Making use of drilled holes whose coordinates are precisely known in the frame associated to the plate, several cylinders can be accurately plugged on different circles C_k. The plate is secured on a precision turntable providing O_x, O_y fine translational motions along x and y axis and O_x, O_y, O_z fine rotational motions about x, y and z axis. So the location errors are directly given to the plane P rather than to the robot base. The offsets are introduced on the robot controller.

The sensor is a Keyence LB-12 laser displacement meter (measuring range 30mm–50mm, resolution 2 µm, linearity 0.5%). The controller is the LB-72 unit. The sensor head is housed in a very compact unit which can be easily mounted on the end effector. Data acquisition is done with a PC via an A/D RTI 800 board.

b) Sensor calibration

The sensor is secured on the end effector in such a way that the location errors ($d_{xc}=d_{yc}=d_{zc}=0$ and $\delta_{xc}=\delta_{yc}=\delta_{zc}=0$) are minimized. For both procedures distance between the sensor head and the targets is close to 40 mm. For the identification of d_x, d_y, δ_z, θ_{1off}, θ_{2off}, θ_{3off}, it comes that the sensor has to be oriented in such a way that the plane formed by the emitted and received beams is orthogonal to the displacement direction. Furthermore, to increase the sensitivity of the sensor, for the procedure 1 the plane is painted in white whereas for the procedure 2 the top of cylinders are painted in white and a black support is put on plane P.

c) Experimental results

Since the absolute orientation of the support plane and the absolute location of the cylinders on the plane are not known in R_w, a first series of measurements is done in order to identify a reference orientation and position of the plane and a reference location of the cylinders.

d) Identification of δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off}

Several grid patterns with a different number of knots M are used. For each knot, two series of 30 measurements D_{i1} and D_{i2} are performed for the sensor position θ_4 and $\theta_4+\pi$. The mean values m_{i1}, m_{i2} and the standard deviations σ_{i1}, σ_{i2} of D_{i1} and D_{i2} are computed, so d_i is defined as:

$$d_i = \frac{\sigma_{i1} \cdot \sigma_{i2}}{\sigma_{i1} + \sigma_{i2}} \cdot \left(\frac{m_{i1}}{\sigma_1} + \frac{m_{i2}}{\sigma_2} \right).$$

When using the precision turntable the rotation angles δ_{xP} and δ_{yP} are given to the plane P. The turntable does not allow to give d_{zP} errors so this parameter is not identified. The procedure is carried out in less than 8 minutes. The identified parameters are shown in table 1.

These results show that with the proposed procedure, δ_x, δ_y, θ_{1off}, θ_{2off}, θ_{3off} may be accurately identified. The worst parameter accuracy is ± 0.17° for δ_x, δ_y and ±0.31° for the offsets.

M	δ_{xP} ° nominal	δ_{yP} ° nominal	θ_{1off} ° nominal	θ_{2off} ° nominal	θ_{3off} ° nominal	δ_{xP} ° identified	δ_{yP} ° identified	θ_{1off} ° identified	θ_{2off} ° identified	θ_{3off} ° identified
49	0	-1	0	0	0	0.03	1.11	0.11	-0.18	0.12
121	-1	0	0	0	0	-1.12	-0.05	0.07	-0.13	0.13
49	1	0	0	0	0	1.12	0.12	0.16	-0.14	0.28
121	0	2	0	0	0	-0.17	1.91	0.12	-0.17	0.23
121	-2	0	0	0	0	-2.07	-0.12	0.26	-0.19	0.27
121	-0.5	1	0	0	0	-0.41	1.07	0.09	0.04	0.22
121	0	0	2	-1.5	-2	-0.07	0.12	2.18	-1.39	-1.84
121	0	0	2	2	0	0.11	0.07	1.76	1.82	0.12

Table 1: Experimental results for δ_x, δ_y, θ_{1off}, θ_{2off}, θ_{3off}

e) Identification of d_x, d_y, δ_z, (θ_{1off}, θ_{2off}, θ_{3off})

The plane P is oriented in such a way that $\delta_{xP}=\delta_{yP}=0$; no offsets are introduced in the robot controller. So using the first procedure, the real values of the robot parameters δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off} are computed. Then d_{xP}, d_{yP}, d_{zP} are given to the plane P where 8 cylinders are plugged uniformly on the circle C_k whose radius is 200 mm. The procedure is run in less than 15 mn, then using δ_x, δ_y, d_z, θ_{1off}, θ_{2off}, θ_{3off} identified with the first procedure the parameters d_x, d_y, δ_z are computed . Experimental results are shown in table 2. Here again, they validate the proposed procedure.

d_{xP} mm nominal	d_{yP} mm nominal	δ_{zP}° nominal	d_{xP} mm identified	d_{yP} mm identified	δ_{zP} ° identified
0	-1	0	0.13	-1.13	-0.05
0	2	0	0.06	2.08	-0.04
2	3	0	2.16	2.89	0.00
2	-5	-1	2.07	-4.87	-0.96
-2	-3	0	-1.86	-3.09	0.02
-3	4	1	-3.07	3.97	1.16
5	3	3	4.95	2.78	2.82
2	-1	0	1.87	-1.13	-0.03
-5	-3	0	-5.20	-3.06	0.07
1	-1	1	0.82	-1.12	1.01

Table 2 Experimental results for d_x, d_y, δ_z

8 Conclusion

We have developed a two stage calibration method to identify on one hand the offsets on the three first joints of the parallel robot Delta 4 and on the other hand the robot registration in the environment. This procedure is well suitable for Delta 4 robot but it may be used for other structures. It is easy to implement on the shop floor. It involves an inexpensive displacement sensor.

Intensive simulations have been performed to evaluate the sensitivity with respect to the sensor location errors, the measurement number and the measurement noise. They show that identification procedure is robust with respect to these variations. Experimental results validate these procedures. Current works concern the optimization of these procedures in terms of accuracy.

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