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1 Introduction

Due to the inaccurate mechanical parts of the robot and imprecise mounting, the robot kinematics parameters have to be calibrated to improve the precision of the end effector positioning. In CloPeMa project two independent calibrations were performed, first using RedCam [7, 2, 5] and second using Leica Laser Tracker (LT) [1]. From calibration data the robot dimensions were computed [6, 3]. The goal of this report is to evaluate the precision of calibrations.

2 Calibrated Dimensions

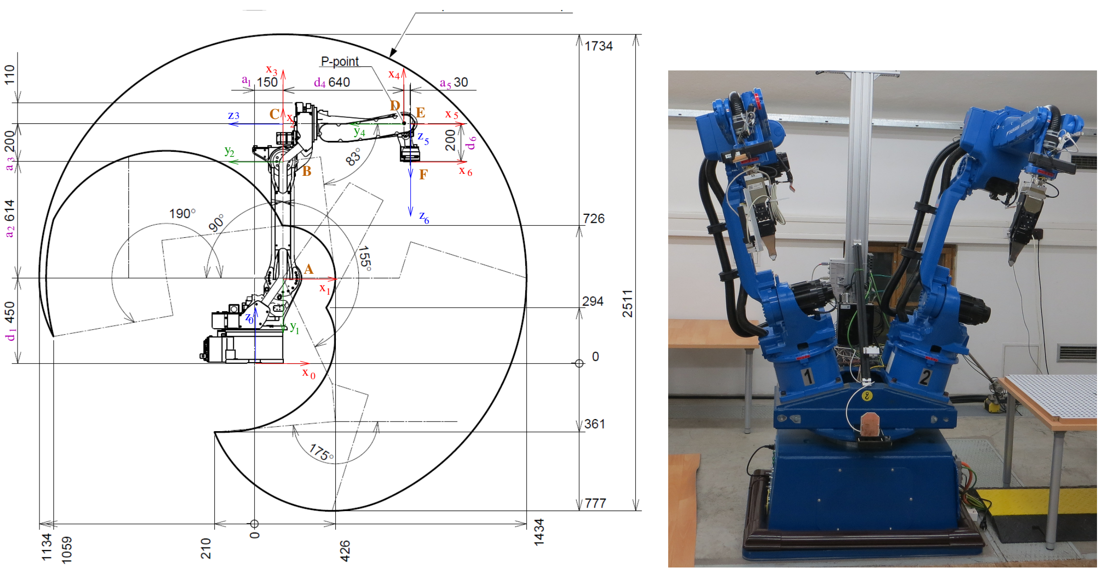

Figure 1: Frames of the arm and photography of the real robot

Uncalibrated (CAD) and calibrated (RedCam, LT) kinematics parameters are shown in the following tables. Each table contains 6×4 Denavit-Hartenberg (DH) parameters [4]

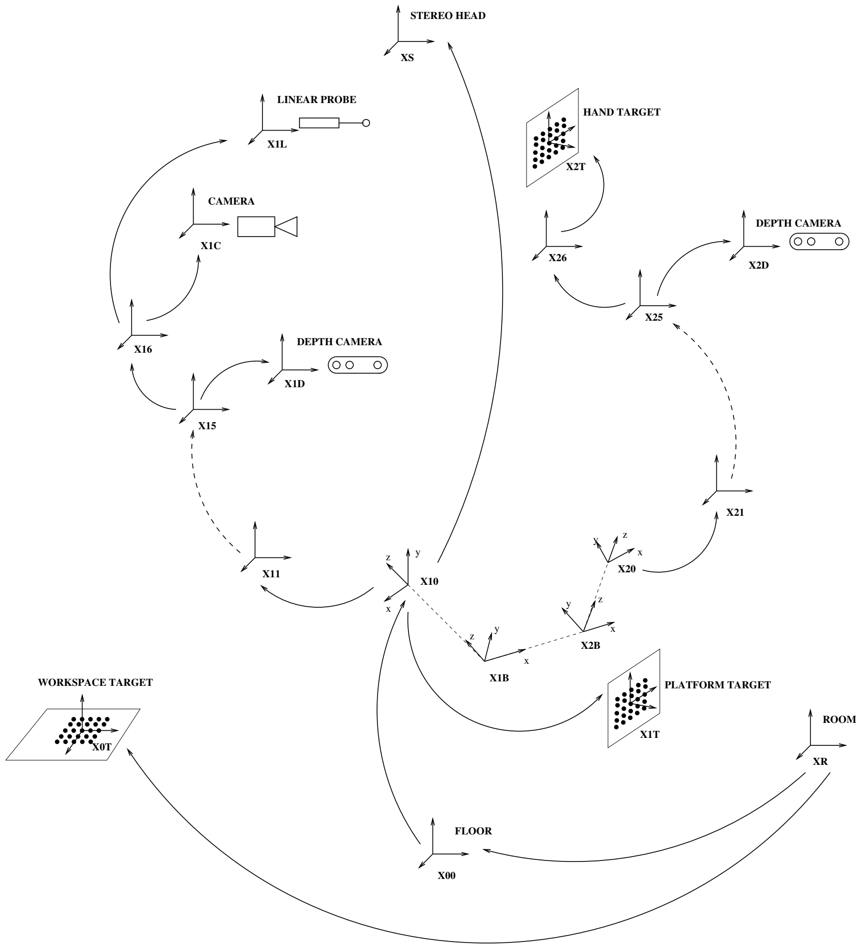

Figure 2: Frames of the robot with the calibration tools

for each of two arms. Additionally, each calibration contains two transformations which represent the mounting of the arms on the turntable.

First Arm				Second Arm			
$\boldsymbol{\theta}$	**d**	$\boldsymbol{\alpha}$	**a**	$\boldsymbol{\theta}$	**d**	$\boldsymbol{\alpha}$	**a**
0.000	450.000	-90.000	150.000	0.000	450.000	-90.000	150.000
270.000	0.000	180.000	614.000	270.000	0.000	180.000	614.000
0.000	0.000	-90.000	200.000	0.000	0.000	-90.000	200.000
0.000	-640.000	90.000	0.000	0.000	-640.000	90.000	0.000
270.000	0.000	90.000	30.000	270.000	0.000	90.000	30.000
0.000	200.000	0.000	0.000	0.000	200.000	0.000	0.000

Table 1: CAD DH parameters [mm, deg]

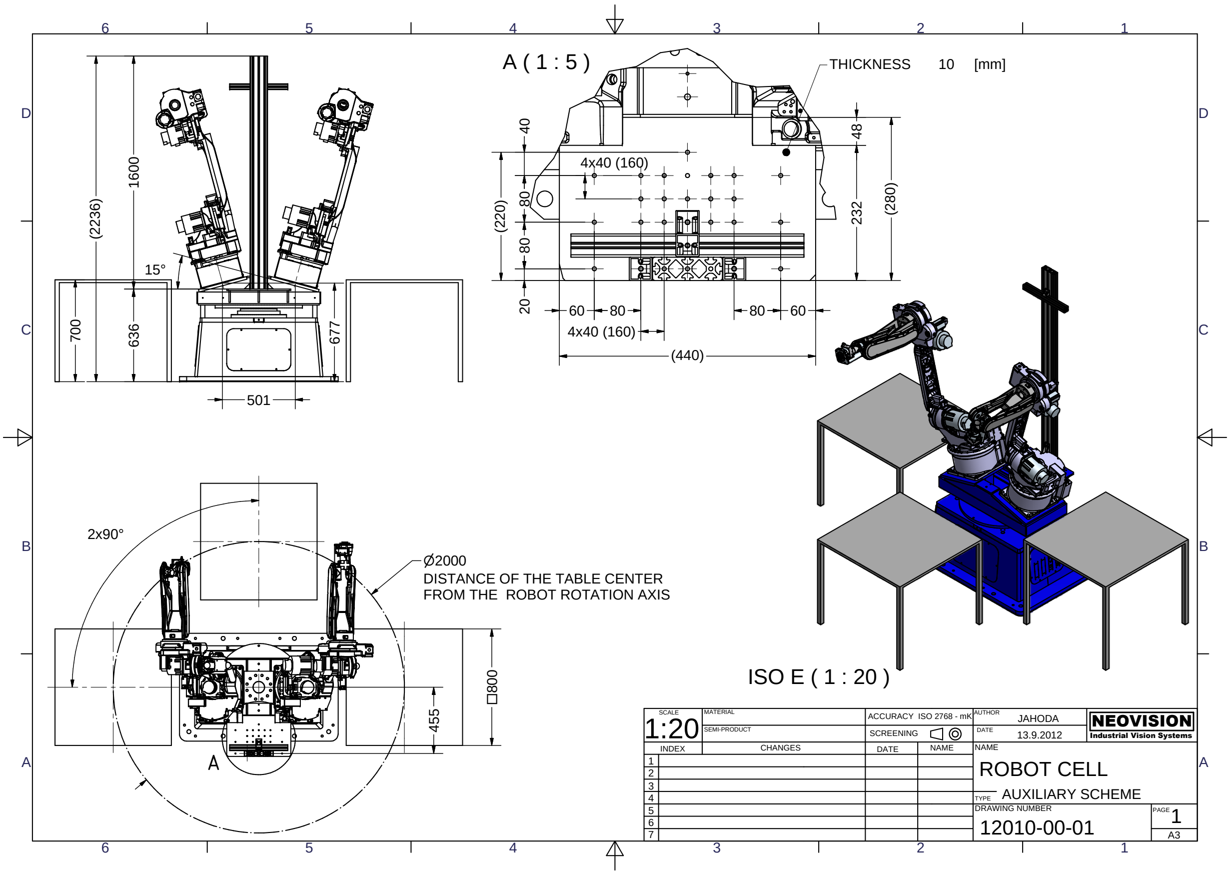

Figure 3: The arrangement of the CloPeMa robot in the lab

	First Arm			Second Arm		
XYZ	0.000	-250.000	160.000	0.000	250.000	160.000
RPY	15.000	0.000	0.000	-15.000	0.000	0.000

Table 2: CAD arms on table mounting [mm, deg]

First Arm				Second Arm			
$\boldsymbol{\theta}$	**d**	$\boldsymbol{\alpha}$	**a**	$\boldsymbol{\theta}$	**d**	$\boldsymbol{\alpha}$	**a**
0.000	450.000	-89.993	149.005	0.000	450.000	-89.997	148.969
270.122	3.746	179.980	614.810	270.053	8.254	180.030	614.872
0.007	4.168	-89.899	200.928	-0.053	9.085	-89.983	200.811
-0.020	-639.716	90.003	-0.676	-0.007	-640.015	90.026	-0.534
269.826	0.725	90.085	30.761	270.035	1.044	90.153	29.954
0.000	200.000	0.000	0.000	0.000	200.000	0.000	0.000

Table 3: LT DH parameters [mm, deg]

	First Arm			Second Arm		
XYZ	0.000	-250.000	160.000	-1.106	248.559	159.715
RPY	15.011	0.000	0.000	-15.017	-0.054	0.006

Table 4: LT arms on table mounting [mm, deg]

First Arm				Second Arm			
$\boldsymbol{\theta}$	**d**	$\boldsymbol{\alpha}$	**a**	$\boldsymbol{\theta}$	**d**	$\boldsymbol{\alpha}$	**a**
0.000	450.000	-89.993	149.005	0.000	450.000	-89.997	148.969
270.122	3.746	179.980	614.810	270.053	8.254	180.030	614.872
0.007	4.168	-89.899	200.928	-0.053	9.085	-89.983	200.811
-0.020	-639.716	90.003	-0.676	-0.007	-640.015	90.026	-0.534
269.826	0.725	90.085	30.761	270.035	1.044	90.153	29.954
0.000	200.000	0.000	0.000	0.000	200.000	0.000	0.000

Table 5: RedCam DH parameters [mm, deg]

	First Arm			Second Arm		
XYZ	0.000	-250.000	160.000	-1.106	248.559	159.715
RPY	15.011	0.000	0.000	-15.017	-0.054	0.006

Table 6: RedCam arms on table mounting [mm, deg]

3 Experiments

To evaluate precision of the calibrations, the linear probe was used. The probe can measure the linear distance with precision up to 1μm. Two experiments were done, first evaluating the relative precision between arms and second evaluating precision of the first arm. In the both experiments the probe was mounted on the first arm so that probe was pointing approximately in the direction of z-axis with respect to the end effector frame. Exact position of the probe was not calibrated and is considered as unknown in the rest of this report.

3.1 Touching Experiment

In the first experiment linear probe was touching the second arm end effector at the various robot configurations. The contact point on the end effector was always the same, but the touching poses were different with respect to global reference frame. The distance between the end effectors was measured by the linear probe.

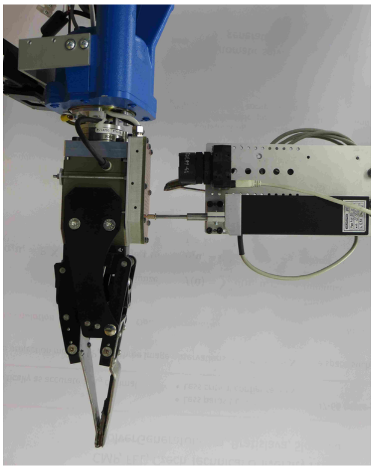

Figure 4: Linear probe in measurement position

Poses Generation Poses were generated on the regular grid in the Cartesian space in front of the robot. Dimensions (in mm) of the grid in x, y, and z axis of the global reference frame were:

$$\begin{aligned}&\big(x,\quad y,\quad z\big)\in\\&\big\{-400,\quad -200,\quad 0,\quad 200,\quad 400\big\}\times\big\{-1300,\quad -1000,\quad -600,\big\}\times\big\{800,\quad 1200,\quad 1600\big\}\,.\end{aligned}$$

For each position on the grid there were three rotations so that the linear probe was pointing in z, y and x axis in global reference frame. Due to the limited robot range and due to the robot self collisions only 43 out of 135 poses were reachable.

Error Vector Computation Using the poses of the robot and the distance which was measured by the linear probe, the error vector size was computed as difference between expected and measured distance. Because the exact position of the linear probe with respect to the end effector is not known, the mean value of the differences will be meaningless. Therefore, only the deviation will be reported here. The orientation of the vector was set to be equal with the orientation of the linear probe. The error vector size computation:

$$\begin{aligned}T_2^1 &= T_{\mathrm{1LT}}^{-1}\,T_{\mathrm{2LT}}\\ \boldsymbol{v} &= T_2^1\begin{pmatrix}0 & 0 & 0 & 1\end{pmatrix}^T\\ |\boldsymbol{err}| &= v_z - l_{LT}\end{aligned}$$

where v_z is z-part of the vector $\boldsymbol{v}$, T_a is transformation from frame a to global reference frame and l_{LT} is the distance measured by the linear probe. Ideally, the transformation T_2^1 is supposed to be constant for each robot configuration. To incorporate possible non zero steady state error of the robot controller, the transformation is computed for each position based on the joint coordinates reported by a robot at the time of linear probe reading.

Comparison of Calibrations Statistical data for the calibrations can be seen in the Table 7 and the graphs with the error vectors are shown in Figures 5, 6 and 7.

CAD		**LT**		**RedCam**	
σ	range	σ	range	σ	range
0.666891	2.917386	0.539572	2.553577	2.453668	9.915636

Table 7: Statistical data for the distance between the end effectors [mm]

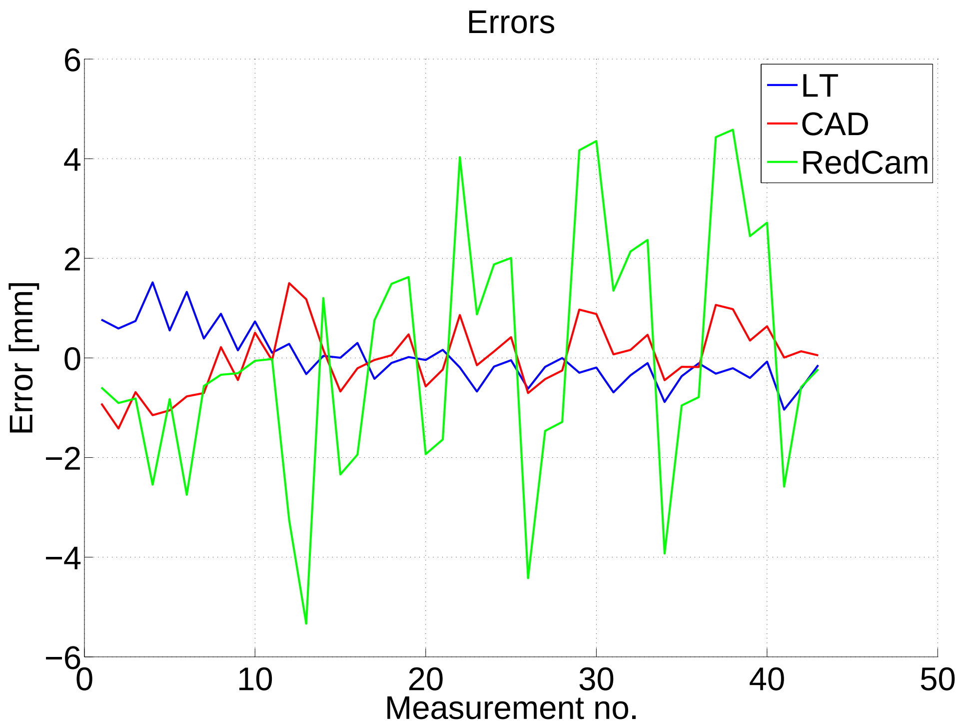

Figure 5: Touch errors

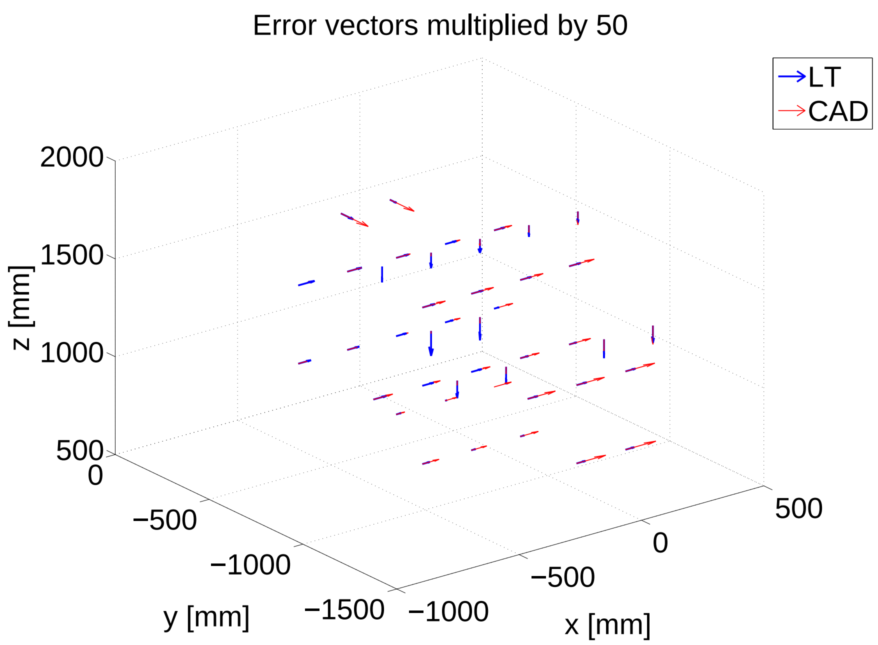

Figure 6: Touch error vectors LT vs. CAD

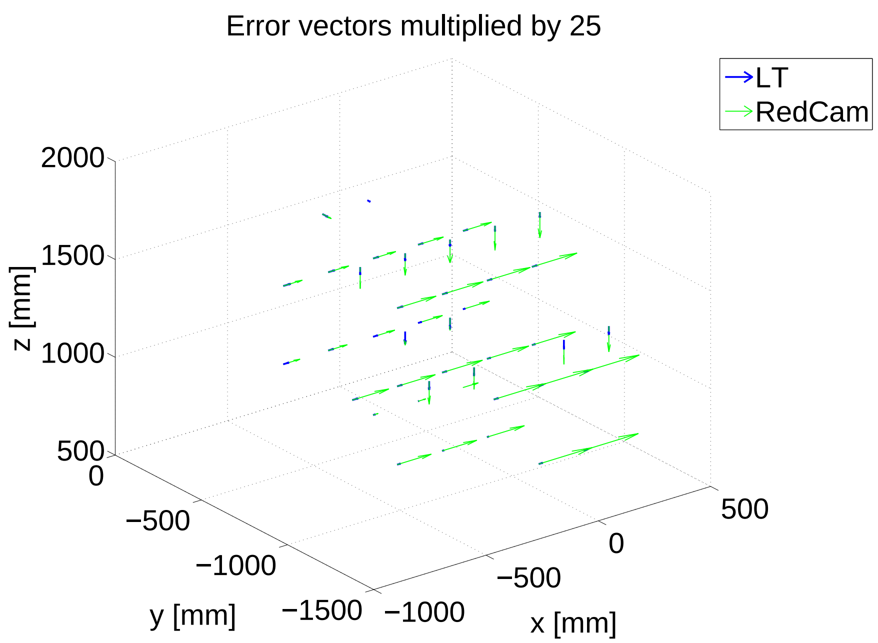

Figure 7: Touch error vectors LT vs. RedCam

3.2 Planar Experiment

The second experiment evaluate the precision of the first arm by touching flat table at the various positions. The flat table is shown in Figure 9 and the touching positions are shown in Figure 10. The measured distance is subtracted from the end effector height for each measured position and plane is fitted to the points. Errors are computed as distance to the fitted plane, results are shown in Table 8 and in Figure 8.

CAD		**LT**		**RedCam**	
σ	range	σ	range	σ	range
0.037681	0.096243	0.034207	0.086391	0.043160	0.106901

Table 8: Statistical data for distances from the table [mm]

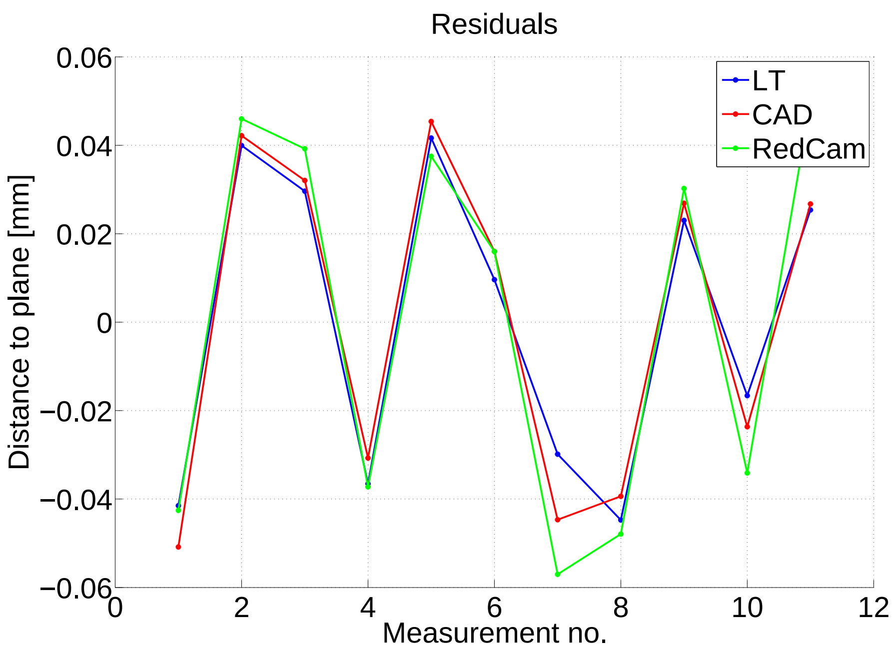

Figure 8: Residual errors for table experiment

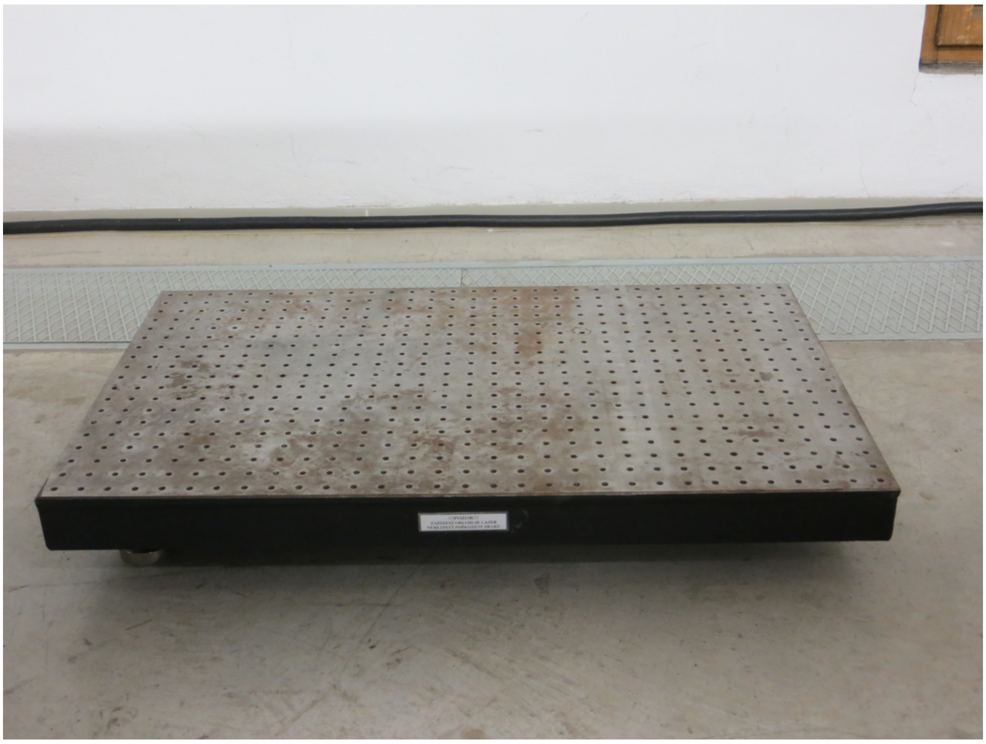

Figure 9: Flat table

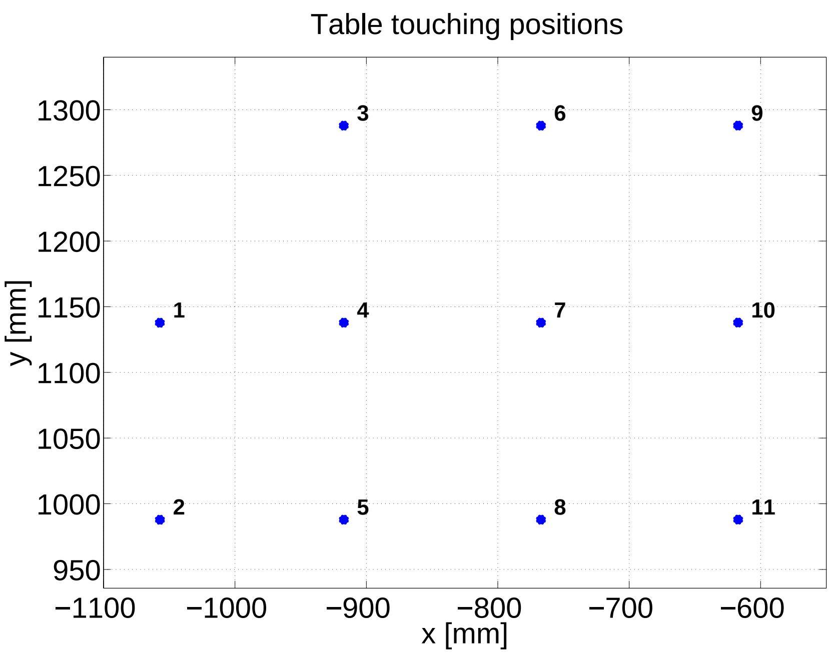

Figure 10: Table touching positions in global reference frame

3.3 Repeatability

Another important property of robots is the repeatability. Repeatability describe the ability of robot to reach the same position repeatedly. To evaluate repeatability of CloPeMa robot the first arm was touching the flat table 9 at the same position. The touching was done by following the straight line trajectory of length 320 mm perpendicular to the table surface. Touching was done 50 times and the linear probe was used to measure the distance between end effector position and the table. After robot reached the measurement position it wait for a second and the mean value was computed from measurements during this period. The computed mean values as well as original measurements are shown in Figure 11. The standard deviation computed from the mean values is 0.0097 mm and the range is 0.04081 mm.

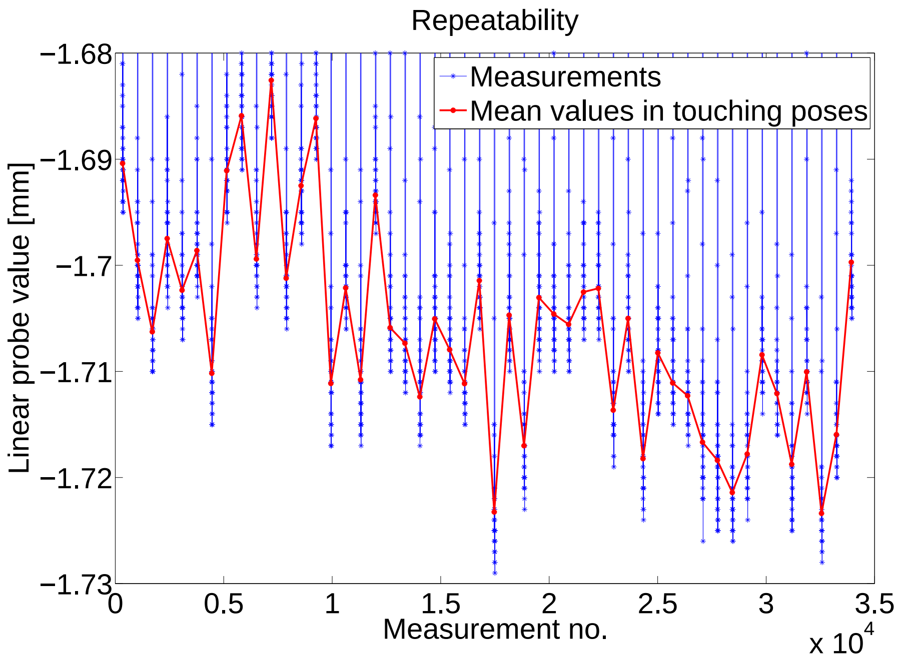

Figure 11: Repeatability measurements

4 Conclusion

The calibrated dimensions were compared to the CAD dimensions. Two experiments were done to compare the calibrations of the robot. Computed statistical data shows that the RedCam calibration achieves worse result. On the other hand, the laser tracker calibration improves precision of the robot at least at the measured positions. The results are shown in Tables 7 and 8.

Even though the precision of the end effector was improved by the calibration, the CAD dimensions seems to be precise enough for the garment manipulation and thus mechanical calibration of the robot is not necessary.

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