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Characterization of the positioning accuracy and precision of MEMS die servoing using model-based visual tracking

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Abstract. This work deals with an automated micro-assembly of MEMS die holders using a 3D visual servoing approach. Visual positioning which was used is based on eye-to-hand tracking principle. The 3D poses of the MEMS are supplied in a real-time by a 3D (CAD) model-based tracking algorithm. Having executed the visual servoing the accuracy and repeatability of this method was examined. The micro-assembly process was performed and the accuracy calculated according to ISO 9283. The achieved accuracy was 0.345 μm and repeatability was 4.3 μm . The rotation accuracy was less than 0.13°.

Introduction

This work arose in cooperation with the AS2M department of FEMTO-ST Institute, ENSMM, Besançon, France. This institute manages research activities in the fields of micro-robotics, micro-actuation, automatic control and micro-assembly.

Micro-assembly has been identified to be a critical technology in the microsystems technology and nanotechnology. The increasing need of MEMS / MOEMS (Micro-Opto-Electro-Mechanical Systems) for the microsystems leads to a development of new concepts and skilled micro-assembly stations. Several micro-assembly platforms have been developed allowing the assembly of components smaller than few tens of micrometers. This is more in detail described in [1] and [2].

Despite numerous work done, achieving controlled micro-assembly task still remains extremely challenging due to difficulties connected with this task, such as the limitation of vision based control, components fragility, complex trajectory to control with extremely good accuracy etc. Very few works deal with the quantification of positioning accuracies after assembling at the micro-scale.

Considering the operations in the macro-world, conventional robotic assembly rely on accurate robots that provide back recorded motions. However, this form of open-loop manipulation is not suitable to the micro-scale. The precision requirements are much higher and the technique of manipulation is different. So, the closed-loop is a good solution to automate MEMS assembly processes essentially using vision-based control. Vision feedback control might also be combined with force control [3], [4] and [5].

The first section describes a task specification. What the objective was and a summary of input parameters. The second section deals with the actual experiment. The last section summarizes obtained results in conclusion.

Task specification

Objectives. The first objective of the proposed work is to achieve automated assembly of MEMS holders of optical components. These dies are shown in fig. 1a as CAD model. Fig. 1b shows the actual acquired image of the holder. Outer dimensions of the holder are 1.2 x 0.8 x 0.05 mm. The main part of the work consists in the tracking of the object. This means to follow the position of the object in the camera frame. The goal is realized on a micro-assembly station and with a use of C++ programming code and ViSP and OpenCV third party libraries.

The second main objective of the work consists in quantifying the positioning accuracy and repeatability obtained after assembling.

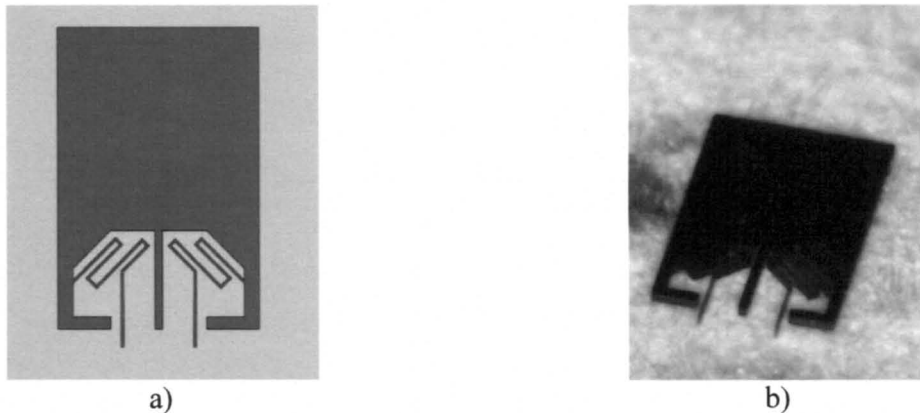


Fig. 1 MEMS die holder a) CAD model, b) acquired image

The workplace. Tracking of the micro-scaled models brings few difficulties, which are connected with the micro size. The most notable one is the influence of vibration. To avoid this, the actual working setup (fig. 2) was placed onto an anti-vibration table. The workplace consists of the micro positioning stage with three degrees of freedom (two translations x , y and a rotation θ), camera with illumination, computer evaluating the position of the object and computer controlling the PI micro-positioning stage.

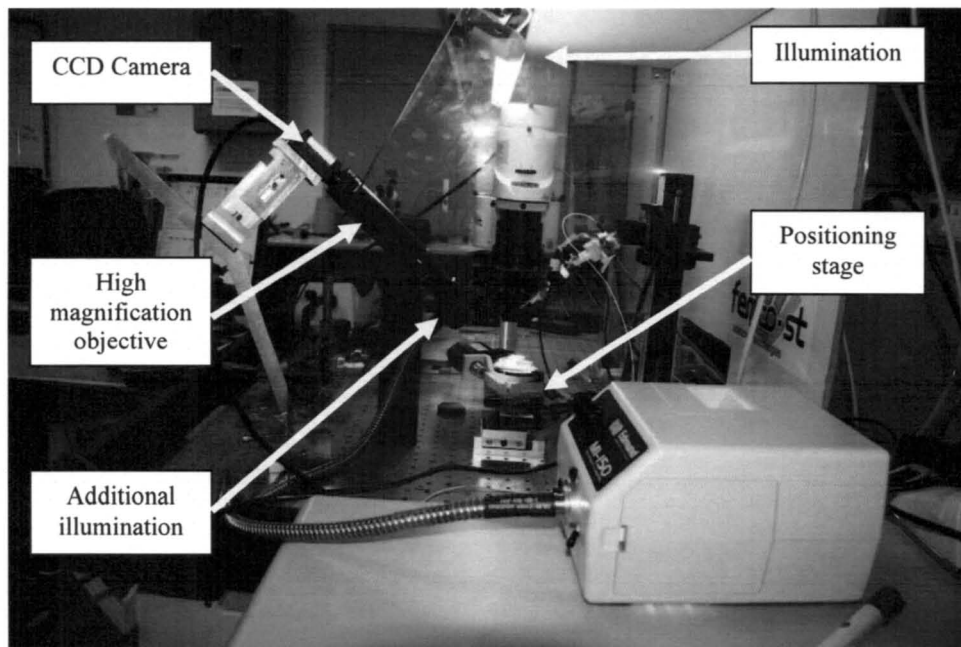


Fig.2 Working setup

Model-based tracking script. There are various approaches in object tracking problematic. Used library disposes of several types of trackers. The basic blob detection, line (edge) detection and more sophisticated 3D model based tracker. The possibilities are described more in detail in [6].

The 3D model based tracker (3DMBT) allows the tracking of the position of the 3D object in the scene by calculating the pose between the camera and the objects [7], [8]. Here, non-linear pose estimation is formulated by means of a virtual visual servoing approach. This tracker is based on line tracking. It uses a pre-defined virtual model. This model is saved in cao or wrml file and it consists of points (corners) and lines (edges). However, for more complicated shapes it is possible to alternatively add circles or ellipses. Once the camera is calibrated, these are aligned with object's edges and the position of the object is subsequently monitored. A local moving edges tracker is used in order to provide real-time tracking of points normal to the object contours. Robustness is obtained by integrating an M-estimator into the visual control law via an iteratively re-weighted least squares implementation [9].

Camera calibration. Functionality of the 3DMBT is dependent on a proper camera calibration. This consists in defining of its intrinsic parameters. Knowing of these inner camera parameters allows us to accurately determine the position in space using one camera only. These intrinsic camera parameters are p_x , p_y , u_0 and v_0 . The calibration problematic is more in detail described in [10] and [11].

u_0 : This parameter corresponds to the horizontal coordinate in pixel of the principal point

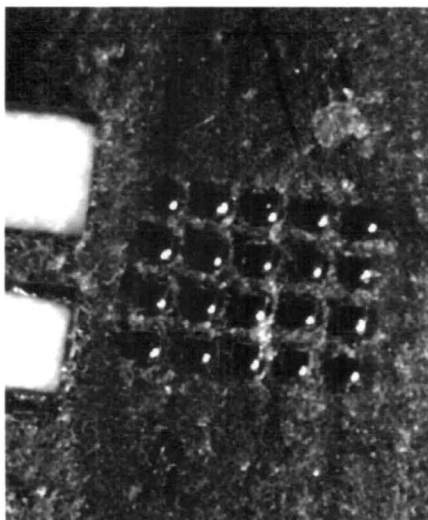
v_0 : This parameter corresponds to the vertical coordinate in pixel of the principal point.

p_x : This parameter corresponds to the ratio between the focal length and the size of a pixel along the x axis.

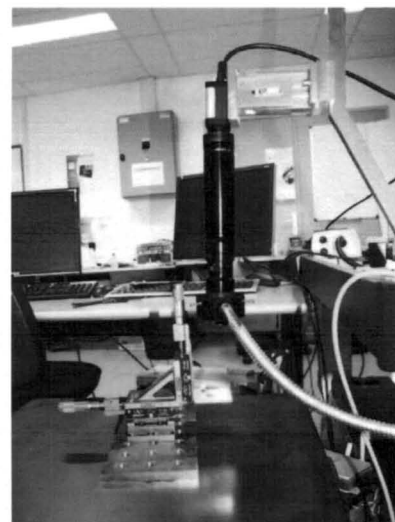
p_y : This parameter corresponds to the ratio between the focal length and the size of a pixel along the y axis. If the pixels are square, $p_x=p_y$.

The tracker is not able to consider the intrinsic camera distortion parameters. If the distortion has to be considered, the images need first to be undistorted before the tracking is applied. There are more ways how to get these parameters for camera calibration. The easiest is to use one of prepared toolboxes for Visp or Matlab. For our case, Matlab calibration toolbox was used.

Calibration of a camera with such a big magnification brings a really difficult task. The micro-pattern with square-shaped wholes was used. As the field of focus for used objective is very low, it was impossible to calibrate the camera in the setup position. For this reason the camera was placed vertically (fig. 3b) and the pattern was moving with use of fine manual positioning stage. Matlab toolbox was used for subsequent image processing.



a)



b)

Fig. 3 a) Calibration pattern, b) Calibration of the camera with big magnification objective

Tracking of the MEMS holder. Several virtual models were created. These models are projected onto the acquired image. The tracker needs also an initial pose of the object in the camera frame. This pose initialisation requires a human click interaction. In this case, the 3D coordinates in the object frame of at least four points are required [9]. These specific points are defined in a file with .init extension. Usually these are visible corners. The clicking must not be really exact; once the virtual model is projected and confirmed it also checks the surrounding of the line.

Knowing the intrinsic parameters from camera calibration is essential for the projection. These parameters are read from the XML config file or their definition may be implemented into the code. Virtual edges are afterwards aligned with those actual ones so the virtual model is aligned with the real object. This process allows the holder's real position detection. Described situation is shown on figure 4.

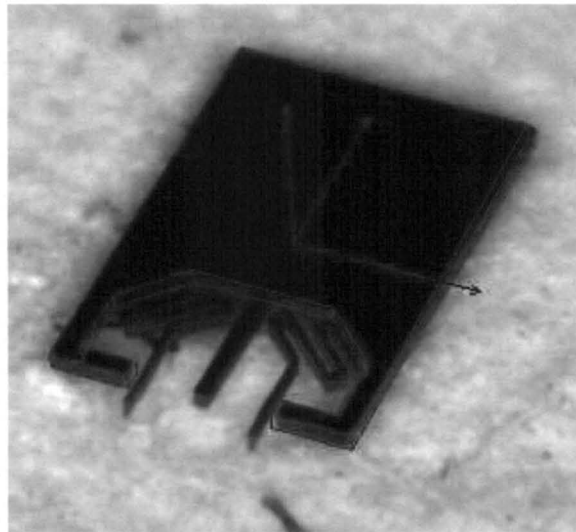


Fig. 4 Virtual model aligned with the real object

Boundary conditions for robust tracking. There are few parameters that are possible to be changed in a script in order to get higher precision of the tracking. These parameters are dependent on boundaries and may differ for each situation.

Therefore, mentioned parameters are the speed of the movement, suitable illumination, field of focus, frame-rate of the camera. Different speed was tested to determine the maximum speed when the tracker is still robust. The achieved value was $60 \mu\text{m/s}$ for both translations and $2^\circ/\text{s}$ for a rotation.

The system is very sensitive for a proper illumination. If there are shades of the object in the image, this can be evaluated as a part of the object and it might cause the inaccuracy of the measurement. In our case the intensive ring illumination was used together with the flat dispersed light of the working table.

It is also important to have the light condition stable as the tracker works with point intensities. For this purpose every camera automatic function (such as white balancing or automatic computing of a gain and shutter) was prohibited in software. Gain was manually set to 0 and shutter to maximum.

The field of focus is a problem connected with acquiring of micro scaled images. Unfortunately used objective didn't have a control of diaphragm, so additional diaphragm was made and mounted on the objective in order to increase the field of focus. Finally the field of view where it was possible to track the holder was $4 \times 2.5 \text{ mm}$.

Positioning using the visual servoing. Defining of stable conditions was necessary for holder tracking. Another part of the task was to implement a visual positioning and afterwards to measure the positioning accuracy. The process of visual positioning is based on the tracking algorithm. The

holder is placed manually into the desired position. This is done by joystick connected to a controlling computer. This position is then saved in a script by clicking in the image, the same procedure as for initialization of the tracking. Once the desired position is saved it is possible to start the positioning from any other place. Of course the holder must be visible.

After the determination of an initial position the algorithm calculates the error between the current and desired position. This is done separately for each axis. This information is send to a controlling computer and axes are adjusted by calculated differences. The positioning process is performed on-line in a loop; the object is positioned continually in a real time. In the fig. 5 there is the tracked holder (framed red) and saved desired position is projected as a cyan frame.

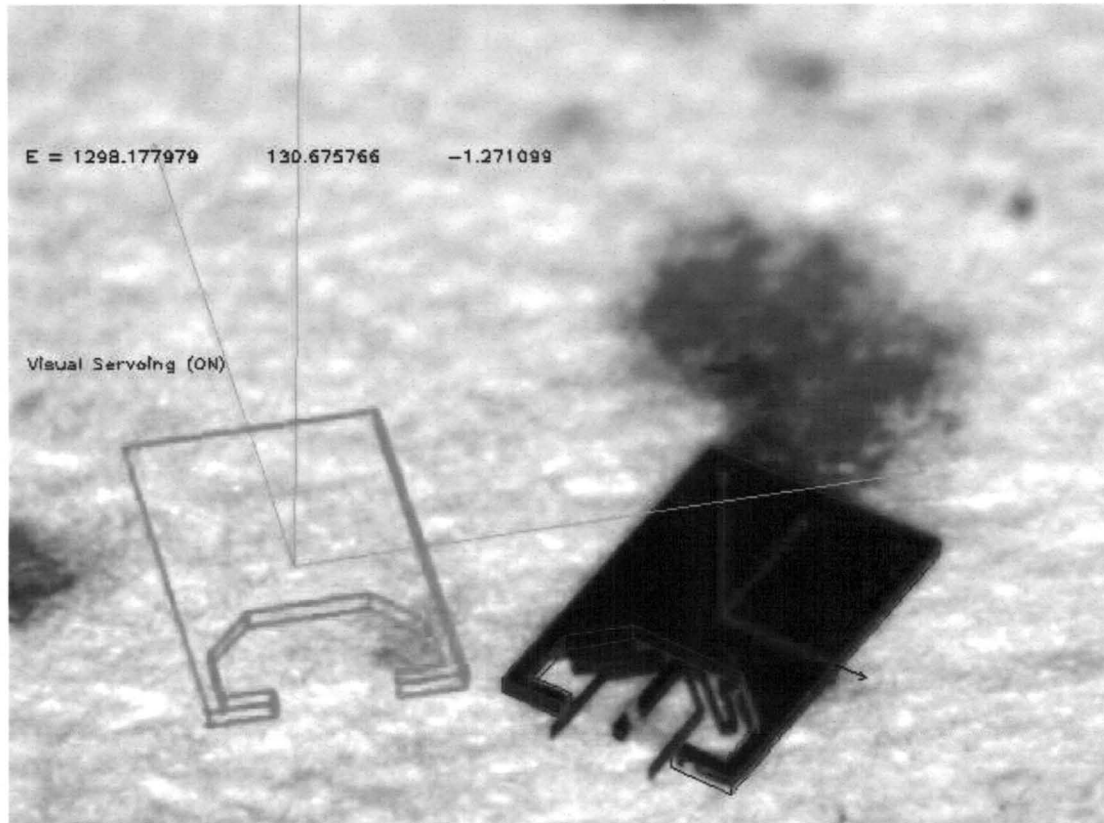


Fig. 5 Positioning of the holder

Experiment

Several measurements were done in the aim to measure the tracking accuracy and the repeatability of the process. The program ran in a loop. It moved the holder into a pre-defined position. After the tracker was initiated, the automatic control moved the holder into desired position. Once it reached the desired position, the program was stopped and run again from the beginning. This was executed twenty times to obtain suitable data. Graphs attached on figures 6, 7, and 8 show the behaviour of movement in each axis. It shows the distance change of the initial and desired position for each axis separately. There is always the whole run displayed and then subsequently there are last 25 loops (approx. 4s) displayed on a following picture.

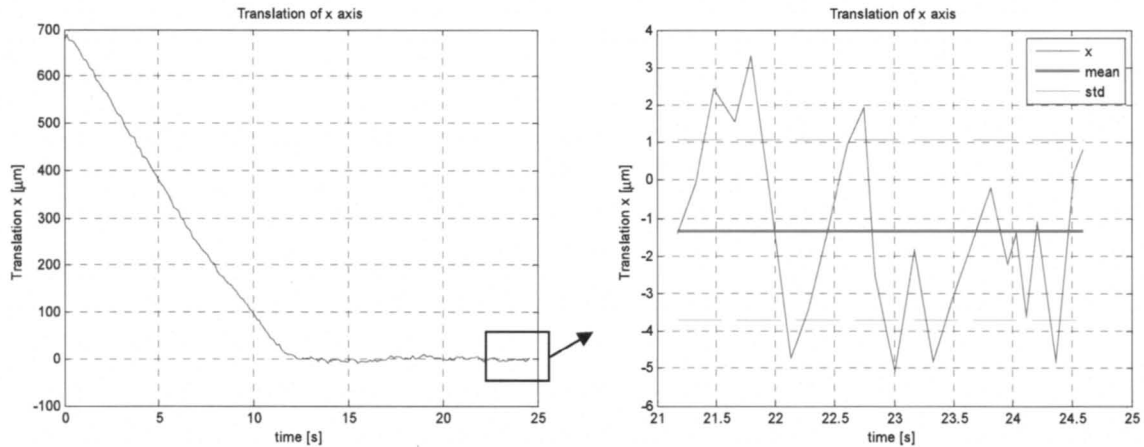


Fig.6 Graph of translation behaviour in x axis and a detail after reaching the desired position

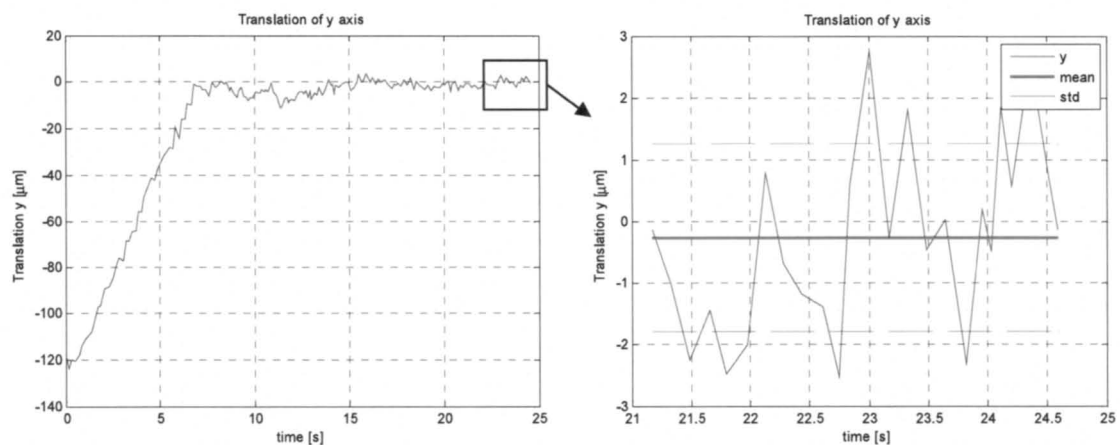


Fig.7 Graph of translation behaviour in y axis and a detail after reaching the desired position

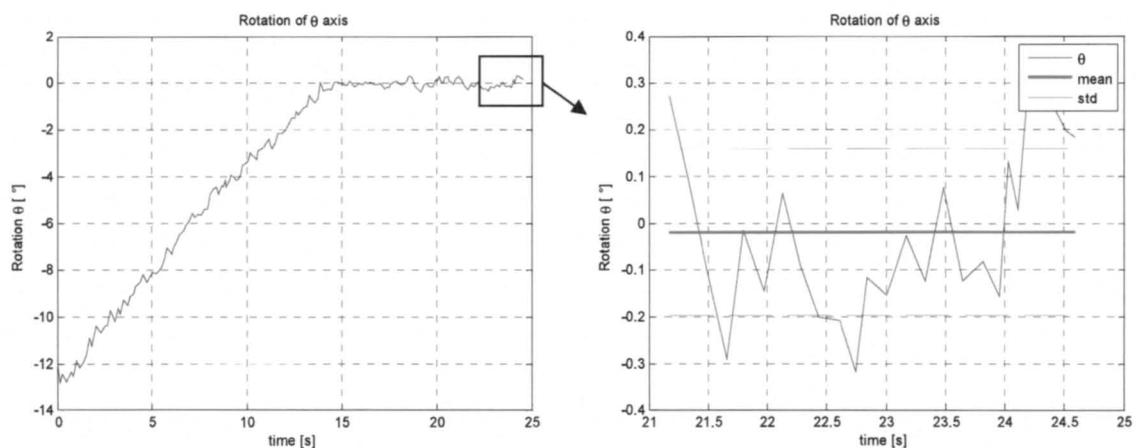


Fig.8 Graph of rotation behaviour in θ axis and a detail after reaching the desired position

After reaching the desired position, data from last 25 loops (approximately 4 seconds) were processed. Mean, standard deviation and mean squared errors were calculated from 20 following runs. Table 1 shows the average and maximum value of mean, standard deviation and mean squared error for each axis (x , y and θ). Moreover, mean and standard deviation are shown in graphs as well.

The translation units had the average value of accuracy approx. $1 \mu\text{m}$ for the x -axis and y -axis. Rotation seems to be very precise; the value of mean was 0.13° .

Table. 1 Average and maximum values of reference parametres

	axis x [μm]		axis y [μm]		axis theta [$^\circ$]	
	average	max	average	max	average	max
Mean	1.077371438	2.9899306	1.059526895	2.884914	0.039949132	0.130752
Std	2.232135429	3.08411119	1.634023627	2.32867403	0.157026351	0.23005349
Mse	6.980092659	17.4976847	4.26196805	11.08192568	0.028145811	0.05084475

The accuracy and repeatability of the positioning was afterwards also evaluated according to the ISO 9283:1998 Norm for Industrial Robots (Manipulating industrial robots - Performance criteria and related test methods). The distribution of reached positions is shown in fig. 9. The accuracy AP was then calculated according to a norm:

$$AP = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2} , \quad (1)$$

where x_c, y_c are the coordinates of desired pose, in our case $[0,0]$, and \bar{x}, \bar{y} are:

$$\bar{x} = \frac{1}{n} \sum_{j=1}^n x_j , \quad \bar{y} = \frac{1}{n} \sum_{j=1}^n y_j , \quad (2)$$

x_j and y_j are coordinates of reached position, n is a total count of measurements. Repeatability RP was calculated as:

$$RP = \bar{l} + 3Sl ; \quad (3)$$

$$\bar{l} = \frac{1}{n} \sum_{j=1}^n l_j ; \quad (4)$$

$$l_j = \sqrt{(\bar{x} - x_j)^2 + (\bar{y} - y_j)^2} ; \quad (5)$$

$$S_l = \sqrt{\frac{\sum_{j=1}^n (l_j - \bar{l})^2}{n-1}} . \quad (6)$$

$x_j, y_j, \bar{x}, \bar{y}$ are values already used in the accuracy calculation.

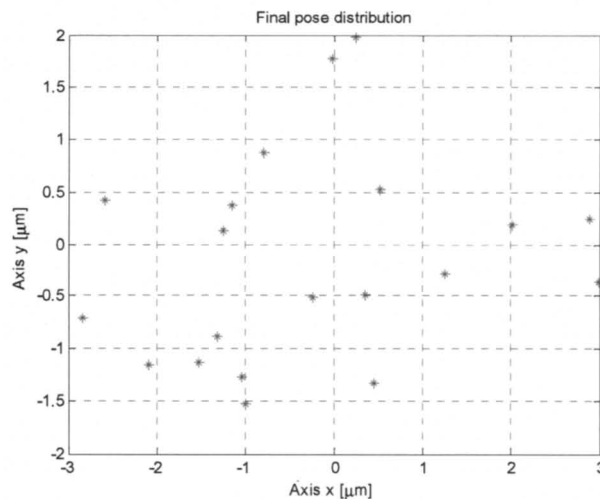


Fig.9 Graph of reached pose distribution

The accuracy and repeatability was computed according to a mentioned norm. Twenty independent trials were executed. The calculated accuracy was $0.345 \mu\text{m}$. The repeatability was determined to $4.3 \mu\text{m}$.

Conclusion

This work deals with the visual positioning of MEMS die holders. The positioning is based on C++ programming with a use of the 3D model based tracking offered by ViSP third party library. The positioning was executed in three dimensions, micro stage with two translations and a rotation was used. An experiment was executed in order to measure the accuracy of the tracking. The accuracy of reaching the desired position was examined. In this case motion of the die holder was executed always from the same initial and to the same desired position. The accuracy according to ISO 9283 was $0.345\ \mu\text{m}$ and repeatability was $4.3\ \mu\text{m}$. The rotation accuracy was less than 0.13° . The accuracy might be increased by proper calibration of camera or by a use of camera with higher resolution. Better objective would allow following bigger field of view.

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