Characterization of Repeatability of XY-Theta Platform Held by Robotic Manipulator Arms using a Camera

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Abstract: This paper presents a XY-Theta micrometric platform, which is extremely compact and offers a wide 300 x 300 mm workspace. This platform is held by a serial kinematic chain of four revolute joints, constituting a redundant robot. Each point of the horizontal platform can be positioned under a vertical axis in a two-step approach: in a coarse positioning mode, the four axes are controlled to position and orientate the object with a position error less than 7 μm; in a fine mode, two axes are mechanically blocked while two others are controlled to reduce the final position error below 2 μm. The choice of the blocked and moving axes depends on the lever arm length and the mechanism is designed to optimize the link lengths to reduce the final position error. The aim of the paper is to characterize the platform repeatability performances. An estimation of the repeatability is performed with a camera. These results are then compared to previous results based on the stationary cube method. The two measurements methods lead to similar results with a repeatability close to 2 μm showing a significant improvement of the performances.

1 INTRODUCTION

Choosing and designing the adequate robot to perform a task is not easy. Manufacturers provide some performance criteria such as payload, workspace dimensions, acceleration and repeatability. Most manufacturers advertise that their robot repeatability performances are close to 10 micrometers. These performances are generally sufficient to meet most industrial requirements, but it seems that they are difficult to improve as far as serial robots are concerned. Some authors claimed that parallel robots could do better (Merlet, 2006),(Rauf et al., 2004),(Briot and Bonev, 2007) but for the few industrial parallel robots on the market, the repeatability performances are not better and the best repeatability is close to 5 μm. For the XY-Theta platform hold by a parallel robot built in (Joubair et al., 2012), the repeatability performance is estimated between 3 and 30 μm depending on the workspace location.

The estimation of industrial robot precision is based on a test where the robot is set up to attain a desired point and come back, this cycle being repeated several times in the same conditions. Measurements of the final robot positions show that they are near the desired point and all the final positions constitute a cloud of points. Precision is then described in accuracy and repeatability as displayed in Fig. 1.

* **Accuracy:** in the ISO procedure (ISO9283, 1998), the distance between the mean of the different final positions and the target position will characterize accuracy. The ANSI definition (Institute, 1990) is slightly different as it considers different locations on a standard path.

* **Repeatability:** the repeatability index estimates the closeness of the different points to the cloud center. Many factors have been suspected to influence repeatability, as speed, load, workspace location, backlash, temperature,... Statistical analysis has been performed to discriminate which factor was the most influent. For example, it was proved that for two 6-axis serial robot studied, the load influence was far less important than the workspace location influence (Brethé and Dakyo, 2002),(Brethé et al., 2006). Riemer and Edan were interested in workspace location influence (Riemer and Edan, 2000), Offodile and Ugwu in load and speed influence (Offodile and Ugwu, 1991). For serial robots with revolute joints, it is now clear that the workspace location is the most important influence factor. The distance between the target and one joint axis can show wide variations in the workspace. The resulting lever arm distance amplifies the joint

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uncertainty.

Industrial solutions to reach high precision require the integration of vision systems to control the robot. But to succeed in the fine positioning, the repeatability performances of the robot must be very good. We developed a planar redundant structure to improve precision performances in X and Y directions. This structure is explained in section 2. In (Brethé et al., 2013), we displayed an innovative XY-Theta platform built in our laboratory that can greatly improve precision in the whole workspace. This platform will be described in section 3. The repeatability of this platform was then measured using a hardened steel cube attached to the vertical axis and one trihedron supporting two Mitutoyo micrometers, fixed on the platform. It was based on the stationary cube method. This method has though a disadvantage: the mechanical contact between the Mitutoyo micrometers and the cube can disturb the measurements. The goal of this paper is to avoid this problem by estimating the platform repeatability with a camera. When using the camera, any short or long trajectory could be realized in the workspace which is not the case when using the Mitutoyo micrometers. The procedure is based on the position estimation of an object lying on the platform. The vision system and the steps necessary to use the vision system as a metrological tool are described in section 4: autofocus setup, camera calibration, image acquisition and processing through the geometric model finder toolbox of the Matrox Imaging Library. In section 5, the platform's repeatability performances are measured in coarse and fine mode and the results obtained with the vision system are compared to the stationary cube method. The conclusions are presented in section 6.

2 INNOVATIVE DISSYMETRICAL 3-LINK ROBOT

2.1 Artificial Isotropy Point

Our laboratory (GREAH) owns a patent of a 3-link special redundant manipulator designed to obtain high precision performances in X and Y directions (Brethé, 2009). This innovative robot is presented in Fig. 2. It consists of a 3-link serial kinematic chain with three revolute joints. The 1st link length is 30 mm and the 2nd and 3rd link lengths are 120 mm. This robot is designed to achieve fine positioning near a specific point in the workspace. This specific point will be named PI "point of interest". The procedure used to obtain the high precision performances is the following:

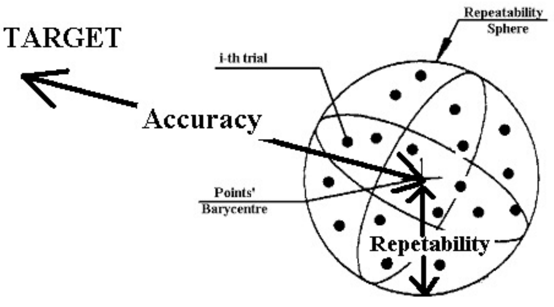

Figure 1: ISO approach of accuracy and repeatability.

- a fine positioning is demanded around this point, so the final precision must be fine in two orthogonal directions. This could be done using two revolute joints whose rotation centers are as close as possible to PI. In Fig. 2, it corresponds to the 1st and 2nd axes. Doing so, an isotropy point is artificially created in PI.
- To enlarge the workspace, it is necessary to add a third axis. Consequently, the robot is able to grasp an object in a wider area.

Let us study the precision performances. In the design stage, it is considered that the repeatability and the resolution of the revolute axes are in the same order of magnitude. For instance, the granularity ratio τ of the axes is set to $\tau = \frac{\sigma}{\Delta} = \frac{1}{6}$ where σ is the standard deviation of the Gaussian distribution of the angular position and Δ is the axis resolution. Considering the robot structure, the repeatability in PI depends on 3 axes. The third axis angular uncertainty is amplified by the third link length. In Fig.3, the blue hexagon is the uncertainty area characterizing the repeatability when the 3 axes are controlled and the red square is the uncertainty area when the 3rd axis is blocked and only the 1st and 2nd axes are moving. The hexagon is much larger than the square. More details can be found in (Brethe, 2010). The idea is then to propose an innovative control strategy based on a coarse and a fine mode.

2.2 Coarse and Fine Mode

The control strategy consists of two steps: in a first step, the robot endpoint is brought close to the desired target PI using the three axes. Then the 3rd axis is mechanically blocked by means of a brake. The position error is estimated from external sensor information and the new target is computed. In the second step, the robot comes closer to PI using only the 1st and 2nd axes. This fine positioning is still true if the final point moves away from PI but stays near PI. The

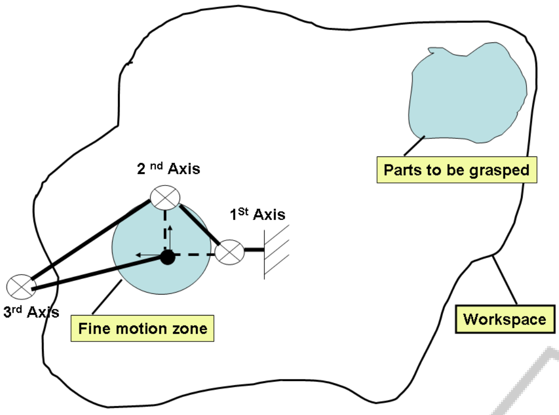

Figure 2: Innovative planar redundant structure SCARA3

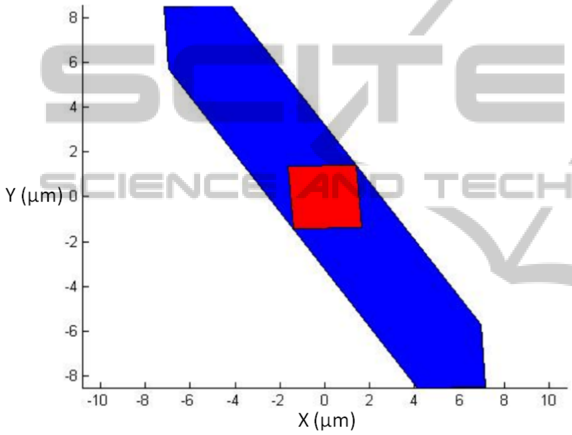

Figure 3: Repeatability depending on moving axes

spatial resolution mesh is slightly changed in orientation and the square becomes a parallelogram, but the dimensions of the parallelogram remain small as long as the final point stays in a disk centered on PI.

3 XY-Theta PLATFORM

We designed and prototyped a XY-Theta platform consisting of a 300 x 300 mm square platform held by a redundant kinematic chain of four motorized revolute joints. With this design, it is possible to set the position (X,Y) and orientation Ω of a workpiece situated anywhere on the platform. A vertical linear axis motorized with a stepper motor can hold various tools, such as measuring or grinding devices, grippers, camera etc. This axis is fixed on the frame. The location of the tool center in the XY plane lies exactly at PI (point of interest) (Brethé, 2011). The prototype is displayed in Fig. 5.

The platform can be operated in two different modes as it is explained in section 2:

- The coarse positioning mode uses the four axes. In this case, the expected repeatability is in the 5-10 micrometers range, which is equivalent to high quality industrial SCARA of the same reach.
- The fine positioning mode consists of two steps. In the first step, the part is moved under the vertical axis to point PI with the correct orientation using the four axes. The 1st axis θ_1 is set to $\frac{\pi}{4}$ where the lever arms of the 1st and second axis are minimum and identical at PI so that the final lever arm length corresponds to $L_1 \times \cos(\frac{\pi}{4}) = \frac{30}{\sqrt{2}} = 20.1$ mm and is 6 times shorter than the 2nd or 3rd arm lengths of 120 mm. Then, in the second step, the 3rd and 4th axes are mechanically blocked using the brakes and the positioning error can then be reduced moving only the 1st and 2nd axes. The choice of the blocked and moving axes depend on the lever arm length and the mechanism is designed to optimize the link lengths to reduce the final error. If the platform is considered to be the entire workspace, all points of the workspace can benefit from the high precision performance.

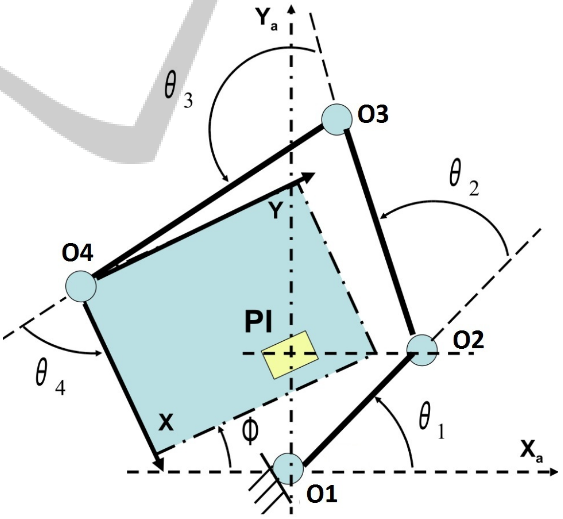

Figure 4: Diagram of the XY-Theta platform Kinematics.

4 SETTING UP THE CAMERA TO ESTIMATE THE REPEATABILITY

The camera chosen for the vision system is a Basler acA1600-20gm/gc with a telecentric imaging optics. This optics is useful to reduce the distortion during image acquisition. This camera is displayed in Fig. 5. The connection to the computer is done with Ethernet protocol. The camera has a high resolution of 1628 ×

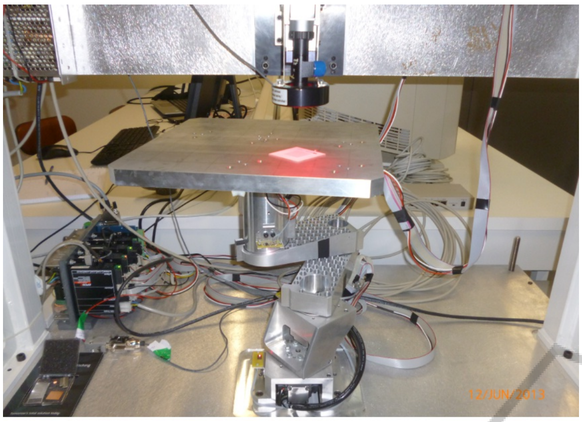

Figure 5: Micropositioning platform: general view.

1236 Pixels, a small vision field dimension of 7.1 × 5.4 mm, a pixel size of 4.4 × 4.4μm and it is located approximately 65mm above the platform. The 25 × 25 mm calibration grid displayed in Fig. 6 is used to calibrate this camera. It is a grid of small dots with a 0.0625 mm diameter, a inter space of 0.125 mm and a thickness of 2 mm.

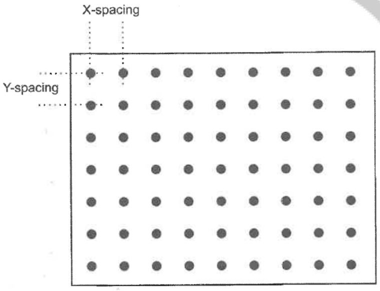

Figure 6: The calibration grid.

Four steps are necessary to use the camera as a metrological tool to estimate repeatability. These steps are detailed below.

4.1 Acquisition and Image Processing in the Matrox Imaging Library (MIL)

MIL (mat, 2008) offers several toolboxes and functions for image processing. First, the MIL is used to load one image from the camera and store it for further processing. A clear image is needed and for this purpose the focus must be set properly. An autofocus procedure is implemented as detailed below.

4.2 Autofocus of the Vision System

An autofocus procedure using the MIL functions is proposed. The goal is to find automatically the optimal distance between the camera and the calibration grid for optimal contrast. The camera is fixed on a motorized linear vertical axis as displayed in Fig. 7.

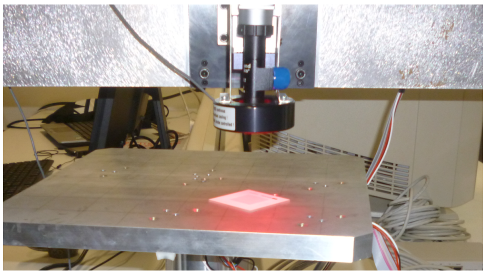

Figure 7: The camera and the calibration grid.

The camera is controlled to move slowly in an interval of 0.25 mm. Meanwhile images are acquired and stored. The contrast of each image is then computed. The contrast is an intrinsic property of an image that refers to and quantifies the difference between the light and dark parts of an image. The contrast is here calculated by the Root Mean Square (RMS) (Peli, 1990) which is defined as the standard deviation of pixel intensities:

$$RMS = \sqrt{\frac{1}{M.N}\cdot\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}(I_{ij}-\bar{I})^2} \tag{1}$$

Where:

- Intensities I_{ij} are the i_{th} and j_{th} element of the two dimensional image of size M by N.
- $M \times N$ is the resolution of the Image.
- $\bar{I}$ is the average intensity of all pixels values in the image.

In the experimental setup, 20 images are captured from several heights and the optimal height corresponding to the maximum contrast is computed.

The image with maximum contrast is obtained but its unit is in pixel and not in millimeters, so the image has to be calibrated to obtain its coordinates in millimeters (Tamadazte et al., 2009), (Ammi et al., 2005), (Zhou and Nelson, 1999).

4.3 Camera Calibration

The objective of camera calibration is to determine all the parameters necessary to predict the image pixel coordinates (r, c) of the projection of a point in the camera's field of view, given that the coordinates of that point with respect to the world coordinate frame are known (Tamadazte et al., 2009),(Ammi et al., 2005),(Zhou and Nelson, 1999). In other words, given the coordinates of P relative to the world coordinate frame, the coordinate in mm could be read. After performing the calibration, this file could be saved as a calibration object and stored as a model. To calibrate another image, it is sufficient to allocate this model to the calibration object already saved in MIL.

4.4 Geometric Model Finder (GMF)

Before measuring repeatability, we must understand how to define a pattern in the image and be able to determine the difference of position of the pattern in two different images.

MIL includes a tool for performing pattern recognition that it is primarily used to locate complex objects for guiding a gantry, stage or robot, or for processing measurement operations. This tool named Geometric Model Finder (GMF) tool is based on a patented technique that uses geometric features and contours to find an object.

In our case, a pattern of about 1 × 1 mm dimensions is chosen, this pattern is engraved on a metal sheet and an arbitrary letter (e) is chosen as a model as displayed in Fig. 8 but it is of course possible to choose any letter as model. The small square around the letter shows that it is the model with 130 × 120 Pixels and the large square corresponds to a fraction of the camera vision field 640 × 480 Pixels.

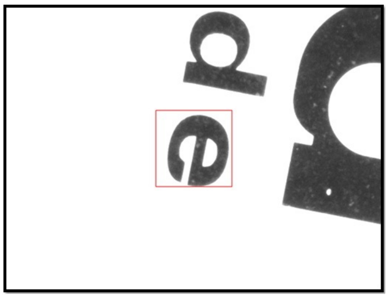

Figure 8: The model chosen to estimate repeatability.

MIL computes directly the coordinates of the center of gravity of a selected pattern. Moreover when the image is calibrated, these coordinates are given in millimeters.

5 REPEATABILITY PERFORMANCES AND DISCUSSION

5.1 Repeatability Performances in Coarse Mode

In this repeatability estimation, the four axes are moving. The harmonization point (HP) is set 25.353 mm away from the measurement point (MP). The target is brought at the PI (point of interest), the position is measured, then the tool moves to harmonization point (HP) and the cycle is repeated 100 times. This trajectory is displayed in the Fig. 9.

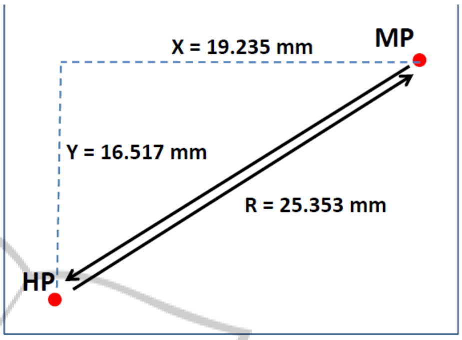

Figure 9: Trajectory which is carried out in coarse mode.

The resulting XY positions of the (MP) are displayed in Fig. 10.

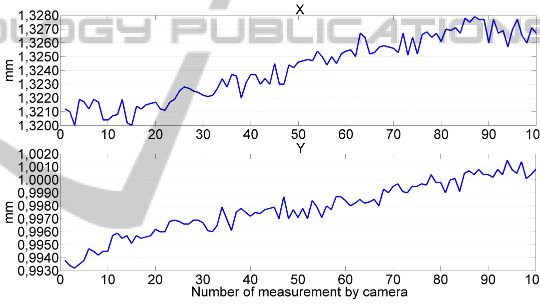

Figure 10: XY final position at MP when all axes are moving.

The width of the X and Y final position interval is between 7 and 8 micrometers. The computation of the ISO repeatability based on the 100 sample leads to a performance of 7.0μm. The corresponding cloud of points is displayed in Fig. 11.

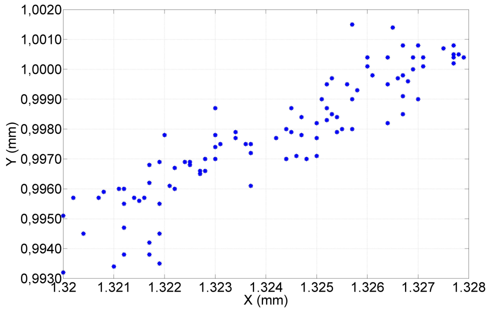

Figure 11: The cloud of points when arriving to MP in coarse mode.

5.2 Repeatability Performances in Fine Mode

The harmonization point (HP) is set 2.331 mm away from the measured final position. The (MP) is brought at the PI, the position is measured, then the harmonization point is brought at the PI, and the cycle is repeated 100 times. In this repeatability estimation, only the first and second axes can move, the other axes being mechanically blocked with the brakes. This trajectory is displayed in the Fig. 12.

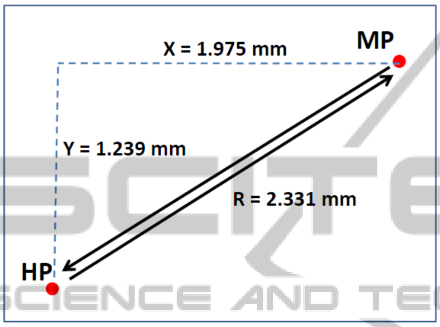

Figure 12: Trajectory which is carried out in fine mode.

The resulting X and Y final positions at MP in fine mode when 3rd and 4th axes are blocked are displayed in Fig. 13.

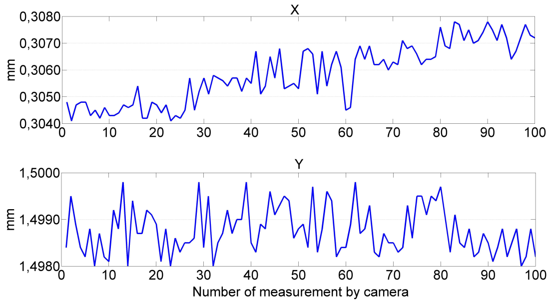

Figure 13: XY final positions at MP when 3rd and 4th axes are blocked.

The maximum width of the X and Y final position interval is between 2 and 4 micrometers. The computation of the ISO repeatability based on the 100 sample leads to a performance of 2.1μm. The corresponding cloud of points is displayed in Fig. 14.

5.3 Discussion

In this paper, the vision system is used to estimate repeatability, no mechanical contact occurs with the robot. The repeatability in coarse mode is 7μm and in fine mode is 2μm.

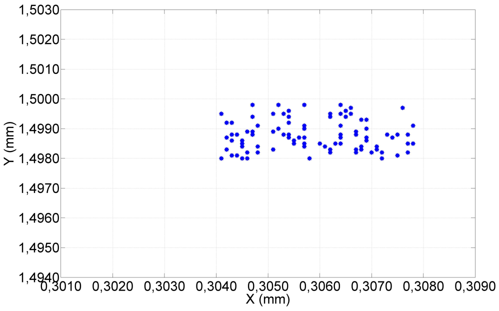

Figure 14: The cloud of points arrived in X and Y directions at MP in fine mode.

It is worth mentioning that a larger measuring campaign has been performed. Ten more trajectories have been tested all around the workspace of 300 × 300 mm. The results of these several tests lead to the same conclusion.

In (Brethé et al., 2013), the platform repeatability performance was estimated with the stationary cube method. The measurement device was using two Mitutoyo micrometers with a resolution of one micrometer. The hardened steel cube was held by the vertical axis. The Mitutoyo micrometers were on the platform. In this method, there is a mechanical contact between the micrometers and the hardened steel cube. A general view of this measurement system is given in Fig. 15. The repeatability in coarse mode was4μm and in fine mode it was 2μm.

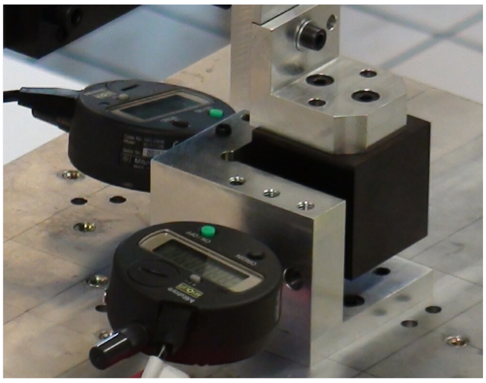

Figure 15: Measuring with the Mitutoyo micrometers.

When comparing the repeatability estimation with the two measuring systems, we notice that for the fine mode, the repeatability performance is nearly identical. On the other hand concerning the coarse mode, the non-contact measurement system gives a global estimation worst than the contact measurement system. In fact, when using the Mitutoyo micrometers, the maximum trajectory length is about 5 mm to keep a constant contact between the micrometers and the robot. But, when using the camera, any short or long trajectory could be realized in the workspace. So larger trajectories can be tested, for instance, some trajectory lengths are about 25 mm. The possibility to make the platform move along longer trajectories is a major advantage of the measuring system based on the camera compared to our previous measuring method. But if the trajectory is longer, it makes sense that the repeatability performance is lower. Another advantage of the camera versus the mechanical measuring system is its flexibility and easy implementation.

6 CONCLUSIONS

In this paper, the XY-Theta Platform is presented, designed with the same mechanical and control components of usual industrial robots. But based on a specific design and control, this platform improves repeatability performances significantly. The repeatability performances of this platform have been previously estimated using the stationary cube method. In this paper, another method based on a vision system is used to compute the repeatability performances. The results of these two methods all point in the same direction: the repeatability in the fine positioning mode is close to $2\mu m$ when the repeatability in the coarse positioning mode is close to $4-7\mu m$.

More studies will be performed on this platform. For instance, the platform performances concerning orientation repeatability of the workpiece are now been investigating. Another scientific interesting topic is the study of the singularities locations in the workspace, dealing with redundancy and singularities when planning a trajectory from (X_1,Y_1,Ω_1) to (X_2,Y_2,Ω_2).

The GREAH laboratory is now looking for partners to develop these concepts in industrial or academic applications with high precision performances.

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