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A new strategy for correction of Eye-to-hand camera pose errors in dynamic environments

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Abstract:
Vision sensors have gained significant attention due to their non-contact features and potential for relatively high accuracy. In addition, their affordability in terms of hardware costs has dropped precipitously over the last decade. The visual information extracted from the sensor can assist the robots to perform a variety of engineering tasks with a positioning accuracy that satisfactorily meets the demands of many industries. There are two configurations to set up a vision system namely eye-in-hand and eye-to-hand. The eye-in-hand camera configuration (ENH) involves visual systems that are usually used by composing two or more cameras that can be rigidly attached to the robot end-effectors, whereas the eye-to-hand camera configuration (E2H) involves the vision systems that are fixed in the workspace. The ENH camera method enables the robot to view the workspace more flexibly, but with restricted field of view (FOV). However, E2H camera ensures a panoramic view of the workspace, this makes the E2H is more preferred than the ENH in machining tasks that require from the camera to cover a wide measurement volume.
One of the problems with the use of E2H in tracking tasks is the incorrect detection for the targets in the camera images, this problem cannot be easily detected because it can occur by many reasons, such as due to the light sources in the room, occlusion of the targets, the covered lenses of the camera or an unexpected change in the camera pose. The last reason is less investigated by the researchers, despite of the fact the pose of fixed cameras can be easily changed in dynamic environments when the operator accidently touches the camera holder or when the camera was not properly fixed on the tripod or on the ceiling. This paper deals with the inaccurate detection problem of E2H cameras resulted from the unplanned change in the E2H camera position. A novel technique for detecting and correcting of the detection errors will be introduced. The proposed technique comprises of a feature extraction algorithm (namely Two-Stage Circular Hough Transform) and a Hybrid Median filter. The experiments have been performed in three motion scenarios for a fiduial object, which are translation, rotation, and translation plus rotation. The results showed the capability of the introduced algorithm in detecting and correcting of the camera positioning errors without any need for stopping the execution of the machining task or for readjusting of the camera pose.
Keywords: *Visual Tracking, Camera Pose, Hybrid Median Filtering, Positioning Accuracy, Moving Targets, Hough Transform.*

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I. Introduction

Camera systems have been widely preferred for real-time tracking applications, such as in machining tasks where they provide a sufficient information about tool condition. Also, in robotic tasks such as in drilling and welding tasks [1] where the core of the vision sensor is to enhance the positioning accuracy of the drilled holes[2] or to track different welding seams [3].

There are two common setups for the vision sensors in the industrial applications. The first type is called an Eye In Hand configuration [4-7] which can be briefly defined as a rigid touch for the camera at the end of the robot arm (robot end-effector), this type of a configuration is often used for robot guidance missions, such as in drilling tasks [2, 8], where the articulated robot relies on the visual information from the camera in order improve the positioning accuracy of the drilling systems by measuring the workpiece position, correcting the drilling position. The advantage of using the ENH setups is in their capability in assisting the robot to view the workspace more flexibly, but with limited field of view (FOV). On the other hand, the second type of camera configuration is called an Eye To Hand setup which the camera is mounted close to the measurement volume, either by being fixed on a stationary holder like a tripod [9] or fixed on the ceiling [10] for providing a panoramic view of the workspace. The E2H setup is preferred in trajectory tracking tasks, such as in robotic grasping applications, where the camera is used for tracking of the robot end-effector trajectory during the performance of reaching tasks [11, 12]. The E2H camera setup produces a wide field of view (FOV), but typically with lower resolution images [13].

Problem statement: In object tracking applications, an E2H camera as a wide FOV camera should be used if a large area of interest needs to be viewed, but as stated the downside will be obtaining of low resolution images which in turns makes the measurement accuracy of the vision sensor is quite low [13]. The low detection accuracy for E2H cameras can be partially solved via higher resolution cameras but this may not be a practical solution due to the high hardware cost. Another solution to avoid depending on the visual information obtained by a single camera, and using of multiple cameras. However, this solution is not feasible because of the high computational cost.

Another way to cope with the problem of poor imaging quality is to accept the degradations of the image and use Super Resolution (SR) or Resolution Enhancement (RE) techniques [14]. The aforementioned solutions dealt with the problem of low detection accuracy produced by using of wide FOV or low resolution sensors. However, the measurement and detection accuracy for these cameras can also be degraded by other factors such as the dynamic environment such as light [15], the structure of the object [16-18], and the camera pose location [19]. Alzarok et al [19]showed that the detection accuracy of the vision system can be significantly enhanced if the camera was positioned in a proper location, they introduced a mathematical predictive model for the calculation of the optimum location for E2H cameras. The scope of this paper is to cope with the problem of low detection accuracy for the camera produced from the sudden changes in the camera location due to human faults. A new technique for detecting and correcting of the positioning errors caused by the displacements in the camera pose. A combination of a feature extraction algorithm, namely Hough transform (two-stage method), a Hybrid median filter and a 2D transformation matrix were applied for detecting and tracking of 2D targets in the images captured during the performance of a machining task with different motion scenarios. The results showed the capability of detecting any sudden changes in the camera pose, and also the capability to correct the visual information of the tracked target without any need for stopping of the machining task in order to relocate the camera, and thus saves the production time and enhances safety for both the machine and the human operator.

This paper is organized as follows: Section II describes the experimental setup of the proposed visual tracking system. Section III and IV introduces the stages followed for detecting and correcting of the camera errors. Section VV presents and discusses the experimental results obtained via the proposed visual tracking module. Section VII summarizes the main outcomes of the proposed approach.

II. Experimental setup

The proposed tracking system (as shown in Figure 1) combines two stages: Motion estimation process and error correction process. The motion estimation process consists of a combination of a Hybrid median filter and Circular Hough Transform (CHT), a Hybrid median filter is applied for coping with the problem of image segmentation, it has the capability of retaining narrow lines and protecting corners which makes it suited for the tracking applications that require detecting and tracking of objects with primitive shapes. The core of this filtering technique is to focus on selecting the pixels of object boundaries that are often rejected by classic filtering operations due to their strong variations in image intensities [20]. After applying the HM filter for obtaining clear images, the Circular Hough Transform which was using the two-stage method is applied on the filtered images in order to identify and track the target through the consecutive captured images and thus estimating its motion path in pixel coordinates. The key idea of this method is based on finding of two thresholds to detect strong and weak edges, it has better performance compared to other edge finder methods such as Laplacian of Gaussian method. The main advantage of two-stage method is less likely to be affected by noise compared to other CHT methods such as the Phase Coding method and is more likely to detect true weak edges. In this paper, the two-stage CHT algorithm is used for extracting two features of the object (a circular fiducially target), these features are the color and edge of the circular object, both features will be used for identifying and tracking the target through the consecutive captured images, they provide more robustness to noise and illumination. The object was mounted on a high precision 5-axis CNC machine (namely Hurco) which controls the translation and rotation of the object with a positioning accuracy of ±0.005 *mm* and repeatability of ±0.0025 *mm*. Moreover, a personal use camera (namely Samsung ST150F) (see Figure 3) was fixed in the ceiling of the Hurco machine in order to provide a full view of the tracked object without being occluded or obstructed. The 2D information of the tracked target obtained by the camera is then converted from image units (*pixels*) to world units (*mm*).

The second and last part of the tracking process is the error correction process which relies on measuring the changes in the position and orientation of the target in the consecutive frames by comparing the location of the target in each captured frame with its similar location in the reference frame. The significance of this process is in the ability to discover any sudden change in the camera pose by measuring the camera positioning and angular errors , and applying an online correction without any need to stop both the machining and visual tracking tasks. The details of the two stages are explained in the next sections.

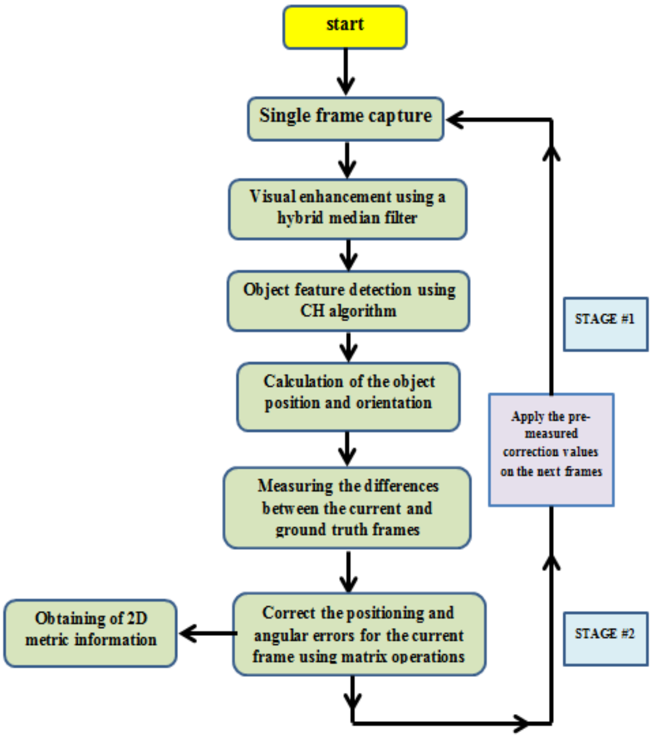

Figure 1: Flowchart of the proposed technique.

III. Motion estimation process

In this section, the object motion estimation process will be described. As mentioned earlier, a personal camera (namely Samsung ST200F) was used for performing visual tracking tasks, the camera has an effective resolution of 16.1 *megapixels* for still images, and almost 1 mega pixel (0.9216 *megapixels*) for video mode. It is worth mentioning that the camera will be used in video mode during the tracking experiments, thus the spatial resolution of the used camera will be quite low and will lead to image errors because of the poor visual quality. Therefore, there is a need to apply an imaging filter in order to enhance the visual quality for the captured low resolution frames. However, the low resolution for camera is not the only challenging issue in this experimental work, the changing light in the lab environment also affects the object detection accuracy by the camera, it has a bad influence on the color segmentation for the object to be tracked, thus it badly affect the performance of the Two-Stage CHT transform which utilizes the color and edge features in order to detect the coordinates of the moving objects. Therefore, in order to cope with the two aforementioned problems, a hybrid median filter was used for visual enhancement and can correct restoration of color. The reason behind the selection of this filter instead of other popular filtering techniques is in their capability to enhance the visual information for the circular shaped objects. The work introduced by GourandKhanna[20] showed how the hybrid filter successfully provides clear and steady images for the blood vessels which have similar geometric features to our proposed fiducial target.

A cooperation of the standard camera with a hybrid median filter will be used for acquiring high resolution images, then, the CHT algorithm will be used for extracting two features of the object from the captured frames, these features are the center and radius, once the center of the target is measured, then the position and orientation of the target can be determined and its motion path can be tracked along the consecutive frames. In the next section, the description of the target and the technique used for the calculation of the position and orientation of the target will be explained in details.

a. Object description

In this work, the 2D target used is a fiducial object (seeFigure 2) which consists of two circles that are used for measuring the orientation of the object, the object was designed and printed on a paper which can be easily attached to the machine bed or the rotary table (seeFigure 3). The fiducial object was used as a target in the 2D tracking experiments that only require a single camera.

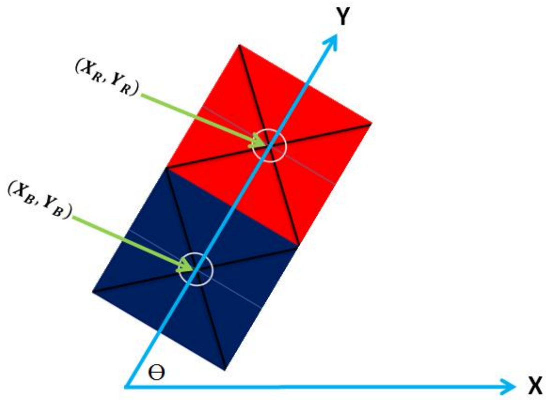

Figure 2: The object shape in the image frames.

The first step in the experiment is to measure the position and orientation of the object, the CHT was used for measuring the central points of the red and blue parts of the object (seeFigure 2), so four parameters will be used for identifying the location of the object, and can be defined as follows:

X_R= x coordinate of midpoint of red color
Y_R= y coordinate of midpoint of red color
X_B= x coordinate of midpoint of blue color
Y_B= y coordinate of midpoint of blue color

Then orientation of the object can be measured by the following equation:

$$\theta = \tan^{-1}\frac{Y_R - Y_B}{X_R - X_B} \quad (1)$$

IV. Image error correction

The second stage of the tracking process is to correct the positioning and angular displacements for the location of the target in the image frame. First of all, the reference frame and the current captured frame are overlaid in order to calculate the angular and position correction values as described below:

Angularcorrectionvalue=orientationoftheobjectinthereferenceframe- orientationoftheobjectinthe current captured frame

$$\theta = \theta_1 - \theta_2 \quad (2)$$

Position correction value = position of the object in the reference frame- position of the object in the second frame

$$(\Delta x, \Delta y) = (x_1, y_1) - (x_2, y_2) \quad (3)$$

Where:

Δx represents the number of shifting pixels in the horizontal axis (image columns).
Δy represents the number of shifting pixels in the vertical axis (image rows).

Since the position of the tracked object can be measured in pixels, therefore, the scaling factor that defines the relationship between the image coordinates (pixels) and world coordinates (*mm*) has to be known. In order to achieve that, the horizontal resolution of the captured images must be first calculated.

Since the measured width of the image in world coordinates is 36 cm**,** the base resolution of the image can be calculated as follow:

Horizontal resolution=(360×1000)/1280=281.25 *(μm)/pixels*

V. Experimental results and discussion

The aim of this part is to track the motion of the object by using a phase coding method, namely Two-Stage Method, the algorithm provides the ability to detect and measure the coordinates of the moving object. However, the orientation of the object will be mathematically calculated as mentioned in a previous section. There are three possible scenarios for the object motion which are: rotation case, translation plus orientation case, and a translation case, the experiment at each motion case has been repeated three times.

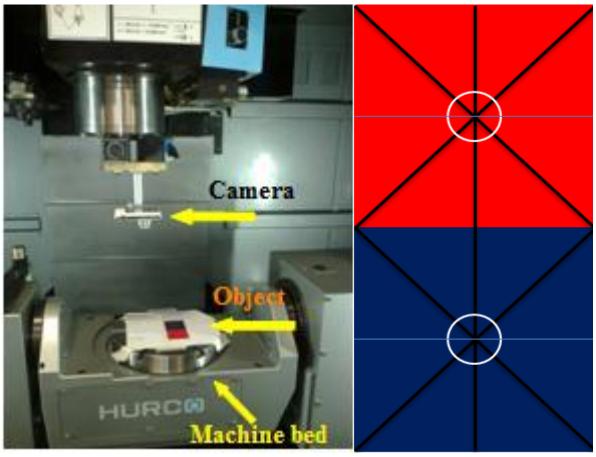

Figure 3: Experimental work.

a. Case one: Rotation case

In the rotation case, the aforementioned high accuracy CNC machine tool (Hurco machine, see Figure 3) was programmed to control the rotation of the object (10 *degrees* at each second), Figure 4and Figure 5show the measurements of the position and orientation for the tracked object during the three experiments, it can be also seen that the motion path of the object during experiments is similar. However, by comparing the motion path of the object in the first experiment (reference data) with the two iterations, position and angular changes can be detected, the detected changes happened due to the camera vibration during the experiments, the motion path of the object during the first tracking experiment was assumed as a reference path, thus the positioning and angular errors for iterated experiments have been measured from the difference of the position and orientation readings between the reference and the iterated paths.

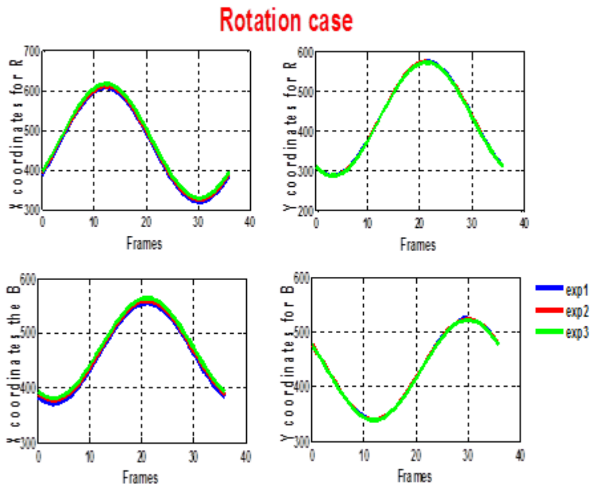

Figure 4: Position measurements during the tracking experiment.

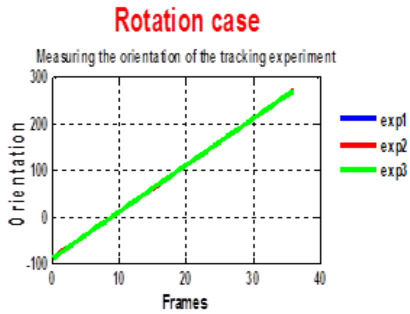

Figure 5: Orientation measurements during the tracking experiment.

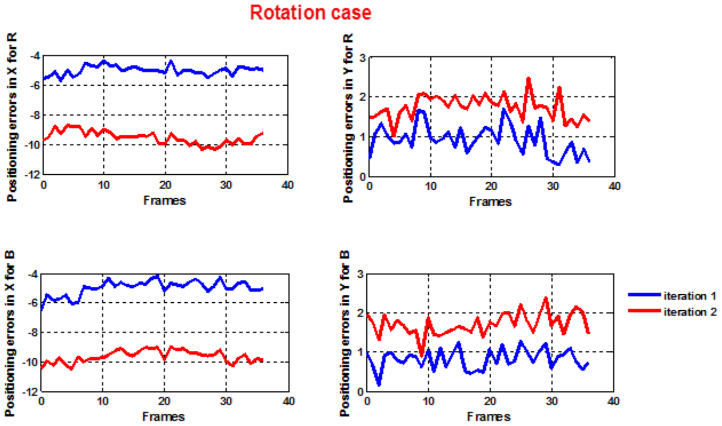

Figure 6: Positioning error measurements during the tracking experiment.

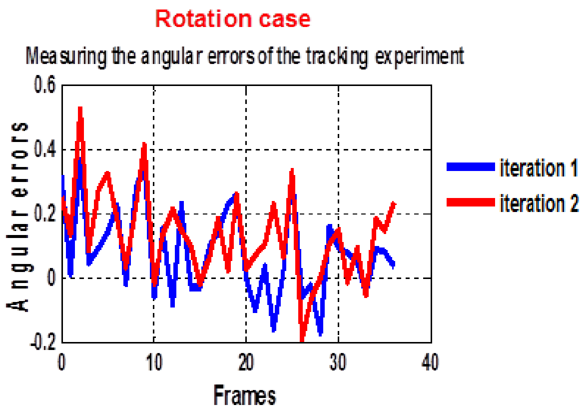

Figure 7: Angular error measurements during the tracking experiment.

Table 1: Positioning and angular errors.

Iterations	**Positioning errors (*mm*)**				**Angular errors (*degrees*)**
	Xr	Yr	Xb	Yb	
1	-1.414	0.2578	-1.4029	0.2294	0.081336
2	-2.681	0.4860	-2.7124	0.4803	0.131489

It can be notified from

Table **1**that there is a considerable value of positioning errors, the difference between charts in Figure 6indicates that these values have been considerably increased after each iteration. However, Figure 7shows that small angular errors measured in the two iterated experiments (0.081336 *degrees*, and 0.131489 *degrees*). After measuring the positioning and angular errors for the two iterated experiments. The second step is to correct the position and orientation of the object in the iterated experiments to be identical to those in the reference path.

Table **2**and Figure 8show that the correction method succeeded in reducing the values of positioning and angular errors.

Table 2: Positioning and angular errors before and after corrections.

	Positioning errors(*mm*)				**Angular errors (*degrees*)**
	Xr	Yr	Xb	Yb	
BC	-1.414	0.2577	-1.4029	0.2294	0.08134
AC	-0.0086	0.0132	0.0263	-0.0003	-0.03828

It can be notified from simulation results (Figure 8) that the correction values for object positions are quite similar, so in order to reduce the computational cost of the tracking process, the position correction value at the first point in the object motion path (from first captured frame) can be applied for all points for the same path.

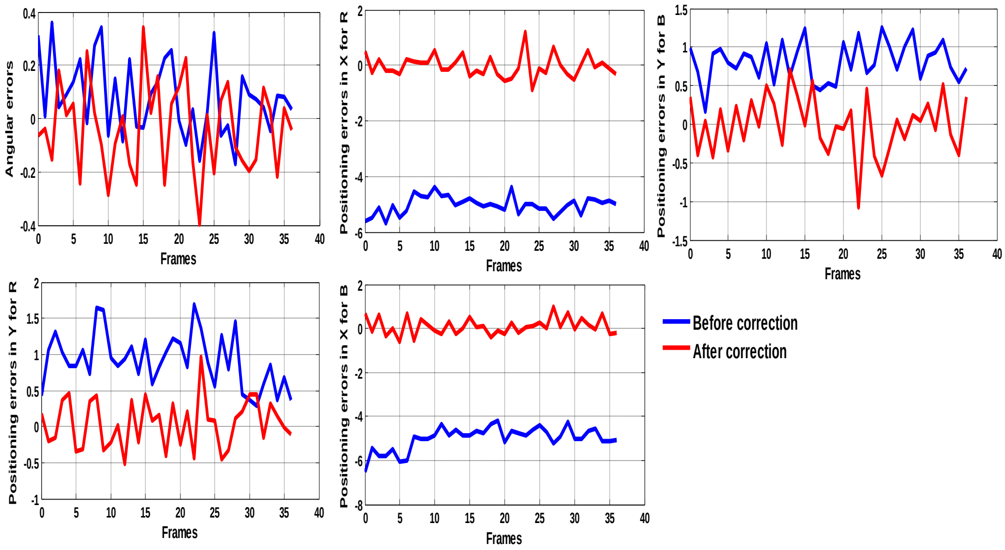

Figure 8: Positioning and Angular errors (before and after the correction process).

b. Case two: translation and rotation case

In this case, the machine was programmed to control the motion of the object (shifts of 500 μm in XY axes and then rotation of 10 *degrees* at each new location). The obtained results (Table 3andFigure 11) showed that positioning errors for tracked object motion have a significant increase after the first iteration. However, the angular errors for the object motion have lower values in the second iteration compared with the first one (Figure 12).

Table 3: Positioning and angular errors.

Iterations	Positioning errors (*mm*)				Angular errors (*degrees*)
	Xr	Yr	Xb	Yb	
1	-4.7709	0.12236	-4.8143	0.1394	0.1035
2	-8.3736	-0.2414	-8.4506	-0.2069	-0.0294

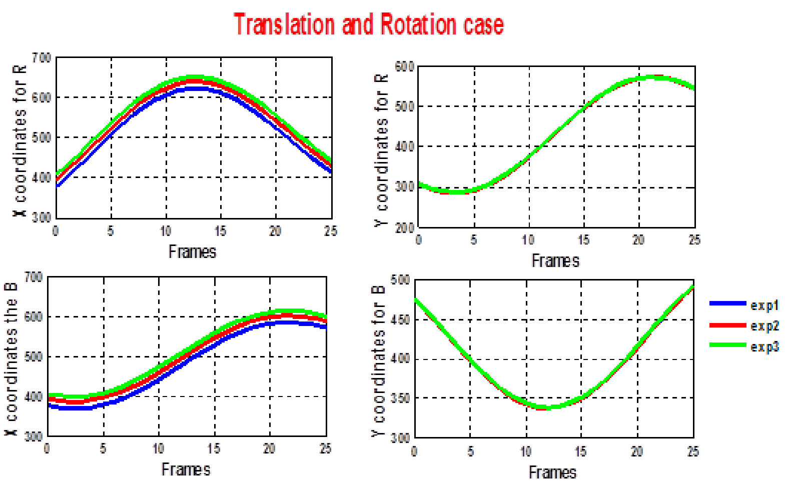

Figure 9: Position measurements during the tracking experiment.

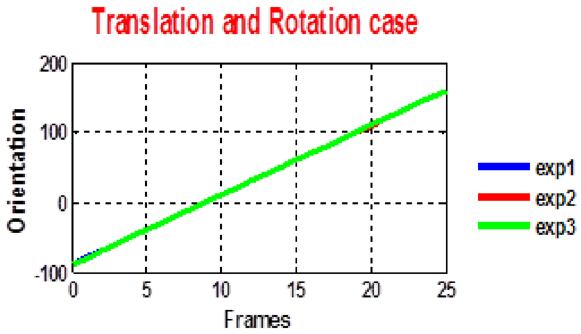

Figure 10: Orientation measurements during the tracking experiment.

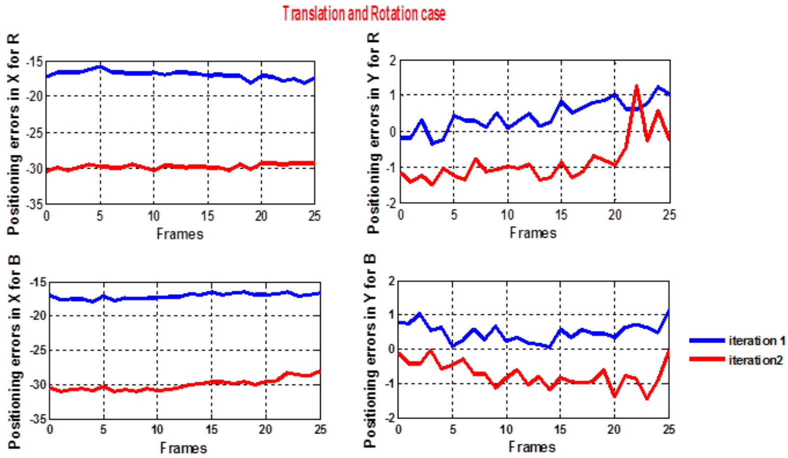

Figure 11: Positioning error measurements during the tracking experiment.

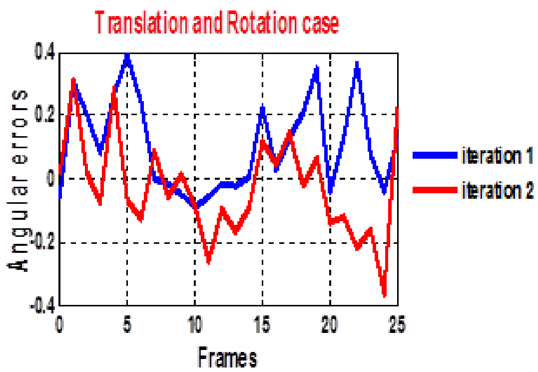

Figure 12: Angular error measurements during the tracking experiment.

c. Case three: translation case

In this case, the machine was programmed to shift the object 50 µm in two dimensions. It can be seen from

Table **4Error! Reference source not found.**, Figure 15and Figure 16that the values of positioning and angular errors are quite high in the iteration 2 compared to the iteration 1. In this part of the experiment, a positioning correction will be only applied for the iteration 2 in order to see whether the positioning correction would have an effect on the angular errors of the object or not.

Table 4: Positioning and angular errors.

Iterations	Positioning errors (*mm*)				Angular errors (*degrees*)
	Xr	Yr	Xb	Yb	
1	0.3501	3.2513	0.2314	3.102	0.1395
2	2.8571	-14.292	1.4331	-13.723	1.7239

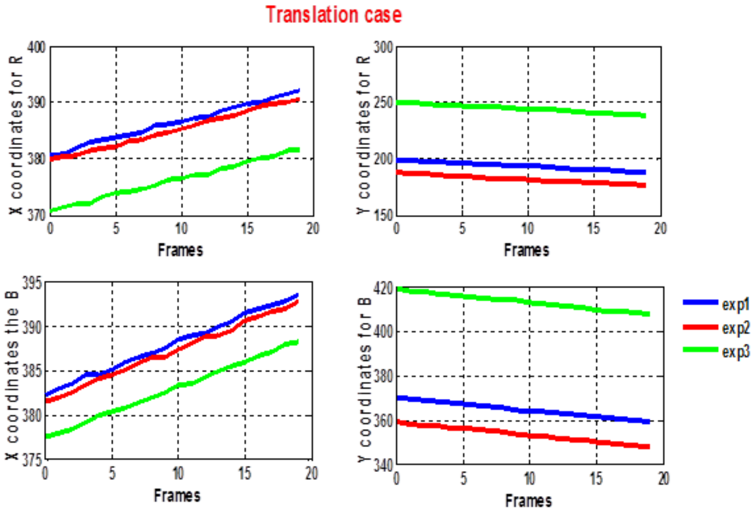

Figure 13: Position measurements during the tracking experiment.

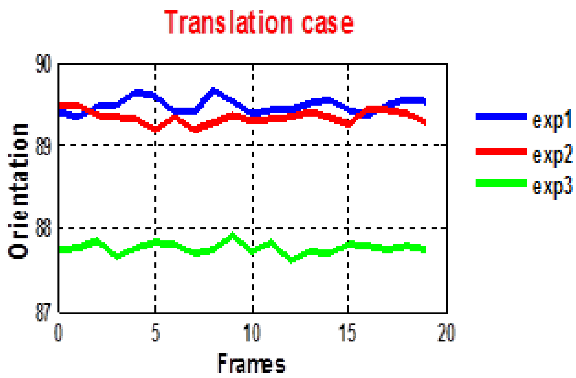

Figure 14: Orientation measurements during the tracking experiment.

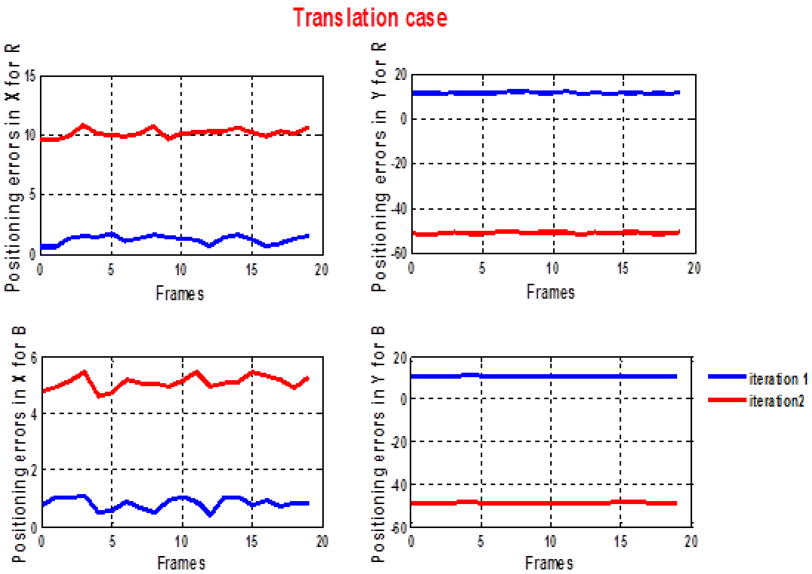

Figure 15: Positioning error measurements during the tracking experiment.

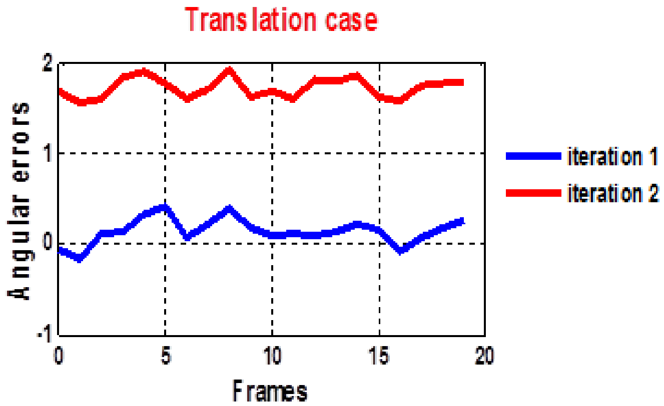

Figure 16: Angular error measurements during the tracking experiment.

Table 5: Positioning errors before and after applying only position correction.

	Positioning errors(*mm*)				**Angular errors (*degrees*)**
	Xr	Yr	Xb	Yb	
BC	2.857	-14.292	1.4331	-13.723	1.724
AC	-0.004	-0.0536	-1.4265	0.5501	1.7221

It can be clearly seen from

Table **5**that positioning errors have been considerably reduced after applying the positioning correction. Moreover, value of angular errors remains the same as we did not apply any angular correction in this experiment.
Again, it can be notified from Figure 17that the correction values for object positions have very similar values, and that supports the idea of applying the same position correction value at all points in the motion path.

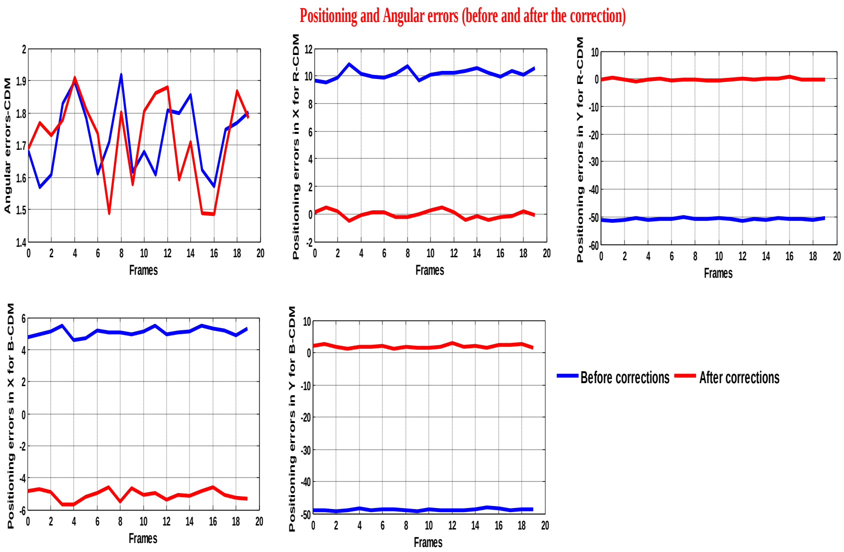

Figure 17: Positioning and Angular errors before and after correction.

VI. Conclusions

A correction technique was introduced for reducing the positioning and angular errors occurred during the object motion, the proposed technique consists of two stages: angular correction stage and positioning correction stage. It can be seen from the results obtained during three motion scenarios that there is a significant increase in the value of positioning errors during iterations of the tracking experiment, although that the axis motion controller used has high positioning accuracy (±0.005 *mm*) and high repeatability (±0.0025 *mm*), and thus in the case of a robot controller will be used to move an object (end-effector) instead of a precise machine controller, the affectivity of the correction process for positioning and angular deviations in the object motion path will be limited due to the low repeatability and positioning accuracy for robots compared to those in CNC machines. In comparison of the results obtained during three motion scenarios, it can be notified that the highest deviations in the object positioning occurred in the case two (translation and rotation case), However, the lowest deviations in the object positioning occurred in the case one (rotation case), the results also showed that correction values for object positions have very similar values, and that supports the idea of applying the same position correction value at all points in the motion path, and thus will lead to a reducing in the total time for image processing.

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