CHARACTERIZATION OF MICRO DISPLACEMENTS OF SERIAL ROBOT

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Abstract—Robot precision is usually characterized by repeatability and accuracy. In this paper, we show that these indices are not sufficient to describe the robot behavior in the micrometer scale. New precision performances are proposed and the experimental procedure to estimate these indices is described. The main results of the experimental work performed on a SCARA robot are displayed. Lostmotion, reversibility and spatial resolution have to be taken into account when the robot has to be controlled precisely in the micrometer scale.

I. INTRODUCTION

The progress in robotics over recent years has dramatically extended our ability to explore, perceive, understand, and manipulate the world on a variety of scales. In important fields like biology and surgery, the development of increasingly small robotics devices is rapidly increasing. In industry, interesting areas for micro-applications of robotics include assembly [1-2], characterization, inspection and maintenance [3-4], micro optics (positioning of micro optical chips) [5] and manufactories [6]. Many of these applications require automated handling and assembly of small parts with accuracy in micron and sub-micron range. This is the reason why it is important to be able to evaluate precision performances in the micrometer scale for industrial robots. In the millimeter scale, robots can perfectly achieve most of the tasks but in the micrometer scale, the behavior of the robot becomes unpredictable and is different from what it is expected in theory. Many factors including manufacturing and assembly tolerances, deviations in actuators controllers, influence the precision performance index [7]. They must be carefully analyzed to obtain a clear insight into manipulator performance. This work will give a model to characterize the micro displacement of a serial robot. We study several aspects of micro movements enforced by the controller, in order to increase our knowledge about the precision and repeatability of a serial robot when doing micro tasks.

We analyze different influence factors impacting on the micro-movement (micro-positioning, repeatability, and so on) of the robot. In our previous works [9] we have presented a new modeling to estimate the position repeatability index and analyzed the influence factors. This estimation was based on a pragmatic approach using one micrometer to compute an angular covariance matrix. This procedure is cheap, simple and time saving and it is based on the stochastic ellipsoid theory [8]. We have obtained interesting results for the position repeatability estimation and the orientation repeatability [9] bringing new elements to the existing literature [10-11] that studied the influence of workspace location, load and speed on the position repeatability.

In the second section, the studied robot is presented as the tests and experimental measurement device. In the third section, a study of the reversibility of each joint of the serial robot is presented. In the fourth and fifth sections, we studied the theoretical resolution and lostmotion areas of each joint, in order to characterize the minimal increments to be given to the robot to have the best possible precision.

II. EPSON ROBOT AND EXPERIMENTAL DEVICE

The experiments are performed on a 4-axis SCARA RS450 Epson robot displayed in fig.1. The robot has 4 degrees of freedom (DOF): three revolute joints (1, 2 and 4) and one vertical prismatic joint (3).

For the estimation of orientation, we chose to use the stationary cube method proposed by the Ford Company, with six micrometers. With this device, it is possible to estimate the relative differences in position and orientation for the consecutive attempts. The experimental measurement device consists of two trihedral. One is an aluminum parallelepiped moving with the robot and is hold by the robot gripper. The other one is fixed on the robot base and supports the measurement device consisting of six micrometers disposed orthogonally as displayed in fig. 2.
Micrometers are laid out by pair of two on three orthogonal sides. We chose this setup to keep the same resolution on the three orientation angle estimation. Six 543-390 Mitutoyo micrometers are used to collect measurements. The micrometers’ accuracy is better than 3 micrometers and the resolution is 1 micrometer. With this device, it is possible to estimate the cube orientation with a resolution of $1.6 \times 10^{-3}$ radians and the cube position with a resolution of 0.5 micrometers. The position and orientation variations are obtained from the six micrometers increments using a linear transformation from the screw theory. The 6 micrometers values are read once the robot has reached its target and transferred to the PC via a multiplexor unit. To estimate the variances of the first and second joints, four micrometers are used to estimate the variations $dx$ and $dy$ of the end-effector. Then the angular variations $d\theta_1$ and $d\theta_2$ are obtained via the inverse Jacobian matrix.

$$
\begin{bmatrix}
    d\theta_1 \\
    d\theta_2
\end{bmatrix} = J^{-1}_{\text{position}} \times 
\begin{bmatrix}
    dx \\
    dy
\end{bmatrix}
$$

All the information about the final pose (position and orientation) is summed up in the homogenous transformation matrix. The consecutive transformation matrices can be computed using the Khalil-Kleinfinger method [9, 12-13]. The Jacobian matrix is computed by differentiation of this homogeneous transformation matrix.

III. REVERSIBILITY PERFORMANCES

There are two possible to reach a target, coming from the left-side (L) or from the right-side (R). Most of the time, the mean of the achieved positions when the target is reached coming from the left is different from the mean of the achieved positions when the target is reached coming from the right. This well-know phenomenon is due to backlash in the gear reductor box or to hysteresis. The goal of the procedure described here is to estimate the difference between the means of the two final distributions.

Once this difference is stochastically known, it is possible to build a strategy to reduce the final position error in the next attempt. This strategy will take into account the direction from which the robot has come in the previous attempt.

A. Reversibility experimental procedure

The next algorithm presents a test for the reversibility of the $i^{th}$ joint. The cycle displayed in fig.3 is the following: the robot comes from a left harmonization point $\theta_L^i$, then goes to the measurement point $\theta_M^i$, goes to the right harmonization point $\theta_R^i$, comes back to the measurement point $\theta_M^i$ and then achieves the cycle going finally to the left harmonization point $\theta_L^i$. The left and right harmonization points are situated symmetrically and at a short distance from the measurement point. This cycle is repeated $N$ times, so we have $N$ positions corresponding at a target attained coming from the left-side and $N$ positions coming from the right-side.

B. First axis reversibility performance

The above detailed cycle is performed for the robot first axis and repeated $N=15$ times. The angular acceleration is set to 3% of the maximal acceleration. When the first axis moves, the second axis is also moving. With the experimental device, the positions increments for the first and second axis can be estimated simultaneously.

In fig.4, the measured positions of the first axis are in continuous blue line when the robot comes from the left and in dotted blue line when the robot comes from the right. In the same figure, the second axis position is also measured and is displayed in continuous red line when the robot first axis is coming from the left and in dotted red line when the robot first axis is coming from the right.

It is interesting to compute the jump $j_{LR} = \theta_L^i - \theta_R^i$, corresponding to the difference of two consecutive positions, coming first from the left and then from the right. The first joint left-right jump is displayed in fig.5 in blue line. In the
same figure, the jump of the second axis is also displayed in red. The advantage of computing this jump is to get rid of the drift phenomenon.

Another way of analyzing the data is to draw a histogram of the first axis left-right jump displayed in fig.6.

Figure 3. Example of ZigZag measurement of the first joint with 2 target B (in red) and C (in green) and the measurement point A (in black)

Figure 4. Positions of the first axis in blue and the second axis in red – solid line coming from the left and dotted line coming from the right (X label: number of cycles, Y label: angular position)

Figure 5. The first axis left-right jumps in blue and the second axis jumps in red (X label: number of cycles, Y label: left-right jumps)

Figure 6. Histogram of the left-right jump for the first axis (X label: left-right jumps, Y label: class cardinality)

C. Second axis reversibility performance

The same reversibility experiment is now done for the second axis and the positions are displayed in fig.7 with the same reference colors as used above. In fig.8, the first and second axes jumps are displayed when the second axis is commanded to come from the left and then from the right. Fig.9 displays the histogram of the second axis left-right jumps.
D. Reversibility performance analysis

The first axis theoretical resolution is 1.92E-5 rad/pulse and the second axis theoretical resolution is 3.0E-5 rad/pulse. All the deviations have to be analyzed taking into account these theoretical resolutions.

First, it can be noticed that when only one arm is commanded to move, the other arm is also moving. This can be easily understood because there is no brake neither on the first nor the second axis. Consequently, when for instance, the first axis is moving, the second axis position is controlled by the regulation loop only. The torque resulting from the dynamical effects tends to create an error in the position regulation loop. This error is then corrected and is nil at the end of the process, but the second axis has then moved.

In the first axis reversibility experiment, the blue dotted line is always over the blue solid line meaning that there is a steady bias if the target is hit coming from the left or from the right. This bias is statistically significant if we consider that the first axis left-right jump has a mean equal to 5.2E-5 rad=2.7 pulses. The variability of the jump random variable is also quite significant because the width of the jump range is much larger than one pulse.

During the first axis reversibility experiment, the red dotted line is always under the solid line meaning that there is a steady bias, concerning the second axis position, which is also affected of a jump equals to -2.6E-5 rad=0.86 pulse. This second axis mean jump is negative, while the first axis mean jump is positive. There is an inverse correlation between the two axis positions as it can be seen in fig.4. This could be explained by the fact that the first motor is set on the robot basis while the second motor is set on the second link. The first link does not support any motor. Thus the reductors have opposite effects on the links.

In the second axis reversibility experiment, it is also very clear that the left or right approach direction has a significant influence on the final angular position. The second axis left-right jump has a mean of 12.6E-5 rad=4.2 pulses which is very significant. Meanwhile the first axis is affected of a mean jump of 3.7E-5 rad=1.9 pulses which is also significant.

The first axis has a 80:1 reduction rate with a high reversibility torque (>4.3 Nm), while the second axis has a 50:1 reduction rate with a lower reversibility torque of 2.6 Nm. Nevertheless, even is the acceleration is low, the first axis position does not stay exactly the same while the second axis is moving. It means that strategies considering to reduce the position error correcting the target for only one axis will fail because the other axis’ position will be changed during the correction.

During the second axis reversibility experiment, the variability of the second axis left-right jump is also superior to the theoretical pulse width.

IV. Hysteresis performances

Sometimes, when the robot is commanded to perform a small jump, no movement is observed on the cube. Meanwhile the motor has moved and this move is observed via the incremental encoders. But solid friction and elasticity
of the reductor prevent the cube from moving. We tried to perform experiments to characterize the minimal incremental value that will produce a movement at the end of the kinematic chain. The idea is to command each joint to move small increments from a given position and measure the displacements at the end of the kinematic chain.

A. Hysteresis test procedure
The robot is controlled to increase and decrease angular positions by increments of n pulses, n=1 to 16, as detailed in fig.10.

B. Hysteresis experimental results

<table>
<thead>
<tr>
<th>n</th>
<th>$d_{\theta_1}$ $\times 10^5$(rad)</th>
<th>$d_{\theta_2}$ $\times 10^5$(rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1pls</td>
<td>1.410</td>
<td>0.203</td>
</tr>
<tr>
<td>2pls</td>
<td>1.058</td>
<td>0.313</td>
</tr>
<tr>
<td>3pls</td>
<td>1.152</td>
<td>1.065</td>
</tr>
<tr>
<td>4pls</td>
<td>1.469</td>
<td>1.361</td>
</tr>
<tr>
<td>5pls</td>
<td>1.775</td>
<td>1.515</td>
</tr>
<tr>
<td>6pls</td>
<td>1.775</td>
<td>1.612</td>
</tr>
<tr>
<td>7pls</td>
<td>1.936</td>
<td>1.670</td>
</tr>
</tbody>
</table>

The experimental results show that it is impossible to move directly the robot by one pulse. Moreover, when two or more pulses are commanded, there is also a non-linearity that should be taken into account.

V. Spatial resolution performances
As seen in the hysteresis procedure, it is sometimes not possible to correct the robot position by changing the target by one pulse. Another strategy is then to come back to a distant point named harmonization point and redo the trajectory with the final target incremented of one pulse. Theoretically, the mean position difference corresponds then to the spatial resolution and this can be verified experimentally.

A. Spatial resolution procedure
The robot $i^{th}$ axis is controlled to reach a position $\theta_{i0}$ coming from a harmonization point PH. The final position is measured. Then the robot comes back to PH and the next target will be $\theta_{i0}+1$ pulse. The final position is measured. The cycle is repeated again with a new target $\theta_{i0}+2$ pulses and so on, as displayed in fig.12.

The tables 2 and 3 summed up the results for the dead zone and sliding cycle tests. For each joint the mean value $d\theta / n$ is reported with respect to the number of pulses $n$. The measurements are provided in radians.
B. Spatial resolution experimental results

<table>
<thead>
<tr>
<th>n</th>
<th>$\theta_1 \times 10^5$</th>
<th>$\theta_2 \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1pls</td>
<td>2.936</td>
<td>1.921</td>
</tr>
<tr>
<td>2pls</td>
<td>2.598</td>
<td>2.050</td>
</tr>
<tr>
<td>3pls</td>
<td>2.711</td>
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</tr>
<tr>
<td>4pls</td>
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<td>2.108</td>
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</tr>
<tr>
<td>6pls</td>
<td>2.728</td>
<td>1.925</td>
</tr>
<tr>
<td>7pls</td>
<td>2.619</td>
<td>2.021</td>
</tr>
</tbody>
</table>

As illustrated in table II, the spatial resolution is weak sensitive with respect to the number of pulses. This last experiment confirms the interest to introduce a harmonization point in the control of the trajectory.

VI. CONCLUSIONS

In this paper, different procedures were proposed to choose the most efficient strategy in order to correct a mispositioning in the micrometer scale.

The reversibility of the axis movement has to be taken into account: hitting the target coming from the right or from the left will introduce a bias in the result. This can be characterized by the reversibility procedure. The left-right jump performances of the first and second axis of the SCARA robot have been estimated. It seems that the variability of the jump is higher than the repeatability of the robot. It seems also that the dynamical effects produce a correlation on the two axes’ movements. These effects will be more investigated in future experimental works.

The hysteresis procedure is useful to find the minimum incremental jump the robot is able to perform on one axis. The experimental results show that it is impossible to move directly the robot by one pulse. When two or more pulses are commanded, there is also a non-linearity that should be taken into account.

If the direct move is not possible, another strategy is to come back to a harmonization point and replay the trajectory with the target incremented of one pulse for instance. Then the final position is increased of a quantity, theoretically equal to the spatial resolution, but the repeatability of the robot has also to be taken into account to characterize the final confidence area.

The purpose of these various procedures is to diagnose the robot ability to reduce the position error, by mean of a direct or indirect move. The experimental results can finally be used to control the robot for micrometric positioning using all information provided by external sensors and the knowledge about the robot behavior.

REFERENCES