End-effector precise hand-guiding for collaborative robots

Mohammad Safeea[1], Richard Bearee[2], and Pedro Neto

[1] University of Coimbra, 3000-033 Coimbra, Portugal,
ms@uc.pt,
[2] Arts et Metiers ParisTech, LSIS Lille 8, Boulevard Louis XIV,
59046 LILLE Cedex, France

Abstract. Hand-guiding is a main functionality of collaborative robots, allowing to rapidly and intuitively interact and program a robot. Many applications require end-effector precision positioning during the teaching process. This paper presents a novel method for precision hand-guiding at the end-effector level. From the end-effector force/torque measurements the hand-guiding force/torque (HGFT) is achieved by compensating for the tools weight/inertia. Inspired by the motion properties of a passive mechanical system, mass subjected to coulomb/viscous friction, it was implemented a control scheme to govern the linear/angular motion of the decoupled end-effector. Experimental tests were conducted in a KUKA iiwa robot in an assembly operation.

Keywords: hand-guiding, collaborative robot, end-effector

1 Introduction

Human-robot interaction has been studied along the last decades, from text-based programming to off-line programming [1] to the more recent intuitive techniques in which humans interact with the robots like interact with each other using natural means like speech, gestures and touch [2, 3]. In the touch interaction mode the robot can be hand guided to teach the required paths.

Hand-guiding is a representative functionality of collaborative robots, allowing unskilled users to interact and program robots in a more intuitive way than using the teach pendant. Existing collaborative robots include hand-guiding functionality with limitations in terms of the accuracy required for many tasks like assembly. For precision positioning (position and orientation of the end-effector) the teach pendant is still used (even for sensotive robots). The use of the teach pendant limits the intuitiveness of the teaching process provided by the hand guiding and it is time consuming (an important parameter on the factory floor). When the operator is using the teach pendant, he/she has to visualize mentally different reference axes of the robot. In some scenarious, the teach pendant based robot positioning can conduct to undesirable collisions, which can cause damage in sensitive equipment.

This paper presents a novel method for end-effector precision hand-guiding to be applied in collaborative robots equipped with joint torque sensors or with a force/torque sensor attached to the end-effector. It was implemented a control scheme that utilizes force feedback to compensate for the end-effector weight, so that a minimal effort is required from the operator to perform the hand-guiding motion. Inspired by the motion properties of a passive mechanical system, mass subjected to coulomb/viscous friction, it was implemented a control scheme to govern the linear/angular motion of the decoupled end-effector. Experimental tests were conducted in a KUKA iiwa 7 R800 robotic manipulator in an assembly operation requiring precision and fine tuning. It is demonstrated that the proposed method allows precise hand guiding with smooth robot motion in terms of position and orientation of the end-effector.

1.1 State of the art

The importance of collaborative robots and hand-guiding teaching is well known in the robotics community. It is still a challenge to have robots and humans sharing the same space performing collaborative tasks with the required safety levels to minimize the risk of injuries [4]. Human subjects can interact physically with a robot arm moving and guiding the robot into the desired grasping poses, while the robot's configuration is recorded [5]. Different control schemes for human-robot cooperation have been proposed, for example physical interaction in 6 DOF space using a controller that allows asymmetric cooperation [6]. Robot assistance through hand-guiding is also used to assist in the transport of heavy parts. In [7] it is studied the application of a human-industrial robot cooperative system to a production line. Safety, operability and the assistance of human skills were studied as they relate to hand-guiding. Hand-guiding teaching for conventional industrial robots are normally sensor based. In [8] it is proposed a sensor less hand guiding method based on torque control. The dynamic model of a robot along with the motor current and friction model is used to determine the users intention to move the end-effector of a robot instead of directly sensing the external force by the user.

The problem of Cartesian impedance control of a redundant robot executing a cooperative task with a human has been addressed in [9]. Redundancy was used to keep robots natural behavior as close as possible to the desired impedance behavior, by decoupling the end effector equivalent inertia. The authors claim that this allows easily finding a region in the impedance parameter space where stability is preserved. A method for using impedance control of multiple robots to aid a human moving an object and conducted an experiment with motion along one degree of freedom (DOF) was presented in [10].

In [11] it is proposed an approach for collision detection and reaction for an industrial manipulator with a closed control architecture and without external sensors. The robot requirements are the joint velocity, motor currents and joint positions. Robot assisted surgery demands high precision hand-guiding accuracy. An approach that enables an operator to guide a robot along a predefined geometric path while taking required joint constraints into account and thus implicitly considering the actuator dynamics is proposed in [12].

2 Work principal

Assuming force feedback at the robot end-effector (the robot may have joint torque sensors or a force/torque sensor attached to the end-effector), three groups of robot hand-guiding motion are considered, Fig. 1:

1. The first motion-group represent the positioning (with linear displacements) of the end-effector in the X,Y and Z coordinates system of the robot base;
2. The second motion-group is used for orienting the end-effector in the Cartesian space;
3. The third motion group is used to rotate the end-effector around its axis.

Those motion groups are introduced because they are the most intuitive for humans when we perform a motion that requires precision.

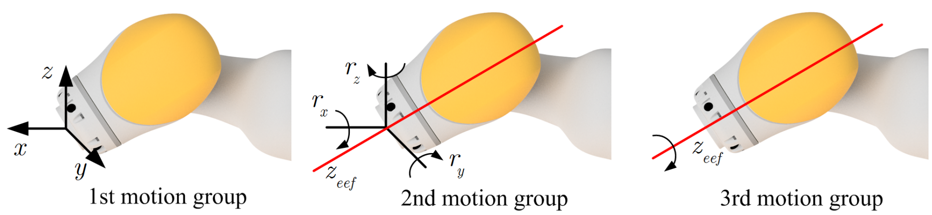

Fig. 1. The proposed robot motion groups for precision hand-guiding

Let us consider the hand-guiding force the force applied by the operator at the end-effector for linear positioning, and the hand-guiding moment the moment applied by the operator at the end-effector for angular positioning. The force/moment measurements represent the forces/moments due to (1) end-effector weight (2) the inertial forces/moments due to the acceleration of the end-effector, and (3) the external hand-guiding force/moment (to be applied by the operator for achieving hand-guiding). To simplify the calculations we omit the inertial forces/moments due to end-effector acceleration because in precise hand-guiding applications these inertial forces are relatively small compared to its weight and to the external forces/moments. The measured forces and torques can be approximated to be due to the hand-guiding forces and the weight of the end-effector. The components of the hand-guiding force described relative to the robot base frame are used as inputs for the proposed linear motion controller, i.e., for positioning the end-effector according to the robot base frame.

2.1 Hand-guiding force

The components of the hand-guiding force described in robot base frame $f^b = (f_x, f_y, f_z)$ serve as input to move the robot end-effector along the X, Y or Z directions of the robot base, 1st motion group. The maximum of the components (f_x, f_y, f_z) is used to calculate the control command to control the end-effector one axis at a time. Those hand-guiding forces (f_x^e, f_y^e, f_z^e) described on the end-effector reference frame are calculated by subtracting the weight of the end-effector from the measured forces:

$$\begin{bmatrix} f_x^e \\ f_y^e \\ f_z^e \end{bmatrix} = \begin{bmatrix} u_x^e \\ u_y^e \\ u_z^e \end{bmatrix} - \mathrm{R}_b^e \begin{bmatrix} 0 \\ 0 \\ w \end{bmatrix} \tag{1}$$

where (u_x^e, u_y^e, u_z^e) are the components of end-effector force/torque measurements, described in sensor frame (in this study the frame of the force/torque measurements is the same as the frame of the end-effector, otherwise a constant transform between the two frames can be introduced and the methodology described is still valid). Here, w is the weight of the end-effector and R_b^e is the rotation matrix from base frame to end-effector frame. This matrix is obtained from the transpose of the rotation matrix from the end-effector to the base frame:

$$\mathrm{R}_b^e = \left(\mathrm{R}_e^b\right)^{\mathrm{T}} \tag{2}$$

where R_e^b is obtained from the direct kinematics.

The hand-guiding force f^b described in base frame is calculated from:

$$f^b = \mathrm{R}_e^b \begin{bmatrix} f_x^e \\ f_y^e \\ f_z^e \end{bmatrix} \tag{3}$$

The force command f sent to the control algorithm is:

$$f = \begin{bmatrix} a & 0 & 0 \\ 0 & b & 0 \\ 0 & 0 & c \end{bmatrix} f^b \tag{4}$$

where we have to respect the following conditions:

a	b	c	*Condition*
1	0	0	$\lvert f_x\rvert > \lvert f_y\rvert$ && $\lvert f_x\rvert > \lvert f_z\rvert$
0	1	0	$\lvert f_y\rvert > \lvert f_x\rvert$ && $\lvert f_y\rvert > \lvert f_z\rvert$
0	0	1	$\lvert f_z\rvert > \lvert f_x\rvert$ && $\lvert f_z\rvert > \lvert f_y\rvert$

2.2 Hand-guiding moment

For end-effector orientation (2nd and 3rd motion group) the hand-guiding moment m^e shall be calculated from the end-effector force/torque measurements:

$$m^e = \begin{bmatrix} \tau_x^e \\ \tau_y^e \\ \tau_z^e \end{bmatrix} - \begin{bmatrix} \mu_x^e \\ \mu_y^e \\ \mu_z^e \end{bmatrix} \quad (5)$$

where $\left(\tau_x^e, \tau_y^e, \tau_z^e\right)$ are measurements of the three components of torques from the end-effector force/torque measurements, and $\left(\mu_x^e, \mu_y^e, \mu_z^e\right)$ are components of moment due to weight of end-effector described in end effector frame:

$$\begin{bmatrix} \mu_x^e \\ \mu_y^e \\ \mu_z^e \end{bmatrix} = \begin{bmatrix} 0 & -z_c^e & y_c^e \\ z_c^e & 0 & -x_c^e \\ -y_c^e & x_c^e & 0 \end{bmatrix} \mathrm{R}_b^e \begin{bmatrix} 0 \\ 0 \\ w \end{bmatrix} \quad (6)$$

where (x_c^e, y_c^e, z_c^e) are the coordinates of the center of mass of the end effector, described in the end-effector reference frame.

In the 2nd motion group, the end-effector axis z_{eef} is oriented in space, Fig. 1. For this type of motion the input to the controller is calculated from the hand-guiding moment. The input command is the vector m_{xy}. To calculate this vector, the vector m_{xy}^e shall be calculated first, where it represents the component of the hand-guiding moment in the XY plane of the end-effector frame, Fig. 2. The components of vector m_{xy}^e are described in sensor reference frame. This vector is calculated from:

$$m_{xy}^e = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} m^e \quad (7)$$

The input command for 2nd motion group is calculated from:

$$m_{xy} = \mathrm{R}_e^b m_{xy}^e \quad (8)$$

where m_{xy} represents the vector m_{xy}^e after being transformed to base frame.

For the 3rd motion group, the end-effector is allowed to rotate around its axis z_{eef}. For this type of motion the input command to the controller is the vector m_z^e. To calculate this vector, the vector m_z^e shall be calculated first, where it represents the Z direction of the end effector frame, as shown in the Fig. 3. This vector is calculated from:

$$m_z^e = m^e - m_{xy}^e \quad (9)$$

The controller command for the 3rd motion group is calculated from:

$$m_z = \mathrm{R}_e^b m_z^e \quad (10)$$

where m_z represents the vector m_z^e after being transformed to base frame.

Only one of motion group (2nd and 3rd motion group) is allowed to be performed once at a time. The motion command vector sent to the control algorithm m is calculated from:

$$m = \begin{cases} m_{xy} \ if \ \|m_{xy}\| > \|m_z\| \\ m_z \ \ if \ \|m_z\| > \|m_{xy}\| \end{cases} \quad (11)$$

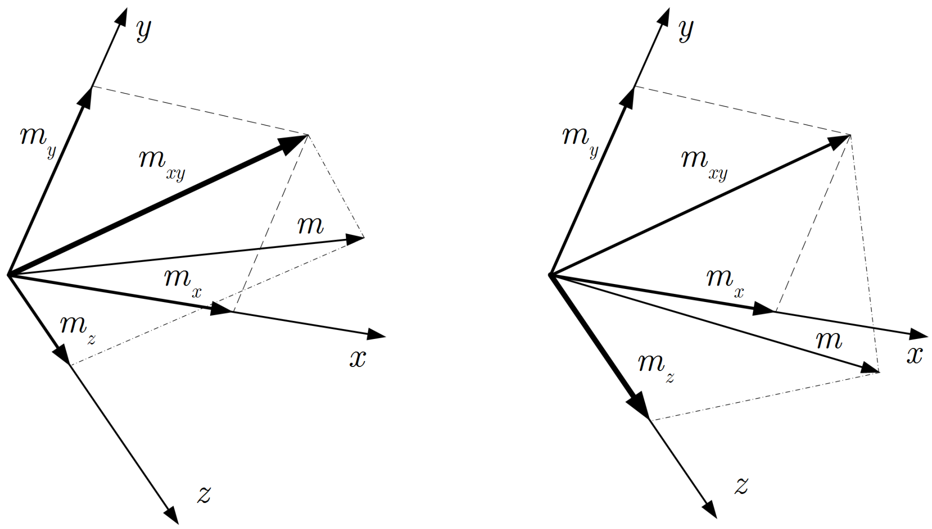

Fig. 2. Hand-guiding moment in sensor reference frame for 2nd motion group (at left) and for the 3rd motion group (at right)

3 Controller

The robot is controlled at the end-effector level, so that we consider the decoupled end-effector as a mass moving under the effect of Coulomb and viscous friction. The equation of linear motion of the center of gravity of the mass moving is:

$$m\ddot{x} + b\dot{x} + f_r = f \tag{12}$$

where $\ddot{x}$ is the linear acceleration of the center of mass, $\dot{x}$ is the linear velocity of the center of mass, m is the mass, b is the damping coefficient, f_r is Coulomb friction, and f is the external force acting on the mass. The equation of angular rotations around the center of gravity of the mass is:

$$i\ddot{\theta} + \beta\dot{\theta} + \tau_r = \tau \tag{13}$$

where $\ddot{\theta}$ is the angular acceleration around rotation axes, $\dot{\theta}$ is the angular velocity, i is the moment of inertia around the rotation axes, β is the damping coefficient, τ_r is the torque due to Coulomb friction, and τ is the external torque.

We consider that the Coulomb and viscous friction effects are much bigger than the effect of the inertia of the mass. In this context, the inertial factors from previous equations are omitted (Fig. 4) so that equation (12) becomes:

$$b\dot{x} + f_r = f \quad |f| > |f_r| \tag{14}$$

and:

$$\dot{x} = 0 \quad otherwise \tag{15}$$

where $|f|$ is the absolute value of the external force.

Equation (13) becomes:

$$\beta\dot{\theta} + \tau_r = \tau \quad |\tau| > |\tau_r| \tag{16}$$

and:

$$\dot{\theta} = 0 \quad otherwise \tag{17}$$

where $|\tau|$ is the absolute value of the external torque.

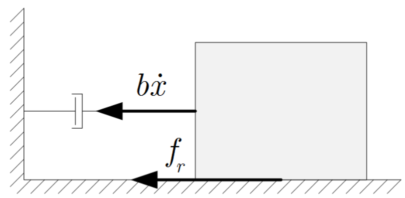

Fig. 3. Damper-mass mechanical system

3.1 Robot control

The linear motion of the end-effector is controlled by:

$$v = \begin{cases} \frac{f(\|f\| - \|f_r\|)}{b\|f\|} & \|f\| > \|f_r\| \\ 0 & otherwise \end{cases} \tag{18}$$

where v is the linear velocity vector of the end-effector, f is the force vector command issued to the controller, f_r is the sensitivity threshold (motion is only executed when the force command reaches a value above this threshold), and b is the motion constant that defines the rate of conversion from force measurement to velocity.

The angular motion of the end-effector is controlled by:

$$\varpi = \begin{cases} \frac{m(\|m\| - \|\tau_r\|)}{\beta\|m\|} & \|m\| > \|\tau_r\| \\ 0 & otherwise \end{cases} \tag{19}$$

where ϖ is the angular velocity vector of the end-effector, m is the moment command issued to the controller, τ_r is the sensitivity threshold (where motion is only valid when the force command value is higher than this threshold), and β is a motion constant that defines the rate of conversion from force measurement to velocity.

The end effector velocity $\dot{x}$ is:

$$\dot{x} = \begin{bmatrix} v \\ \varpi \end{bmatrix} \tag{20}$$

After calculating the velocity of the end-effector, angular and linear, joint velocities are calculated using the pseudo inverse of the Jacobean $\mathrm{J}^{\dagger}$:

$$\dot{q} = \mathrm{J}^{\dagger}\dot{x} \tag{21}$$

From the angular velocities and by using an iterative solution, the state space vector can be calculated, which is used to control the manipulator, Fig. 4.

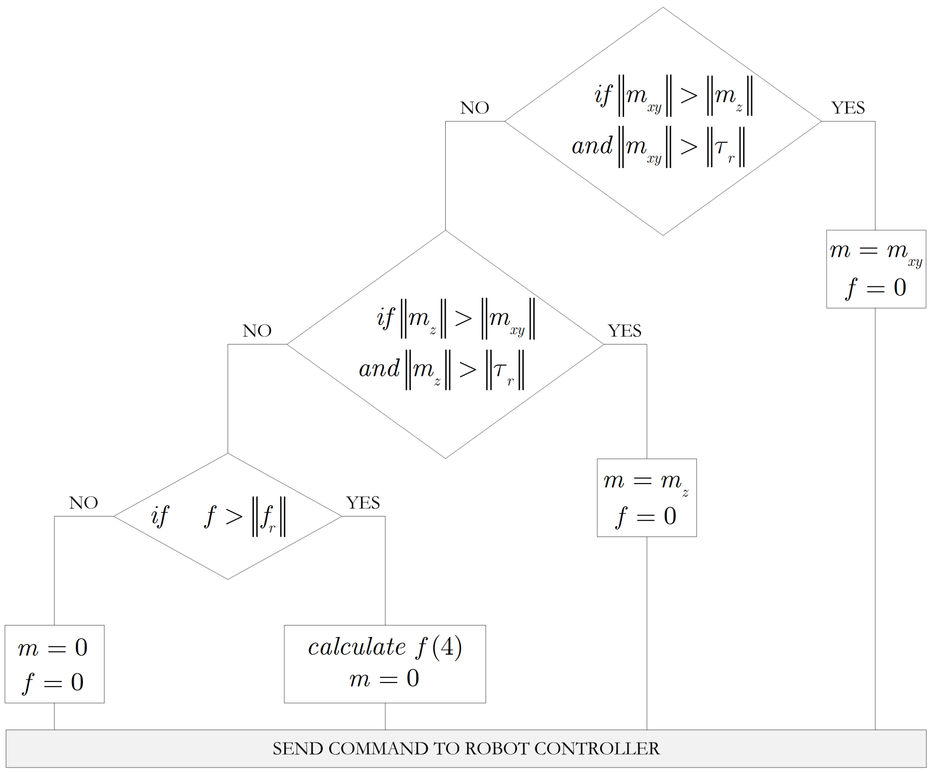

Fig. 4. Robot control algorithm

4 Experiments and results

The experiments were performed in a KUKA iiwa 7 R800 robotic manipulator in an assembly operation requiring precision positioning and fine tuning. The off-the-shelf hand-guiding functionality provided by KUKA lacks in the precision that is crucial for fine and precise positioning of the end-effector for many applications. The proposed method was implemented in a control loop updated at each 8.5 milliseconds. The controller compensates automatically for the piece weight such that when no force is applied by the operator, the piece is held in place by the robot. Different tests demonstrated that in the 1st motion group the robot position along X, Y and Z can be precisely adjusted, in the 2nd motion group the end-effector rotation around X, Y and Z is achieved, while in the 3rd motion group we can rotate around the end-effector axis with accuracy, Fig. 5. Fig. 6 shows the end-effector position along Y axis according to a given applied force. It is clear to visualize the end-effector displacement when the force is applied. The proposed hand-guiding method accuracy was measured and compared with a nominal path in plane xy, Fig. 7. The operator moves the end-effector along the y axis (250 mm) so that it was achieved a maximum error of 0.09 mm along x direction. In summary, it was demonstrated that the precision hand-guiding abilities of the proposed method work well and are useful in collaborative robotics.

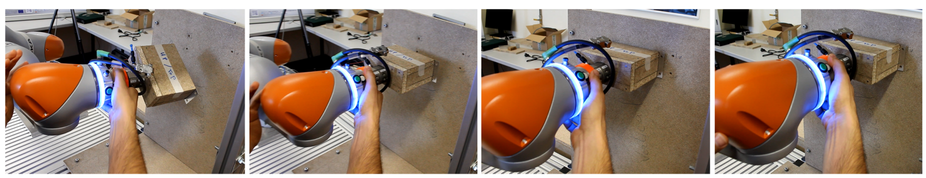

Fig. 5. Precision hand-guiding for assembly operation

5 Conclusion and future work

A novel precision hand-guiding method at end-effector level for collaborative robots was proposed. Experimental tests demonstrated that with the proposed method it is possible to hand-guide the robot with accuracy, with no vibration, and in a natural way by taking advantage of the proposed three motion groups. It was also demonstrated that the system is intuitive and compares favorably with off-the-shelf KUKA hand-guiding. Future work will be focused on optimizing the control by utilizing the redundancy of the KUKA iiwa for achieving better stiffness while hand-guiding, and also for avoiding collisions with obstacles while hand-guiding. In addition the control can be optimized to give some feedback to the user when reaching near the joint limits.

Acknowledgments

This research was partially supported by Portugal 2020 project DM4Manufacturing POCI-01-0145-FEDER-016418 by UE/FEDER through the program COMPETE 2020, the European Unions Horizon 2020 research and innovation programme under grant agreement No 688807 - ColRobot project, and the Portuguese Foundation for Science and Technology (FCT) SFRH/BD/131091/2017.

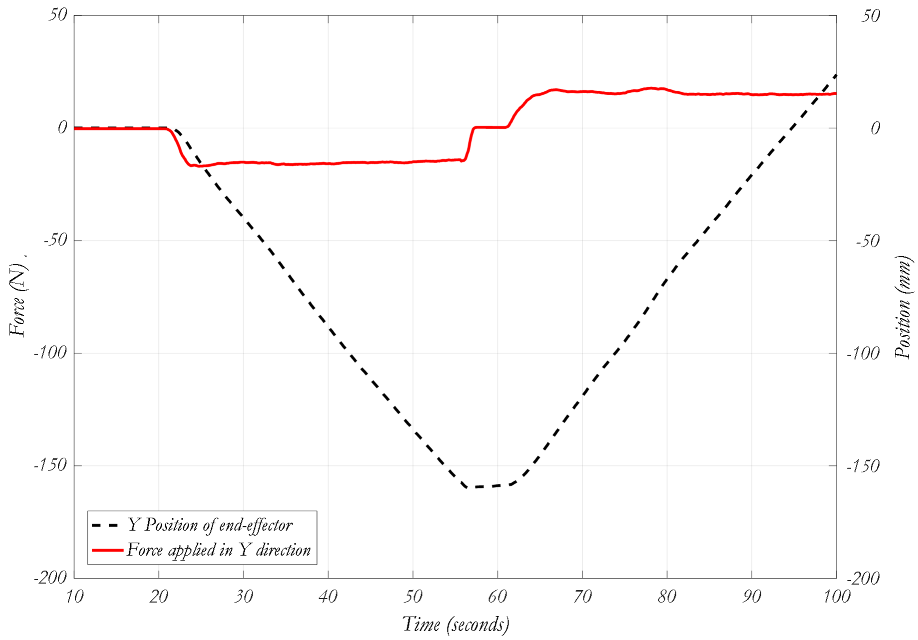

Fig. 6. End-effector position along y axis according to applied force

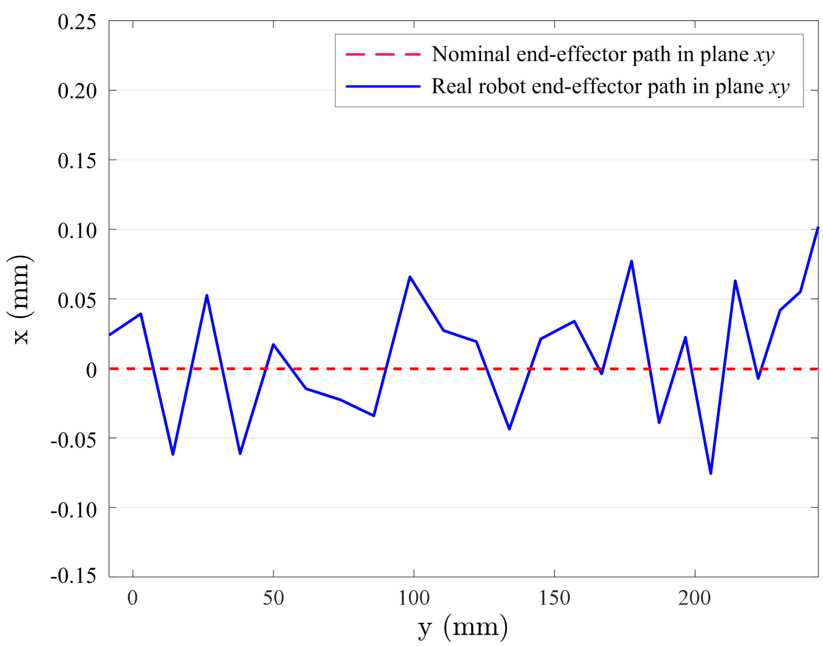

Fig. 7. Nominal end-effector path against the real robot end-effector path in plane xy

References

1. Neto, P., Mendes, N.: Direct off-line robot programming via a common CAD package. Robotics and Autonomous Systems, vol. 61, no. 8, pp. 896-910 (2013). doi:10.1016/j.robot.2013.02.005
2. Neto, P., Pereira, D., Pires, J.N., Moreira, A.P.: Real-time and continuous hand gesture spotting: An approach based on artificial neural networks. 2013 IEEE International Conference on Robotics and Automation (ICRA), pp. 178-183 (2013). doi:10.1109/ICRA.2013.6630573
3. Simao, M.A., Neto, P., Gibaru, O.: Unsupervised Gesture Segmentation by Motion Detection of a Real-Time Data Stream. IEEE Transactions on Industrial Informatics, vol. 13, no. 2, pp. 473-481 (2017). doi:10.1109/TII.2016.2613683
4. Haddadin, S., Albu-Schaffer, A., Hirzinger, G.: Requirements for safe robots: Measurements, analysis and new insights. Int. J. of Robotics Research, vol. 28, no. 11/12, pp. 15071527 (2009). doi:10.1177/0278364909343970
5. Balasubramanian, R., Xu, L., Brook, P.D., Smith, J.R., Matsuoka, Y.: Physical Human Interactive Guidance: Identifying Grasping Principles From Human-Planned Grasps. IEEE Transactions on Robotics, vol. 28, no. 4, pp. 899-910 (2012). doi: 10.1109/TRO.2012.2189498
6. Whitsell, B., Artemiadis, P.: Physical Human-Robot Interaction (pHRI) in 6 DOF with Asymmetric Cooperation. IEEE Access, vol. 5, pp. 10834-10845 (2017). doi: 10.1109/ACCESS.2017.2708658
7. Fujii, M., Murakami, H., Sonehara, M.: Study on Application of a Human-Robot Collaborative System Using Hand-Guiding in a Production Line. IHI Engineering Review, Vol.49 No.1 pp. 24-29 (2016).
8. Lee, S.D., Ahn, K.H., Song, J.B.: Torque control based sensorless hand guiding for direct robot teaching. 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 745-750 (2016). doi:10.1109/IROS.2016.7759135
9. Ficuciello, F., Villani, L., Siciliano, B.: Variable Impedance Control of Redundant Manipulators for Intuitive HumanRobot Physical Interaction. IEEE Transactions on Robotics, vol. 31, no. 4, pp. 850-863 (2015). doi:10.1109/TRO.2015.2430053
10. Kosuge, K., Yoshida, H., Fukuda, T.: Dynamic control for robot-human collaboration. Proceedings of the 2nd IEEE International Workshop on Robot and Human Communication, pp. 398-401 (1993). doi:10.1109/ROMAN.1993.367685
11. Geravand, M., Flacco, F., De Luca, A.: Human-Robot Physical Interaction and Collaboration using an Industrial Robot with a Closed Control Architecture. 2013 IEEE International Conference on Robotics and Automation, pp. 4000-4007 (2013). doi:10.1109/ICRA.2013.6631141
12. Hanses, M., Behrens, R., Elkmann, N.: Hand-guiding robots along predefined geometric paths under hard joint constraints. 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1-5 (2016). doi:10.1109/ETFA.2016.7733600