Precise hand-guiding of redundant manipulators with null space control for in-contact obstacle navigation

Mohammad Safeea
Department of Mechanical Engineering
University of Coimbra
Coimbra, Portugal
ms@uc.pt

Pedro Neto
Department of Mechanical Engineering
University of Coimbra
Coimbra, Portugal
pedro.neto@dem.uc.pt

Richard B*éarée*
Arts et Métiers,
LISPEN,
Lille, France
richard.bearee@ensam.eu

***Abstract*—Hand-guiding of collaborative redundant manipulators allows an unskilled user to interact and program the robot intuitively. Many industrial applications require precise positioning at the end-effector (EEF) level inside cluttered environments, where manipulator's redundancy is required. Yet, the potentialities of redundancy while hand-guiding at EEF level are not fully explored. This paper addresses the subject of precision in hand-guiding at EEF level while using the redundancy for in-contact obstacle navigation. In the presence of a contact with an obstacle, the proposed null space control method actuates in a way that the manipulator slides compliantly with its structure on the body of the obstacle while preserving the precision of the hand-guiding motion at EEF level. Force/torque (FT) data from a FT sensor mounted at the robot flange are the input for EEF precision hand-guiding while the torque data from the joints of the manipulator represent the contact between robot structure and obstacles. Experimental tests were carried out successfully using a KUKA iiwa industrial manipulator with 7 degrees of freedom (DOF). Where, the EEF is hand-guided on a straight line while the robot is sliding on the obstacle with its structure, results indicate the precision of the proposed method.**

***Index Terms*—obstacle avoidance, redundant robots, null space control, precise hand-guiding, collaborative robotics.**

I. Introduction

The paradigm for robot usage has changed in the last few years from a concept in which robots work autonomously to a scenario where robots collaborate with human beings. By taking advantage of the best abilities of each partner, the coordination and cognitive capabilities of humans and the accuracy and capacity to produce monotonous work of robots.

For achieving the long sought goal of having robots in human centred environments, collaborative robots (Cobots) shall be safe to humans during physical human-robot interaction [1] [2], and shall detect collisions with surroundings [3]. In addition, robots and humans have to communicate and interact with each other in a natural and intuitive way. Traditional human-robot interfaces relying on text-based programming or using the teach pendant are not intuitive to use, time-consuming and require technical expertise. As such, hand-guiding is a representative functionality of collaborative robots that allows unskilled users to interact with robots in an intuitive manner. Considering such interface, the robot moves compliantly according to the user guidance by applying an external force/torque on the robot structure, normally on the EEF. Some existing collaborative robots include joint level hand-guiding functionality with limitations concerning the capacity to reach the accuracy required for many industrial tasks [4]. Other robot manipulators, normally equipped with a FT

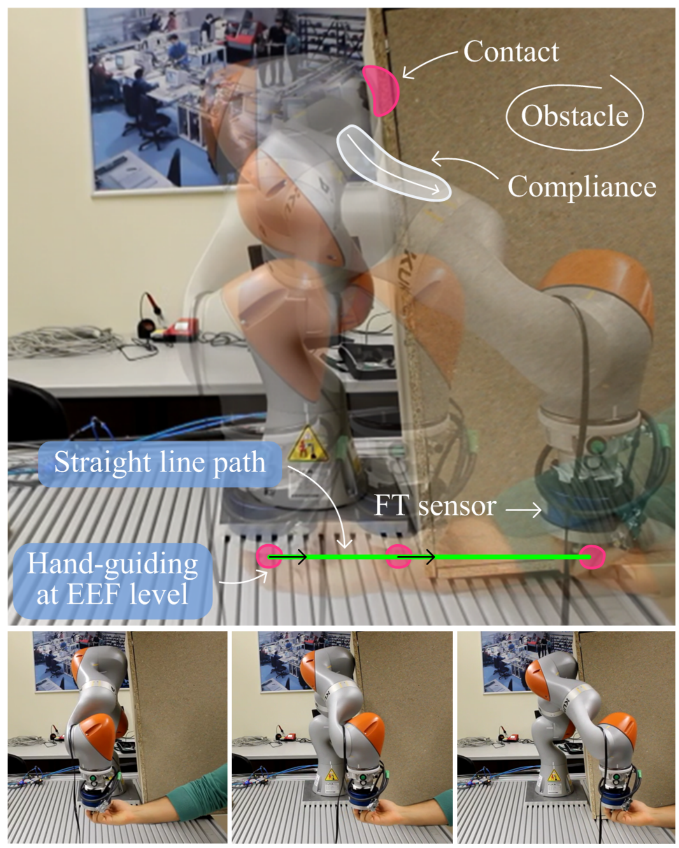

Fig. 1. Precision hand-guiding on a straight line (along y axis) of a redundant robot subject to a contact with obstacle. An external FT sensor is attached at the robot flange.

sensor, allow hand-guiding interface by applying an external force, normally on the EEF. In robotics community, different terminologies have been used by researchers to describe robot hand-guiding and teaching, namely the manual-guidance [5], force-guidance [6], lead-through programming [7], or walk-through programming [8].

Robot hand-guiding associated to robot programming has been extensively studied in recent years. Hand-guiding is gaining popularity in robotics community, offering advantages over the conventional teach-in process. Those advantages are identified in a study that compares different methods to interface a robot [6]. The authors concluded that by comparing the hand-guiding with the teach pendant interface, the hand-guiding offers better performance in terms of agility and level of intuitiveness.

By gaining an access to motor current measurements, hand-guiding can be achieved without the need to install an external FT sensor on the manipulator [9]. A sensorless hand-guiding method based on torque control is proposed in [10]. The dynamic model of the robot along with the motor current and friction model is used to determine the user's intention to move the EEF of a 6 DOF robot. In [7], the authors presented a sensorless method for hand-guiding the EEF in a structured surrounding. Impedance control in Cartesian space and its application for human robot collaboration has been presented in [11]. In another study, the authors explored the use of different input instruments and several implementation techniques for achieving hand-guiding functionality optimized for the use in industrial production lines [12]. The assisted gravity compensation method is presented in [13]. This method facilitates the hand-guiding process, making it more intuitive for unskilled users. A virtual tool method for kinesthetic teaching of robotic manipulators is proposed in [14]. The method builds on an admittance controller that utilizes the feedback from a FT sensor attached at the EEF. In a recent study an operator guides a collaborative robot along a predefined geometric path while taking required joint constraints into account and thus implicitly considering the actuator dynamics [15]. Kinesthetic teaching and learning have been combined to enable non-experts to configure and program a redundant robot in the presence of constraints such as confined spaces [16].

Yet, non of the listed studies, except in [4], has touched on the subject of precision. Accurate positioning of the EEF is required for many industrial applications, for example in precise assembly operations. In such a case, the teach pendant is widely used [17], while it offers precision the teach pendant has several relative drawbacks:

1) When using the teach pendant to position the EEF, the user has to keep a track of the orientation of the motion's reference frame. This lacks intuitiveness [18], and could become confusing even for the experienced worker;
2) The teach pendant convention in describing the orientation is the Euler rotation angles. This way for describing orientation is not intuitive for humans;

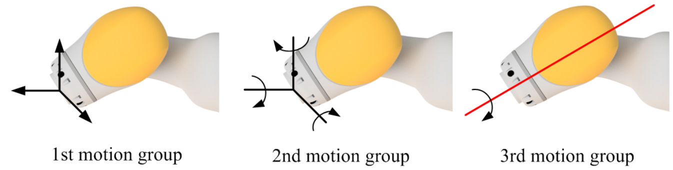

Fig. 2. Precise hand-guiding motion groups.

3) Unlike the hand-guiding, when using the teach pendant the user does not have a feel of the force applied between the robot and its surrounding in case of contact. In sensitive assembly tasks accidents could happen and the user might over press the sensitive instrument against the surrounding without having a feel of it.

We presented the precision hand-guiding functionality [4], a more intuitive way to position the EEF of the robot precisely. Our previous work did not touch on the redundancy of the industrial manipulators, which can be used to achieve secondary tasks, like avoiding obstacles, while performing the primary task, precise guiding of the EEF.

This paper proposes a novel method for precision hand-guiding at EEF level in which the robot redundancy is used to avoid obstacles during contact between the robot structure and the surrounding environment. Force/torque (FT) data from the FT sensor mounted at the manipulator's flange are the input for EEF precision hand-guiding while the torque data from the joints of the robot are the input to sense the contact between robot structure and obstacles. In the presence of physical contact between the obstacle and the manipulator, it compliantly slides with its structure on the body of the obstacle, controlled by the proposed null space control method. According to our knowledge, there is no study that addresses in-contact obstacle avoidance of a manipulator precisely hand-guided at the EEF level. Experimental tests were carried out successfully using a KUKA iiwa industrial manipulator with 7 degrees of freedom (DOF) and a JR3 FT sensor (attached at the EEF), Fig. 1.

II. Precise hand-guiding and motion groups

Recently, we presented a method for precision positioning through hand-guiding for robotic manipulators [4]. 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. The EEF can be guided precisely along a straight line, while its orientation can be adjusted in two steps according to the moment applied at the EEF. To address the precision requirements, each motion allowed by the precision hand-guiding is constrained in specific way, so the allowed motions can be divided into three main motion groups, demonstrated in the multimedia material available in [19]:

1) First motion group, Fig. 2 (left): in this case the motion of the EEF is constrained on a line parallel to the (x,y and z) axes of the robot base frame, once at a time. The

orientation of the EEF is kept fixed while performing the motion similar to teach pendant convention, but with a difference where the velocity is controlled according to hand-guiding force applied by the user at FT sensor;

2) Second motion group, Fig. 2 (middle): in this case the operator can orient the z axis of EEF frame by applying a moment on FT sensor. In such a case the position of the EEF is kept fixed, and there is no rotation of the EEF around its z axis;
3) Third motion group, Fig. 2 (right): in this case the user can rotate the EEF of the robot round its z axis. The position of the EEF is fixed, and the orientation of the EEF's axis is also fixed.

Those motion groups are introduced because they are the most intuitive for humans when positioning/orienting an object in space.

The hand-guiding force is defined as the force applied by the operator at the EEF for linear positioning and the hand-guiding moment is defined as the moment applied by the operator at the EEF for angular positioning. The measurements from the FT sensor represent the forces/moments due to (1) EEF weight (2) the inertial forces/moments due to the acceleration of the EEF, and (3) the external hand-guiding force/moment applied by the operator for achieving hand-guiding. These data are processed so that the hand-guiding force/moment for robot control at the EEF level can be calculated. To simplify calculations, the inertial forces/moments due to EEF linear/angular acceleration are omitted. In precise hand-guiding applications motion accelerations are relatively small, as a result the inertial forces/moments of the EEF are negligible in comparison to the EEF weight and to the external forces required for the hand-guiding operation. The components of the hand-guiding force described in robot base frame serve as an input for moving the EEF along the x, y or z directions of the base frame of the robot (first motion group). The maximum value of the force components along x, y or z is used as command to control the EEF one axis at a time. On the other hand, for performing angular rotation of the end-effector, the hand-guiding moment is utilized. From the hand-guiding force and moment the control command is calculated. This control command acts on a virtual passive-mechanical-model of the decoupled end-effector, causing the motion of the EEF [4].

III. JOINT TORQUES COMPENSATION

For calculating the joint torques generated by the contact between the robot structure and an obstacle, the force/moment due to the (1) hand-guiding, (2) weight of the EEF (tool mounted at FT sensor), and (3) the weight of FT sensor are considered. The effect of those forces/moments on joints torques shall be accounted for. This procedure is referred to as the torques compensation in which two main groups are distinguished:

1) Compensation for the torques due to sensor weight, which also includes the weight of the adapter flange used to mount the FT sensor on the robot. This weight and its Center-Of-Mass (COM) are previously known. Consequently, the torque compensation is applied directly after calculating the Jacobian associated with COM as described in sub-section III-A;
2) Compensation for the torques due to external force/moment acting at the FT sensor. This force/moment is measured by the FT sensor, it includes the weight of EEF (mounted at the FT sensor) and the hand-guiding force/moment applied by the human, as described in sub-section III-B.

A. Sensor weight compensation

For EEF motions with relatively small accelerations (the case in precision hand-guiding), the forces/moments due to the inertia of the sensor, EEF and the mounting flange can be neglected in comparison to their weight. Thus, to compensate the torques generated due to the weight of the sensor and the mounting flange $\boldsymbol{\tau}_{ws}$, the Jacobian $\mathbf{J}_{ws}$ associated with their COM is utilized:

$$\boldsymbol{\tau}_{ws} = \mathbf{J}_{ws}^{\mathrm{T}} \begin{bmatrix} 0 & 0 & -w_s & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} \tag{1}$$

Where w_s is the weight of the sensor (including mounting flange). The previous equation is valid for base mounted robots, where the base is mounted horizontally, otherwise the orientation of the base frame shall be considered.

B. External-Force/Moment compensation

The external forces/moments acting on the FT sensor shall be compensated for. Those forces/moments include: 1) the hand-guiding force/moment applied by the worker and 2) the EEF (tool's) weight and its inertial forces due to motion, both of them are measured directly by the FT sensor (giving that in our method the EEF is mounted at the FT sensor). For calculating the torques $\boldsymbol{\tau}_{fs}$ due to external forces/moments, the Jacobian $\mathbf{J}_s$ associated with the origin of the measurement frame of the FT sensor is considered:

$$\boldsymbol{\tau}_{fs} = \mathbf{J}_{s}^{\mathrm{T}} \begin{bmatrix} \mathbf{R}_s^b & 0 \\ 0 & \mathbf{R}_s^b \end{bmatrix} \begin{bmatrix} \boldsymbol{f}_{fs} \\ \boldsymbol{m}_{fs} \end{bmatrix} \tag{2}$$

Where $\boldsymbol{f}_{fs}$ and $\boldsymbol{m}_{fs}$ are the force and the moment measured at the FT sensor, respectively. Those force and moment quantities are due to the hand-guiding force/moment plus the weight of the EEF. The joint torques vector $\boldsymbol{\tau}_{fs}$ is due to $\boldsymbol{f}_{fs}$ and $\boldsymbol{m}_{fs}$, and $\mathbf{R}_s^b$ is the rotation matrix from the measurement frame of the sensor to the base frame of the robot.

C. Joint torques due to contact with obstacles

After calculating the compensation torques $\boldsymbol{\tau}_{ws}$ and $\boldsymbol{\tau}_{fs}$, the torques due to contact with an obstacle $\boldsymbol{\tau}_c$ can be calculated:

$$\boldsymbol{\tau}_c = \boldsymbol{\tau}_r - \boldsymbol{\tau}_{fs} - \boldsymbol{\tau}_{ws} \tag{3}$$

Where $\boldsymbol{\tau}_r$ is the vector of external torque due to external contact forces. This vector can be directly acquired from the robot controller in case we are using a robot that provides such data, for example the industrial manipulator KUKA iiwa. Alternatively, if only raw torque measurements at robot joints are provided, the inverse dynamics equation of the robot shall be utilized, such that the torques due to (1) joints angular acceleration (2) Coriolis/centrifugal effect, (3) friction at joints and (4) torques due to gravity, are subtracted from the torques measurements acquired at the joints sensors. In such case, the precision of the calculation depends mainly on the precision of the dynamical model used to describe the manipulator's dynamics given that the torque sensors integrated at the robot joints have enough precision.

Finally, the torques vector $\boldsymbol{\tau}_c$ due to external contact forces with an obstacle is used to calculate the motion in the null space, as described in sub-section IV-A.

IV. Control strategy

A. Contact controller

Considering that a human user hand-guides the EEF precisely using the measurements from the FT sensor [4], the least squares solution is used for calculating the joints angular velocities vector $\dot{\boldsymbol{q}}_{hg}$. This control command generates the required hand-guiding motion for the EEF.

In the presence of obstacles, and due to contact forces between the structure of the robot and the obstacles, extra torques start to appear at the joints. Those torques, $\boldsymbol{\tau}_c$, are calculated after acquiring measurements from torque sensors at the joints of the robot and FT sensor measurements at the EEF, as described in the previous section. The torques vector $\boldsymbol{\tau}_c$ is then used as an input to the contact controller. The output of the contact controller is the null space angular velocities $\dot{\boldsymbol{q}}_n$:

$$\dot{\boldsymbol{q}}_n = \mathbf{N}(\boldsymbol{q})\mathbf{A}\boldsymbol{\tau}_c \tag{4}$$

Where, $\mathbf{N}(\boldsymbol{q})$ is the null space matrix of the robot calculated using the joints position feedback $\boldsymbol{q}$ from the robot and $\mathbf{A}$ is a diagonal matrix with constant coefficients.

B. Control command

The total command used to control the robot is the sum of (1) null space angular velocity vector, which allows the robot to slide on the obstacle, and the (2) angular velocity vector for hand-guiding:

$$\dot{\boldsymbol{q}} = \dot{\boldsymbol{q}}_{hg} + \dot{\boldsymbol{q}}_n \tag{5}$$

V. Experiments and results

The proposed methodology was tested using a KUKA iiwa 7 R800 robot. This is an industrial sensitive collaborative robot with 7 DOF provided with torque sensors integrated into its joints. An external FT sensor, JR3, is attached at the flange of the robot. The robot was controlled from external computer using KUKA Sunrise Toolbox [20].

Fig. 3 shows the proposed experimental setup. The robot is hand-guided by applying a force on the FT sensor in the y direction of the robot base frame. In consequence, the robot EEF moves along a straight line in that direction. Meanwhile, during hand-guiding, the robot's structure collides with an obstacle, a box in the way of the robot. The robot adjusts its configuration, by utilizing its redundancy, and slides smoothly on the obstacle with its structure. As a result, the robot is able to keep moving on a straight line along the y direction while navigating the obstacle during the contact. In traditional hand-guiding solutions at EEF level, the robot is blind to its surrounding, such that it keeps pushing with its structure against the obstacle causing joints-torques/motors-currents to increase triggering an emergency stop. The video in [19] demonstrates the experimental test. During the experimental test, various data were recorded including 1) robot joints angular positions, Fig 4, 2) external torque measurements at robot joints, Fig 5, 3) force measurements from the FT sensor, Fig 6 (these measurements, represented in robot base frame, are compensated for the weight of EEF) and 4) positional data of the EEF, Fig 7.

From Fig. 6 it is noticed that at the beginning of the test the operator applies a hand-guiding force at EEF, mainly along the y direction of the base frame. As a result, the EEF starts moving in the positive y direction, Fig. 7. From the joints torques graph, Fig. 5, it is noticed that at around 2 seconds from the beginning of the test, a contact between the robot structure and the obstacle is initiated. After the contact the torques acting on the first and the third joints increase. Owing to the proposed null space control, the rate of motion of the robot joints also increase. This is evident in the joint angles graph, Fig. 4, where the rate of change of the angular positions increase due to the null space motion. This allows the EEF to move as desired by the operator, without conflict due to the presence of the obstacle.

To show the precision of the motion, the actual path of EEF (as recorded from the robot controller) is plotted in the XY plane, Fig. 8, and in the ZY plane, Fig. 9. It is shown that the actual path deviates from a straight line. From the plots the maximum error of the actual path in the x and z directions are 0.52 and 0.51 mm, respectively. As a comparison, we carried out the same test with KUKA off-the-shelf hand-guiding, joint level controlled, moving the EEF in a line parallel to the y direction. The error achieved is of order of centimeters. Depending on the user, errors as big as 3 cm and 5 cm in the x and the z directions respectively has occurred, an expected result since that hand-guiding the robot at the joints level does not guarantee precision at the EEF level (in best case possible the robot can be as precise as the human operator can be).

VI. Conclusion

In this study it was presented a novel method for precision hand-guiding of industrial manipulators with obstacle avoidance capability. Unlike traditional hand-guiding solutions, we take advantage of robot redundancy to avoid in-contact obstacles between the manipulator's structure and the surrounding environment while achieving precision at EEF level. Torque measurements from robot joints are coupled together with the measurements from an external FT sensor. The acquired sensory data are then treated for calculating two

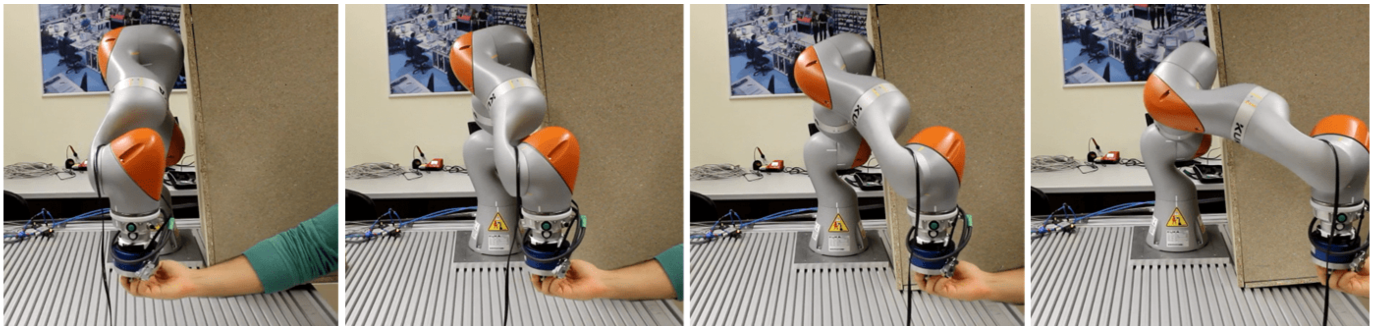

Fig. 3. Experimental setup. The robot is hand-guided to perform a straight line motion and compliantly avoids the obstacle taking advantage of the redundant axis.

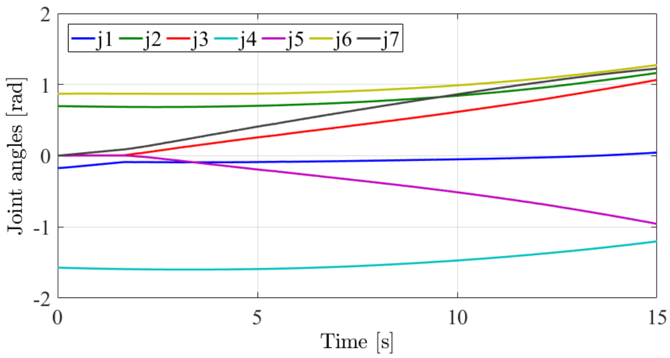

Fig. 4. Robot joints angular positions.

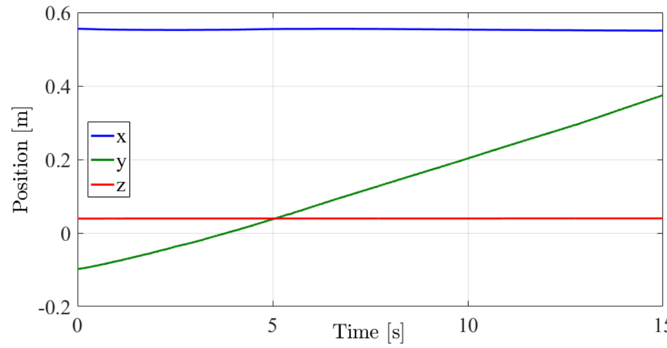

Fig. 5. External torques measurment at the robot joints.

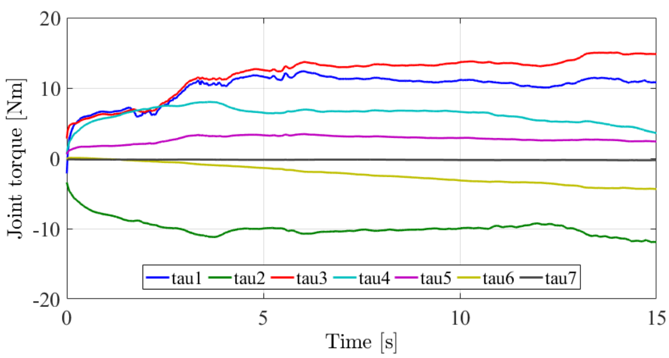

Fig. 6. Components of hand-guiding force described in base frame of the robot (data acquired from the FT sensor).

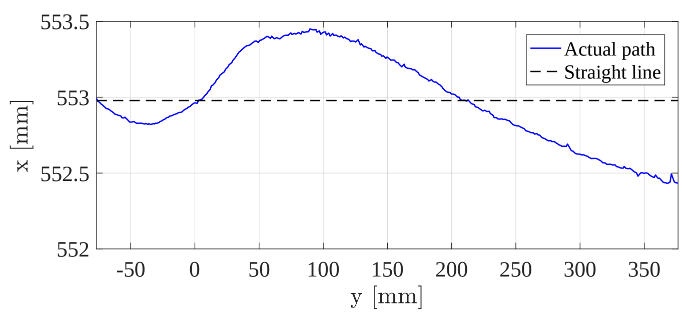

Fig. 7. Positional data of the EEF.

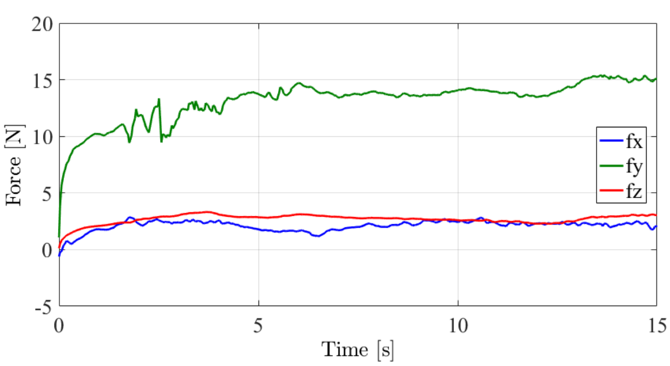

Fig. 8. Actual path in XY plane.

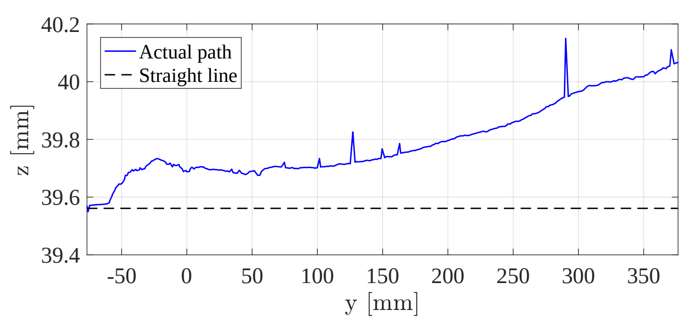

Fig. 9. Actual path in ZY plane.

essential quantities: (1) the torques due to contact forces and (2) the hand-guiding force and moment. Using these data a control scheme is proposed such that the manipulator is able to compliantly slide on obstacles during the contact while precisely hand-guided at the EEF level. Tests were carried out successfully on KUKA iiwa robot. From the results it is concluded that the robot successfully manages to perform the desired hand-guiding path with precision while avoiding excessive contact forces with the surrounding environment. As compared to joint level hand-guiding, the proposed method gives superior precision with order of magnitude.

VII. Acknowledgment

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