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Vision Based Virtual Fixture Generation for Teleoperated Robotic Manipulation

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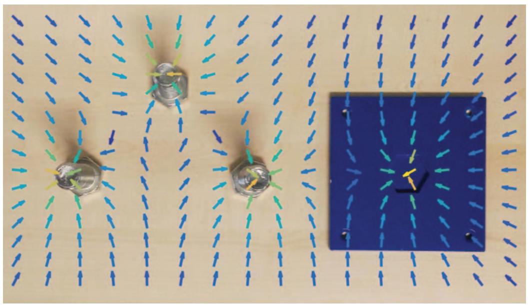
***Abstract*— In this paper we present a vision-based system for online virtual fixture generation suitable for manipulation tasks using remote controlled robots. This system makes use of a stereo camera system which provides accurate pose estimation of parts within the surrounding environment of the robot using features detection algorithms. The proposed approach is suitable for fast adaptation of the teleoperation system to different manipulation tasks without the need of tedious re-implementation of virtual constraints. Our main goal is to improve the efficiency of bilateral teleoperation systems by reducing the human operator effort in programming the system. In fact, using this method virtual guidances do not need to be programmed *a priori* but they can be instead dynamically generated on-the-fly and updated at any time making, in the end, the system suitable for any unstructured environment. In addition, this methodology is easily adaptable to any kind of teleoperation system since it is independent from the used master/slave robots. In order to validate our approach we performed a series of experiments in an emulated industrial scenario. We show how through the use of our approach a generic telemanipulation task can be easily accomplished without influencing the transparency of the system.**

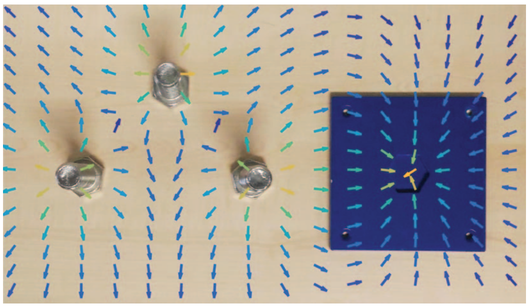
***Index Terms*— vision-based virtual fixtures generation, enhanced telemanipulation, shared control, human-in-the-loop**

I. Introduction

Teleoperated robots represent a great tool for disaster or unknown environments where the level of uncertainty makes autonomous machines hardly employable. In the past decades it has been shown that in these scenarios a human operator teleoperating a robot can overcome challenging tasks thanks to the ability of sensing the remote environment through force feedback. However, when the complexity of the task or the degree of redundancy of the slave robot gets higher, shared or supervisory control can be adopted to help the operator to handle such situations. In particular, shared control has the purpose of enhancing the human experience in teleoperating slave robot mainly through the use of *virtual fixtures*. Virtual fixtures can help the human operator to perform safe and precise movements which are essential in many robotics application such as in robotic surgery. Many types of virtual fixtures have been proposed in the past, an exhaustive overview can be found in [1]. One of the main drawbacks of using virtual fixtures is that they usually require tedious offline programming before they can be efficiently employed. In addition, their usage is often suitable for one particular task and requires re-programming if another task has to be performed with the same telerobotic system. In our work we focus on the enhancement of the shared control technique by presenting the implementation of a vision-based method for efficient online virtual fixtures generation in partially known environments. Our approach is independent from any used master/slave robot making it suitable for any different teleoperation system. In addition, since in such systems the delay makes the closed loop system unstable, we show that our approach does not influence the passivity condition.



(a) Force field obtained from attractive potentials.



(b) Force field obtained from attractive and repulsive potentials.

Fig. 1. Two examples of force fields obtained from artificial potentials projected into the horizontal plane: yellow arrows represent higher magnitude forces.

We tested our approach using a teleoperation system composed of a Force Dimension Omega 7 Haptic Device as master and Kuka LWR4+ robot as slave device. The considered environment is intended to reproduce an industrial application in which only partial knowledge of the environment is provided in advance to the human operator. Virtual constraints, consisting in additional forces on the master side of the teleoperation system, are computed on-the-fly using a stereo camera system mounted on the robot in eye-in-hand

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configuration. Without loss of generality, artificial potentials have been used as constraint enforcement method on particular points provided by the vision, but the system is suitable for any type of both geometric constraints and associated forces. We show how our system can help the operator to perform constrained movement avoiding obstacles thus reducing the overall human workload.

II. Related Work

Virtual fixtures have been originally introduced by Rosemberg in his works [2] and [3]. In these works the author explains the beneficial effects of perceptual overlay at the master interface. During the last years, virtual fixtures have been always used as static constraints programmed *a priori* making them hardly adaptable to different kinds of tasks. Interactive generation of active constraints has been previously investigated by Bettini et al. [4]: in their work the authors used computer vision as sensor for providing reference trajectory to the virtual fixture control algorithm. Recently, many virtual fixtures related issues have been addressed for their safe use in shared control teleoperation. Efficient dynamic virtual fixtures re-computation has been shown in [5] for UAV teleoperation. In this work the authors showed that the operator can provide interventions useful to redirect the autonomous slave robot while receiving force feedback. In this way, unpredictable obstacles can be safely avoided through human input. Ferraguti et al. in [6] proved a passivity preserving condition for redirection of virtual fixture forces in surgical robotics. Shared control teleoperation for industrial applications is an active research topic. Comparison between shared control and normal teleoperation in terms of task performance, control effort and cognitive operator workload in a bolt-spanner task can be found in Boessenkool's work in [7]. In addition, Vozar et al. in [8] analyzed the improvement caused by the use of non-holonomic constraints in time delayed teleoperation in space applications, while Smisek et al. experimentally quantified the effect of guidance inaccuracy during a peg-in-hole insertion task [9].

From a more general point of view, telerobotic systems have been widely investigated in the past in terms of performances. Transparency, intended as the capability of transferring the task impedance to the human operator located at the master side, is mainly limited by stability issues. The destabilizing effect of the closed loop system increases with communication delay, unavoidable in any teleoperation architecture. Lawrence in [10] showed that it is possible to find a trade-off between transparency and stability regardless of the used teleoperation scheme. In our work, for the purpose of achieving passive behavior we use two-layer approach from Franken et al. [11] which is an algorithm based on energy tanks concept.

The main contribution of this paper is the enhancement of robotic bilateral teleoperation through an online virtual fixtures generation technique. Our approach makes the teleoperation system easily adaptable to any unstructured industrial environment by only providing limited offline inputs. This concept extends the use of active constraints making them suitable for multiple manipulation tasks, leaving the freedom of choosing the sequence of the tasks to the user and improving in this way her/his experience in the human-in-the-loop systems.

III. Virtual Fixtures

In this section a brief mathematical background on both geometry and constraint enforcement methods of virtual fixtures used throughout this work is presented. In the last part we show the integration of the additional helping force in the telerobotic system mathematical model useful for passivity analysis.

A. Geometric Description

Different primitives such as points, curves, surfaces, can be used as geometric description for virtual constraints. The most suitable geometric model has to be chosen according to the specific task to be accomplished. In our application various industrial parts have to be picked and placed. Without loss of generality, we make use of points to identify each part in the 3D environment. Each point opportunely identifies the Cartesian position of a given part feature detected by the stereo vision system (e.g. center of the top surface area, see Sec. IV).

Even though other more sophisticated geometric primitives can be used as virtual constraints, associating a point to each part represents the one of the most suitable approach for manipulation tasks. By detecting a previously determined feature in the image, the stereo-vision system outputs the representation of each part in the scene given as

$$p_i = [x_i, y_i, z_i]$$

where x_i, y_i, z_i are the coordinates of the detected feature in 3D environment (see Sec. IV).

B. Force Generation

Regardless of the geometric primitive used for describing a virtual fixture, a constraint enforcement method has to be associated to it in order to opportunely provide helping force to the master side. Various kinds of constraint enforcement method have been proposed in the past for different geometric primitives: *attractive potential fields*, initially used in teleoperation by [12], are used throughout this work.

By choosing appropriate gains, this method allows the operator to move freely when her/his position is away from the parts, while an increasing force is applied to the master side as soon as the corresponding robot position is going to approach a part (see Fig. 1). From a mathematical point of view this can be seen as:

$$P(x) = \sum_{i=0}^{n} e^{-\|x - x_{0i}\|} \tag{1}$$

$$F(x) = K \frac{\partial P(x)}{\partial x} = -K \sum_{i=0}^{n} \frac{x - x_{0i}}{\|x - x_{0i}\|} e^{-\|x - x_{0i}\|} \tag{2}$$

where x is the current robot position, x_{0i} is the position related to each object detected in the scene, n is the number of object in the scene with an associated potential function, K is the force gain, P represents the sum of potential functions and F the total force to be opportunely mapped on the haptic device.

C. Passivity Analysis

Teleoperation systems are composed of master and slave sides, represented by n-degree-of-freedom impedance/admittance controlled robots which, separately, behave as passive decoupled mechanical systems. Once these systems are connected in feedback, if the delay with which they exchange information is negligible the overall system can be considered stable, otherwise passivity preserving controller has to be considered.

In order to enhance the performances of a teleoperation system, virtual constraints impose an additional force on the master side. This can help to keep the teleoperated slave robot moving along a desired path or towards a target zone while leaving ultimate control to the user. For the purpose of evaluating system stability in such conditions, each physical system can be modeled as a two port Hamiltonian mechanism. Formally, it can be represented as:

$$\begin{cases} \dot{x} = [J(x) - R(x)] \frac{\partial H}{\partial x} + g(x)u \\ y = g^T(x) \frac{\partial H}{\partial x} \end{cases} \tag{3}$$

where $x \in \mathbb{R}^n$ is the system state and $H(x) : \mathbb{R}^n \to \mathbb{R}$ is the Hamiltonian function, namely the sum of system stored energy. Moreover, $J(x) = -J(x)^T$ represents the internal power-preserving interconnection, $R(x) > 0$ the internal dissipation, $g(x)$ the input matrix, u the input and y output of the system. It can be shown that for a two port Hamiltonian system passivity condition with respect to $u^T y$ can be written as:

$$u^T y = \dot{H}(x) + \frac{\partial^T H}{\partial x} R(x) \frac{\partial H}{\partial x} \geq \dot{H}(x) \tag{4}$$

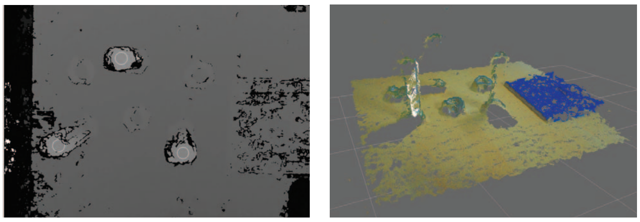
Modeling the master side as a port Hamiltonian system, the effect of additional forces associated with active constraints does not influence passivity condition. In this case the term u in Eq. (3) in presence of virtual fixtures can be specialized as

$$u = F_h + F_{fb} + F_{vf} \tag{5}$$

where F_h is the force exchanged with the human operator, F_{fb} the force feedback and F_{vf} represents the additional guidance force of the virtual fixtures. In particular, the term F_{fb} is the force coming from the slave side and depends on the adopted teleoperation scheme, such as position-position or position-force, while F_{vf} is computed by a suitable constraint enforcement method, in our case using artificial potentials.

IV. Vision

The stereo vision system has the purpose of detecting the poses of the parts in the scene and output them in an opportune reference frame. This is done by detecting proper features in the image and calculating the corresponding 3D pose. The features to detect constitute an input the operator



(a) Disparity map with detected bolts marked with white circles.

(b) Point cloud generated starting from the depth map of Fig. 2(a).

Fig. 2. Depth map and point cloud relative to the illustrated task.

has to specify offline, e.g. before the system starts. In this work, pick and place of known object has to be performed so the relative features are defined in advance. In order to pick and place parts, the positions of the parts in the robot workspace have to be calculated. In our tests, since the bolts are standing upright on the table, they have been identified starting from the depth map of the environment. This has been *cut* at a certain height so that the top of the bolts can be extracted. The positions $[X_{\text{ILi}}\ Y_{\text{ILi}}]$ of the i-th bolt in the left image plane is then evaluated. The 3D coordinates $[x_{\text{i}}\ y_{\text{i}}\ z_{\text{i}}]$ are calculated using pin-hole camera model. As regards the blue fixture in Fig. 1, the strategy for its localization is based on the RGB image rather than the depth map. This because of two reasons. First, its blue color has a strong contrast with the background. Second the reflecting surface has almost no texture, making the disparity computation harder, as it can also be noticed in Fig. 2(a) and Fig. 2(b). As for the case of the bolts, also the position of the fixture in the left image plane is evaluated and then its 3D coordinates are calculated based on that. Through the combination of these two approaches we retain most of industrial parts can be easily detected. For more complicated situations, other techniques, such as point cloud matching, can be used.

V. System Description

The overall teleoperation system including the active constraint generator is depicted as a block diagram in Fig. 3. The absolute input to the system comes from the human operator who moves the haptic device in its Cartesian space.

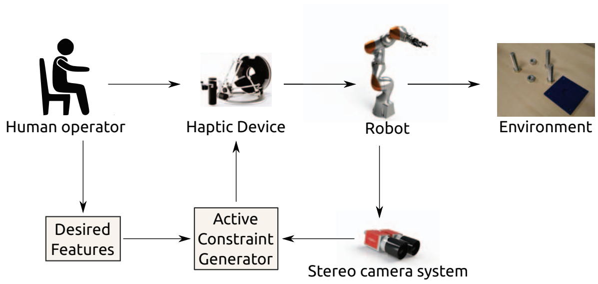


Fig. 3. Block scheme of the presented system. The active constraint generator block computes virtual constraints using feature detection algorithms in the images provided by the stereo-camera system. The desired features are opportunely specified by the operator before the system starts according to the limited knowledge of the task to be performed.

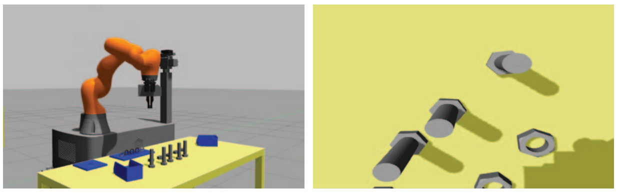
The position and orientation of the haptic device, opportunely scaled and mapped, is sent to the robot as a Cartesian space desired pose. In order to make the connection appear natural to the user, the slave desired pose has been expressed with respect to the stereo-camera frame, following the approach reported in [13]. In addition, as previously mentioned, the operator has to offline specify the desired features according to the parts she/he wants to detect in the scene as explained in Sec. IV. The slave goal poses are computed by the active constraint generator using opportune feature detection algorithms. These poses are then used to compute virtual fixtures and associate forces to be rendered by the haptic device.

A. Hardware

The system hardware consists of a Kuka LWR 4+ slave robot teleoperated by means of a Force Dimension Omega 7 master device. The gripper we used is Robotiq 2-Finger 85. The stereo camera system is composed of two Allied Vision Mako G-125C cameras which provide 1.2 Megapixel (1292 × 964) frames at 30 fps. An external force-torque sensor is mounted on the robot end effector. It is sampled at 1 kHz, and a low pass filter with cutoff frequency $f_c = 100$ Hz is used for filtering the force signal. Two computers running Linux Ubuntu are used: one of these is connected to the two cameras and it is receiving signals by means of Ethernet communication, the other one is connected to the Omega via USB and to the robot via an Ethernet cable. These two laptops are exchanging information by means of a Wi-Fi socket.

B. Software

The Kuka LWR 4+ and one computer are connected through Fast Research Interface provided by the robot. The Fast Research Interface Library [14] runs on a remote computer which is connected to the KRC (Kuka Robot Controller) via an Ethernet connection. This subsystem runs at 5 ms for testing purposes, even though it can be operated up to a frequency of 1 kHz. The robot is commanded in Cartesian Impedance mode with following values for the stiffness $K = [2500\ 2500\ 2500\ 300\ 300\ 300]$ and damping ratio $D = [0.7\ 0.7\ 0.7\ 0.7\ 0.7\ 0.7]$, along and about the x, y, and z Cartesian axes. Data exchange between computers relies on a Wi-Fi TCP/IP socket. The function that takes care of socket communication has been implemented in a separate thread, not to interfere with the teleoperation loop of the robot. The camera node has double function: it communicates with cameras via Ethernet using the Vimba SDK and exploits OpenCV library [15], which contains basic image processing functions, in order to detect and localize features in the image. The Omega 7 device is interfaced to the system by means of the Force Dimension SDK. It provides high frequency signals of haptic device pose, velocities and forces. Before sending position commands to the robot, the haptic device position and orientation are opportunely mapped and scaled to match the desired robot movements. In addition, energy tank based approach, explained in [11] has been used for stabilizing force feedback loop between master and slave side.



(a) Robot approaching tha table. (b) Simulated camera image.

Fig. 4. Snapshots of the simulation environment. In Fig. 4(a) the robot is approaching the parts to manipulate. In Fig. 4(b) the related image published by the camera sensor provided as visual feedback to the human operator.

C. Simulation

For the purpose of quick prototyping and testing of our approach a simulation environment has been prepared (see Fig.4). The teleoperation system has been simulated using ROS [16] and Gazebo dynamic simulator [17]. Both the robot and the parts have been modeled in 3D and the CAD models have been imported in the simulation environment using URDF files. Masses and inertia of the industrial parts have been computed according to the real material properties through MeshLab [18]. By using appropriate plugins Gazebo outputs simulated eye-in-hand camera images and force/torque sensor values at robot wrist through standard ROS topics. In this way, the human operator can stably teleoperate the simulated robot using the haptic device and the passivity controller whose code has been wrapped into ROS nodes.

VI. Experiments and Results

In this section we present both the setup of the experiments conducted on a mock-up of an industrial environment, and the related outcomes. In Subsection VI-A we extensively describe the scenario in which the experiments are carried out while in Subsection VI-B the analysis of the experimental data is presented.

A. Experimental setup

The specific evaluation procedure adopted in this work to demonstrate the validity of the proposed approach consists in picking a bolt in the workspace and opportunely place it in a fixture then used for screwing the nut. A human operator teleoperates the robot by means of the haptic device receiving force feedback from the force torque sensor and, at the same time, the images from the stereo camera system. When the system starts, both the robot and the haptic device poses are recorded in order to compute their offset transformation matrices. This allows to start from generic initial pose of master and slave. The bolts are randomly placed on the table and when the system starts we keep the cameras pointing towards them. This does not constitute an absolute restriction since the poses are updated on-the-fly. Once the parts are in the field of view of the cameras, their positions are calculated in the stereo camera reference frame and translated into the

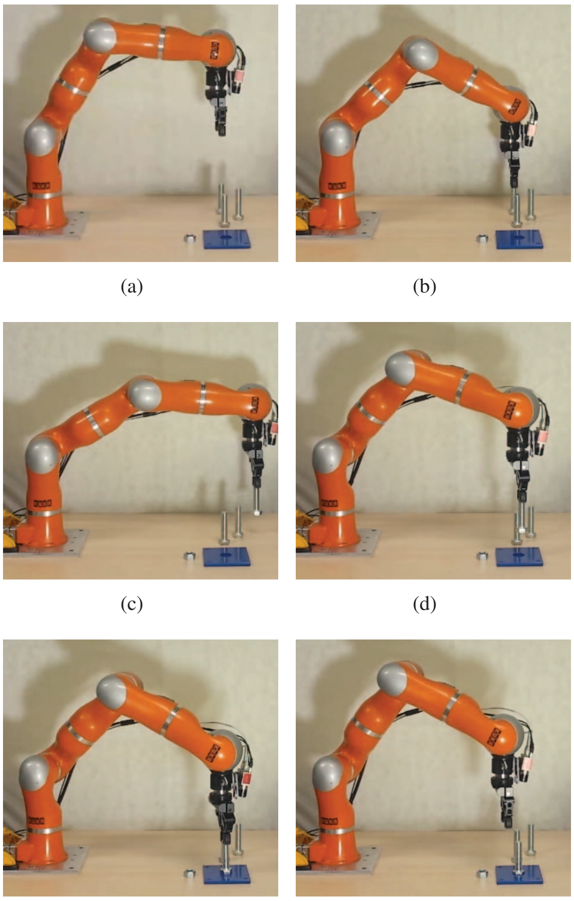


Fig. 5. Sequence of snapshots taken from one of the performed experiments. Fig. 5(a) and Fig. 5(b) show the robot approaching and grasping one bolt. In Fig. 5(c),Fig. 5(d),Fig. 5(e), Fig. 5(f) the bolt is carried from its initial pose to its goal pose (fixture), while the teleoperator is helped through the use of virtual constraints.

robot base frame. These positions are used to generate the virtual fixtures required by the system to operate as described in the previous sections.

B. Outcomes

For the sake of clarity we refer to a generic performed test. In this test one bolt from the scene is grasped and placed in the fixture, as can be seen in the sequence of snapshots in Fig. 5. The starting pose of the robot (Fig. 5(a)) allows the operator to clearly see the parts placed in the scene. When the system starts, the operator is attracted towards all the parts, and is free to choose the one she/he wants to grasp (Fig. 5(b)). When one bolt is grasped, the system is triggered by the closure of the gripper and the artificial potentials associated with other bolts become repulsive, bringing the operator away from them during the following movements (Fig. 5(c) and Fig. 5(d)). This allows her/him to safely approach the fixture and place the bolt in it (Fig. 5(e) and Fig. 5(f)).

Fig. 6 displays the geometric path of the robot, the time series of the components and the magnitude of the force due to the virtual fixtures recorded at the master side. As it can be noticed, in the start up phase, the robot tip is located on top of the parts. The operator starts moving around 2 seconds and the magnitude of the force clearly increases because of the attraction of the bolts the operator is moving toward. This phase lasts for almost 5 seconds until the robot gripper reaches the top of the bolt and successfully grasps it (Fig. 6(a), Fig. 6(b) and Fig. 6(c)). In the second phase the forces start from a slightly greater value because, as soon as a bolt is grasped, the potentials associated with the other bolts are switched to repulsive (see Fig. 1(b)). This makes the teleoperator to move away from other objects and feel an attractive force towards the fixture pose. Finally, around 20 seconds, the magnitude of force starts increasing again because the robot in the neighbourhood of the goal pose (Fig. 6(d), Fig. 6(e) and Fig. 6(f)).

Considering that the force felt by the operator when she/he holds a bolt is approximately 10N, the presence of the virtual fixture does not deteriorate the transparency of the overall teleoperation system. In fact, during the holding and placing phase, the force coming from the active constraint never exceeds the 10% of the external force coming from the environment. It has to be pointed out that the force values in the previous diagrams represent the force after the passivity controller. This prevents the released energy from being larger then the injected one keeping the system stable.

VII. Conclusions

In this paper we presented a vision-based virtual fixtures generation suitable for bilateral teleoperation systems. Using our method virtual fixtures do not need to be programmed *a priori* but they can be generated and updated online making the system easily adaptable to multiple tasks that have to be accomplished in unstructured environments. This approach can avoid tedious offline programming of the virtual fixtures making the teleoperation system quickly and easily adaptable to different tasks/environments. The overall system only requires minimal inputs within the vision sub-system in which the operator has to specify the desired features that have to be detected. Shared control makes the operator able to easily, rapidly and safely move among obstacles making the system more efficient in terms of operator workload. The system has been proven to be a valid alternative with respect to the current consolidated methods based on offline constraints generation. Furthermore, its reliability has been demonstrated to be not decreased by the online update procedure of the virtual fixtures. The performed experiments confirm what has been stated above and provide us with guidelines towards further developments.

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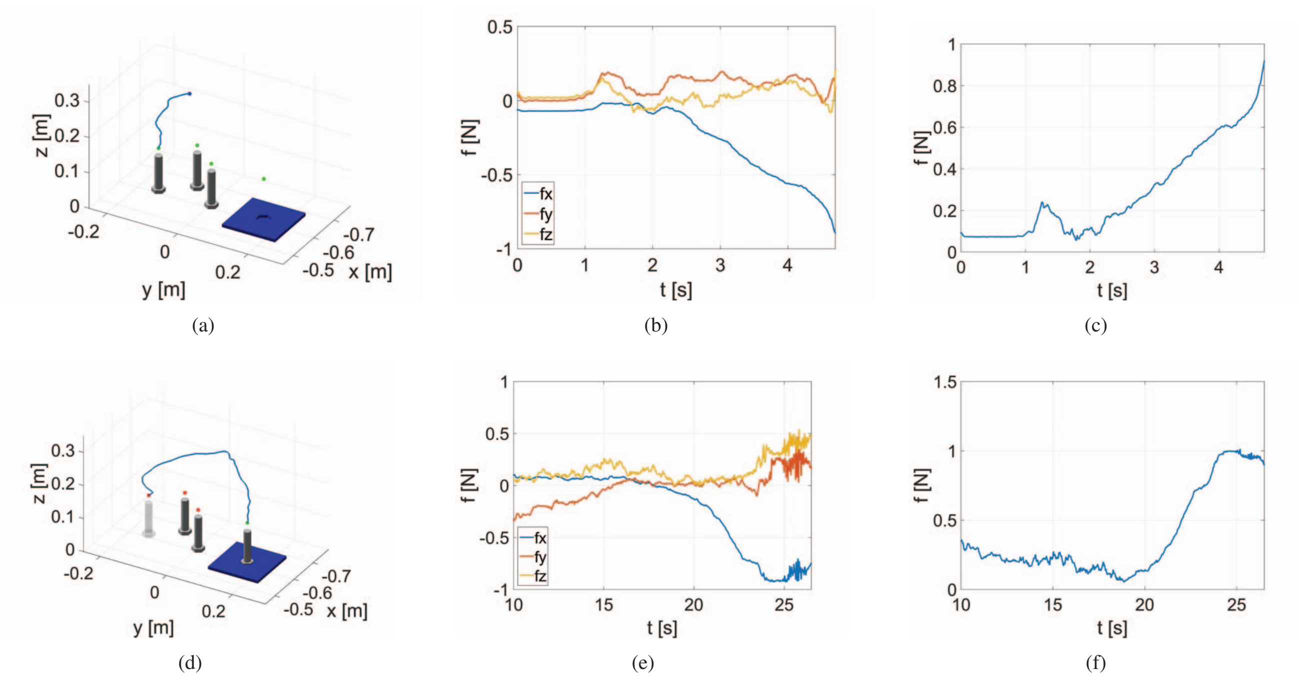

Fig. 6. Render of the recorded data during the considered experiment. In Fig. 6(a), 6(b), 6(c) are depicted the geometric path followed by the robot, the components of the force rendered by the haptic device, and the force magnitude, respectively. In Fig. 6(d), 6(e), 6(f) the same data relative to the moving and placing phases.

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