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Opening a Door with a Humanoid Robot Using Multi-Sensory Tactile Feedback*

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Abstract— **This paper presents a multi-sensor based generic approach to opening doors for a dexterous robot. Once the handle has been located by a computer vision algorithm and properly grasped, we are able to open doors without using a model or other prior knowledge of the door geometry. This is done by combining the sensor information of both a force-torque sensor in the robot wrist and a tactile sensor matrix in the robot gripper itself. Our experimental results show that the combination of both sensors achieves the most successful way to open the door.**

I. INTRODUCTION

Our research is situated in the field of Human-Centered Robotics, the movement toward robotics technology that aids in the course of human everyday life. It is part of the Collaborative Research Center SFB588 on "Humanoid Robots" of the German Research Foundation [1] which is based on the paradigm of a household service robot that assists humans in the kitchen. Example robot activities are laying the table or getting a beverage from the fridge.

One particular challenge for the robot in the kitchen during such scenarios is to open doors and drawers. The doors can belong to cupboards, the fridge, the oven, or the dishwasher. The first issue is to reliably identify and locate the handle of the door to be opened using the robot's stereo camera system. Then the handle has to be grasped safely by the robot hand. When it comes to the actual opening process, one faces the complication that the doors open in different directions (to the left, downwards, upwards etc.) and require different forces (strong, weak, varying). In case of a drawer, on the other hand, there is no turning but rather a linear motion.

Our approach to the door opening challenge deals with these three issues as follows: A color-based segmentation searches for potential door handles in the camera images that in turn are compared to a known model of a door handle. Safe gripping of the handle is ensured by evaluating the robot gripper's tactile sensor data and reactively adjusting the robot grasp. The door is opened by relying on a combination of basic action primitives such as position control and force control, building on earlier work of our research group [2], [3]. As force control based on the data of a force-torque sensor built into the robot's wrist proved to be too unreliable we augmented our sensory equipment with a spatial tactile sensor matrix covering the robot gripper. By fusing all available sensor data appropriately, a door opening algorithm is achieved that is reliable and yet general enough to handle all sorts of drawers and doors in our kitchen scenario without exact knowledge of their geometry.

Related work in this area includes the DLR lightweight robot [4] that boasts a sophisticated position, torque, and impedance control system that can be used to open doors. An industrial robot equipped with a force sensor was used to press down a door handle by employing a hybrid position/force control scheme in [5]. They did not use a spatial sensor matrix, however. Nagatani and Yuta introduced a strategy for opening doors that makes use of an analytical description of the door handle trajectory [6], [7]. A method for opening doors involving only a limited analytical model and force/torque control was detailed by Petersson et al. [8] and was inspirational to our work. This method was also implemented recently on the UJI service robot [9]. Kim et al. worked on door opening robots both in simulation [10] and in practice [11], although in the latter case impedance control was only used to correct a trajectory error. A system employing behavior and sensorimotor control that can push open doors was presented by Brooks et al. [12]. Finally Katsuki et al. [13] have done research on reasoning about door opening tasks on an abstract level. It should be noted that none of these presented approaches to door opening utilizes a spatial tactile sensor matrix in addition to force-torque sensors for a by far more reliable method to open doors with unknown geometry.

The remainder of this paper is structured as follows: In section II we show a general overview of our system, followed by the description of our visual servoing approach in section III. The sections IV and V describe the tactile sensors that are employed to open the door. The door handle grasping method is explained in section VI. Section VII details the control method for opening the door based on tactile sensor information. We show the evaluation results of our method in section VIII and conclude the paper in section IX.

II. SYSTEM OVERVIEW

The robot we will use as our first test bed is a 7 degrees of freedom (DOF) humanoid manipulator shown in Fig. 1. It is composed of PowerCubes by amtec robotics in a modular fashion. For sensing, it is equipped with tactile sensors as

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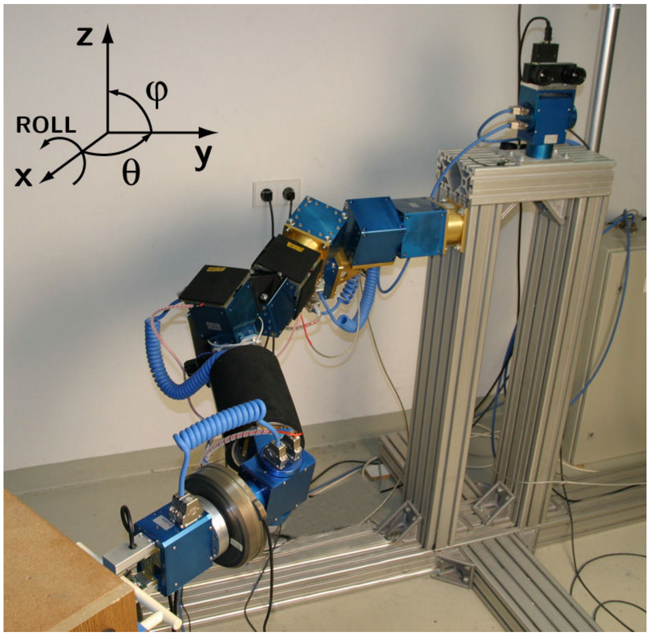

Fig. 1. The humanoid manipulator.

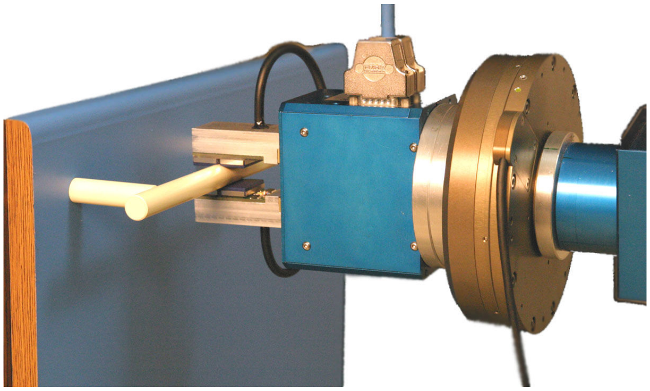

Fig. 2. Close-up on robot gripper and door handle.

an artificial skin on the arm (see [2] for details), a 6DOF force/torque sensor at the wrist which is described in more detail in section V, and a stereo camera on a pan-tilt unit.

On the force-torque sensor we mounted a two-finger gripper. It is actuated electrically and equipped with tactile sensors that are presented in section IV. The handle of the door we open is of cylindrical shape and large enough that it can also be grasped with our humanoid 5-finger pneumatic robot hand. Both gripper and handle are displayed in Fig. 2.

The robot control software runs under Linux and builds on the freely available Modular Controller Architecture (MCA) as a software framework [14].

III. VISUAL LOCALIZATION OF DOOR HANDLE

The vision system performs object recognition and localization as the grasp execution component must be provided with information about identity and location of the door handle that is to be grasped. As the door handle to be recognized might be scattered arbitrarily in the scene, recognition must be invariant against 3D rotation and translation. The door handle must become fully localized in 6D space.

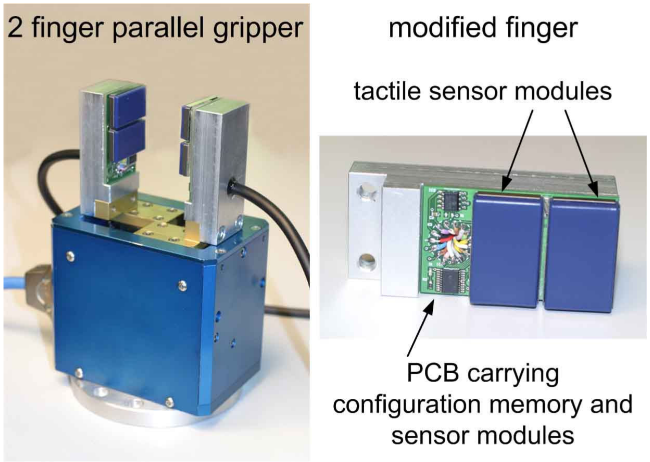

Fig. 3. Modified parallel gripper

For visual recognition and localization, we use a unicolor global appearance-based object recognition approach. It assumes that the door itself can be segmented by a single color and that the door handle lies inside this segmented region. We employ the algorithm from [15] which is suitable for uniformly colored objects. This approach uses a non-adaptive color model, which is sufficient for constant lighting conditions as in our test environment.

During a learning phase the dataset for different views of the door handle is generated automatically using a 3D-model of the door handle. For this reason the method can be regarded as a combination of an appearance-based and a model-based visual recognition system. The dataset is provided with orientation information from the generated model views. For recognition, candidate regions are segmented from the camera image and matched with the formerly acquired dataset.

In this work, we use the color feature to detect the door, not to detect the handle. The inverted image of a potential door region provides a candidate region which is finally matched with the dataset.

IV. SPATIAL TACTILE SENSOR MATRIX

A. Hardware description

We replaced the fingers of a conventional two finger parallel gripper with modified fingers capable of carrying a printed circuit board (PCB) as displayed in Fig. 3. This PCB carries necessary electronic devices such as a configuration memory that stores the configuration data of the of the gripper's sensor modules. The sensor modules we use (Weiss Robotics, type DSA 9335 [16]) provide a spatial resolution of 3.8mm with 28 sensor cells. They are organized as 4×7 matrices. Using 4 modules (2 on each gripper finger), our gripper thus is equipped with 112 sensor cells. The working principle of the tactile sensors depends on an interface effect between metal electrodes and a conductive polymer covering the sensing

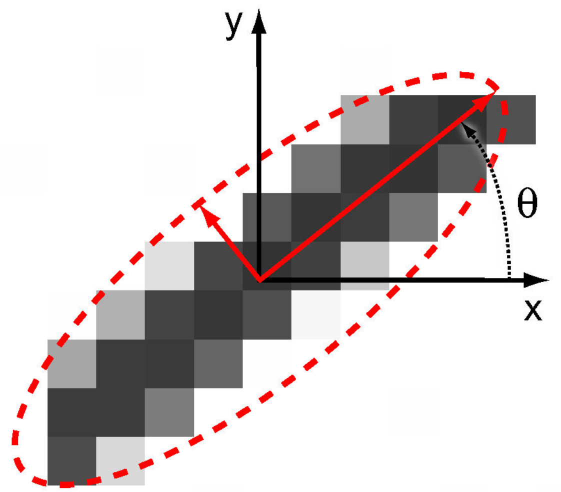

Fig. 4. The angle θ between the principal axes of the tactile image and the sensor coordinate system.

electrodes. The resistance between a common electrode and a sensor cell electrode is a function of the applied load and time. A more detailed description is available in [17].

B. *Sensor data processing*

The data of the tactile sensor matrix corresponds to a two-dimensional planar image. We analyze this image using moments up to the 2^{nd} order [18]. The two-dimensional $(p+q)^{th}$ order moment $m_{p,q}$ of an image is defined as the following double sum over all image pixels (x, y) and their values $f(x, y)$:

$$m_{p,q} = \sum_x \sum_y x^p y^p f(x,y) \qquad p, q \geq 0 \ . \tag{1}$$

The moment $m_{0,0}$ constitutes the total force exerted on the sensor. The centroid $\underline{x}_c = (x_c, y_c)^T$ of this force can be computed to

$$x_c = \frac{m_{1,0}}{m_{0,0}} \tag{2}$$

$$y_c = \frac{m_{0,1}}{m_{0,0}} \ . \tag{3}$$

Using the centroid, we can verify that the door handle was grasped appropriately around the center of the gripper. It also allows to calculate the higher order moments with respect to the centroid, the so-called *central moments* $\mu_{p,q}$:

$$\mu_{p,q} = \sum_x \sum_y (x - x_c)^p (y - y_c)^q f(x,y) \qquad p, q \geq 0 \ . \tag{4}$$

The 2^{nd} order central moments

$$\mu_{2,0} = \sum_x \sum_y (x - x_c)^2 f(x,y) \tag{5}$$

$$\mu_{0,2} = \sum_x \sum_y (y - y_c)^2 f(x,y) \tag{6}$$

$$\mu_{1,1} = \sum_x \sum_y (x - x_c)(y - y_c) f(x,y) \tag{7}$$

Fig. 5. The force-torque sensor.[1]

approximate the image by an ellipse and represent its principal axes. Grasping our door handles results in an oblong ellipse with an eccentricity ε close to 1 when using

$$\varepsilon = \frac{(\mu_{2,0} - \mu_{0,2})^2 + 4\mu_{1,1}^2}{(\mu_{2,0} + \mu_{0,2})^2} \qquad \varepsilon \in [0, 1[\ . \tag{8}$$

To control the orientation of the gripper with respect to the door handle, we are interested in the angle θ between the principal axes and the sensor coordinate system (cf. Fig. 4) which can be readily computed by

$$\theta = \frac{1}{2} \arctan \frac{2\mu_{1,1}}{\mu_{2,0} - \mu_{0,2}} \ . \tag{9}$$

When opening a door or a drawer, the desired angle θ is zero and can thus be directly used as the system deviation input to the controller to control one orientation DOF.

To determine the angles φ and ρ between robot gripper and door handle for the other two orientation DOFs, we use the centroid from (2, 3) of both the upper and the lower sensor, $\underline{x}_{c,u}$ and $\underline{x}_{c,l}$, and the distance h between the two gripper fingers:

$$\varphi = \arctan \frac{x_{c,u} - x_{c,l}}{h} \tag{10}$$

$$\rho = \arctan \frac{y_{c,u} - y_{c,l}}{h} \ . \tag{11}$$

V. FORCE-TORQUE SENSOR

The force-torque sensor that we use is an FTC 50-40 from SCHUNK, see Fig. 5. It has 6DOFs, with a range of $150N$ for the 3 forces, $4Nm$ for torques Mx and My, and $8Nm$ for Mz. The accuracy is 5%. The data is sampled every $1ms$ and transmitted via CAN bus with a baudrate of $500kbit/s$.

Since the data is quite noisy, we use a median filter with window size 7 to remove outliers, followed by a moving average filter with window size 25. Since the robot gripper is mounted on top of the sensor, we deduct its weight from the sensor values before transforming them from the local coordinate system to world coordinates.

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[1] Image courtesy of SCHUNK GmbH & Co. KG / Lauffen

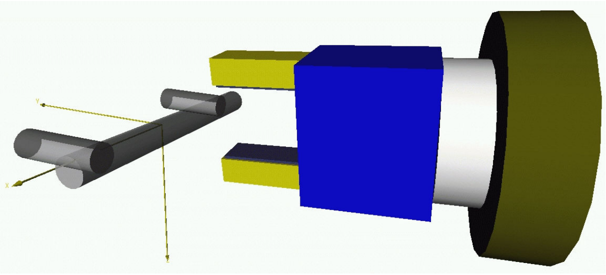

Fig. 6. Offline grasp planner

VI. GRASPING

The grasping approach is based on the work of [19] which combines the previously mentioned visual component with an offline grasp planning component. The grasp planning process is currently executed offline using the program *GraspIt!* [20]. *GraspIt!* is a robotic grasping simulator that uses geometric models of the robot hand and objects in a virtual workspace to determine feasibility and quality of a grasp.

We added a model of the gripper and of the door handle to be grasped to the simulator, as pictured in Fig. 6. As the gripper is restricted to the execution of a parallel grasp, the grasp planning procedure is simplified enormously. The output of the planner module is a set of parameterized grasps comprising the following information:

- Grasp starting point (GSP)
- Grasp approaching vector
- Gripper orientation rotated around the axis of approaching vector.
- Joint closing velocities.

A grasp dataset is generated automatically with primitive models of the door handle following [21]: The planner generates suitable GSPs and approaching vectors and starts to test the parallel grasp. The primitive decomposition of the door handle is given by three narrow cylinders—one long and two small ones. All grasps for which a quality measure value above a certain threshold is calculated are stored in a grasp dataset.

The execution of a grasp is decomposed into four phases as described in the following:

1) **Coarse approach:** The vision system detects the object and gives a position estimate. The arm is moving with comparatively high velocity and the hand moves to pre-grasp configuration which is given by the grasp start point and the gripper orientation provided by the grasp planning component.
2) **Fine approach:** The arm is moving slower along the given grasp approaching vector towards the detected position of the object.
3) **Grasp object:** The arm position is adjusted with small movements while the fingers of the gripper move towards the object with the calculated joint closing velocities. Contact forces are increased to desired values while the grasp configuration is checked using tactile sensor feedback.
4) **Depart:** Slow movements are performed with fixed Cartesian orientation of the hand.

These four phases stem from the concept of synchronization and coordination of arm-hand movements as detailed in [22], [23].

VII. OPENING THE DOOR

A. *Opening algorithm*

The idea behind the door opening algorithm is to relieve the robot from the need to have a model of the door. Rather we rely purely on the sensor information to determine the necessary position and orientation commands for the opening robot gripper.

Thus, once the robot has firmly grasped the door handle, it simply pulls backwards with respect to the local gripper coordinate system. Perpendicular to this motion, the robot uses the forces measured by the force-torque sensor and the tactile sensor matrix to adjust the gripper position relative to the handle. When pulling back, the door has to follow a circular arc and thus will try to change its orientation with respect to the robot gripper. This change is measured by the tactile sensor matrix. Additionally, the torque exerted on the robot gripper by the door handle is measured by the force-torque sensor. We use both data to adjust the orientation of the robot gripper.

In order to achieve the maximum possible flexibility we also consider the case where the handle belongs to a drawer instead of a door. The opening algorithm can handle this as well, the only difference is that the test for completion of the opening is different. Therefore we have to differentiate between doors and drawers. The way we distinguish the two is by observing the orientation of the robot gripper in the course of the opening. This is done when the distance between the start of the opening and the current robot gripper position is greater than $20cm$. At that time, our reference door with a radius of $59cm$ should have turned by $19.5\,^{\circ}$. A larger door of $1m$ radius will have turned by $11.5\,^{\circ}$. Thus, if the change of the robot gripper orientation since the start of the motion is greater than $10\,^{\circ}$, we determine the handle to belong to a door; otherwise, it must be a drawer.

The test for a successful opening follows along the same lines. In case of a door, the motion is ended after turning more than $35\,^{\circ}$. If we are dealing with a drawer, we consider the drawer opened after a distance of $25cm$.

In this way, the door opening algorithm allows us to open previously unknown doors and drawers with arbitrary opening directions (left, right, up, down), as long as we are able to recognize the handle as such and grasp it. Good quality sensor information is chief for this method, though, otherwise the opening will fail miserably. This is why we rely on multiple sensors with different sensing principles to provide us with the necessary, reliable information. The fusion of the sensor data and the respective control laws are described next.

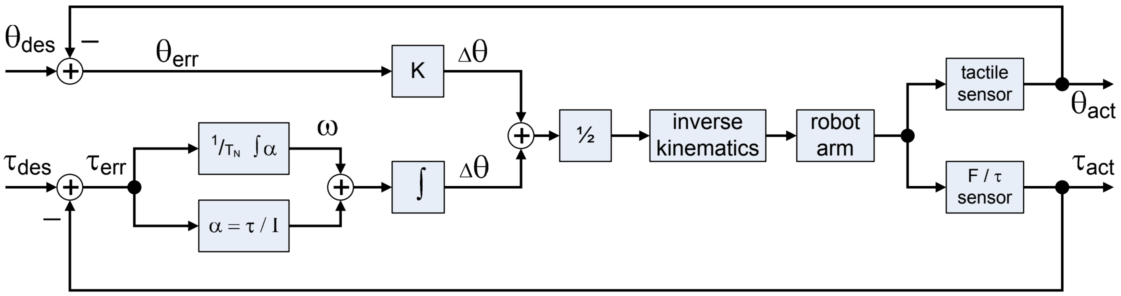

Fig. 7. Orientation control.

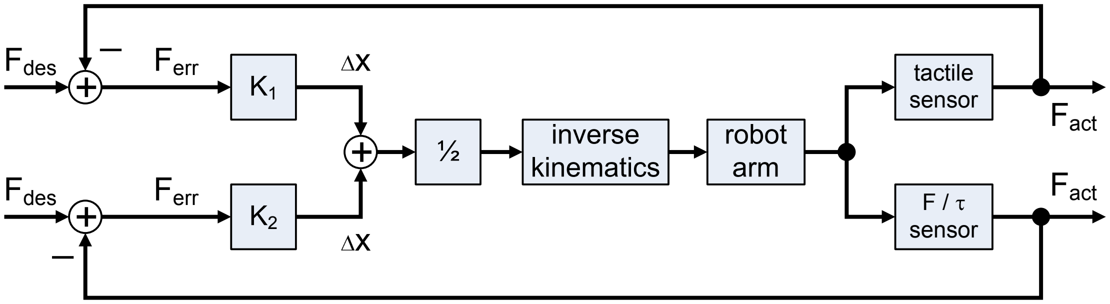

Fig. 8. Position control.

B. Control law for the orientation

The feedback control loops for both orientation and position control were designed along the lines of previously published literature such as [24]–[27]. Our actual control loop for the orientation control is depicted in Fig. 7. It consists of two subloops, one for each sensor. In the torque part, the actual torque τ_{act} exerted on the robot gripper is measured by the force-torque sensor. It is deducted from the desired torque τ_{des}, which is zero in this application. The resulting torque error τ_{err} serves as input to a PI controller with two coefficients I, the "moment of inertia", and T_N, the reset time. The output of the PI controller is integrated again to yield an angle $\Delta\theta$ that is averaged with the corresponding $\Delta\theta$ from the tactile sensor matrix and then added to the current angle of the robot gripper to yield the new angle setpoint for the robot gripper. This control law is used for all 3DOF. The 2 coefficients I and T_N for each DOF were determined using the method by Ziegler and Nichols [28].

As to the tactile sensor matrix, the sensor information processing is different for each DOF. To determine the angle θ_{act} around the axis perpendicular to the sensor area, we use the method described above in section IV-B, specifically (9). For the other 2 DOFs and their corresponding angles φ_{act} and ρ_{act}, we use (10) and (11). In each DOF, the current angle (e.g. θ_{act}) is then deducted from the desired angle θ_{des}, yielding the angle error θ_{err}. The latter is multiplied by a constant K to form a simple P controller. The resulting $\Delta\theta$ is then averaged with the output of the force-torque sensor PI controller as already mentioned above.

C. Control law for the position

Position control works similar to orientation control, except that it uses forces rather than torques. Its feedback control loop is shown in Fig. 8. Since the drawing-open motion consists of simply pulling backwards, the position control described here serves to adjust the robot gripper orthogonally to that pulling motion, thus ensuring a well-balanced grasp of the door handle. To that end, we take the 3-dimensional force vector $\underline{F}_{fts}$ delivered by the force-torque sensor and project it into the plane defined by the normal vector $\underline{x}_{TCP}$ that is the normalized vector in direction of the robot's Tool Center Point (TCP), i.e. the tip of the robot gripper, to obtain $\underline{F}_{act}$:

$$\underline{F}_{act} = (\underline{x}_{TCP} \times \underline{F}_{fts}) \times \underline{x}_{TCP} \ , \tag{12}$$

where $\times$ signifies the cross product. We get a second $\underline{F}_{act}$ by subtracting the moments $m_{0,0}$ of the opposing upper and lower sensor matrices from each other, yielding the resulting force of this sensor type. Both values $\underline{F}_{act}$ are used in P control loops with coefficients K_1 and K_2 that serve as inverse "spring constants", yielding two vectors $\Delta\underline{x}$ that are averaged and added to the robot gripper position setpoint.

VIII. EVALUATION

In order to evaluate the different sensors and their combination, we ran a series of tests. The first one was to try and open the door with only the force-torque sensor. Fig. 9 shows the forces in directions x, y, and z measured by that sensor after smoothing them with the aforementioned filters (top graph), and the position and orientation of the robot gripper (bottom graph). In turned out that, despite tuning each DOF by the

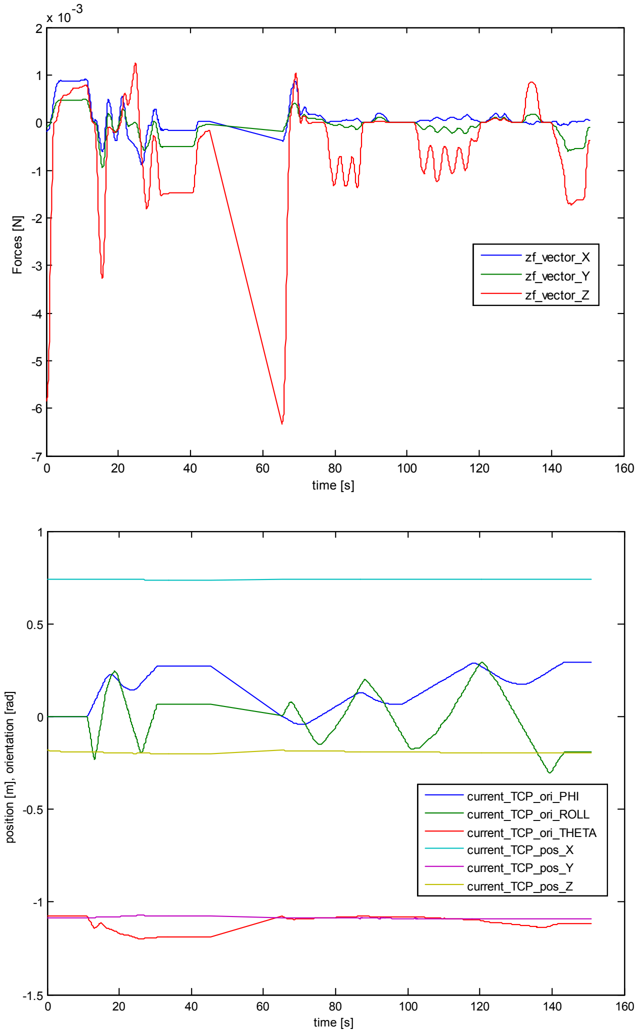

Fig. 9. Opening the door using the force-torque sensor only.

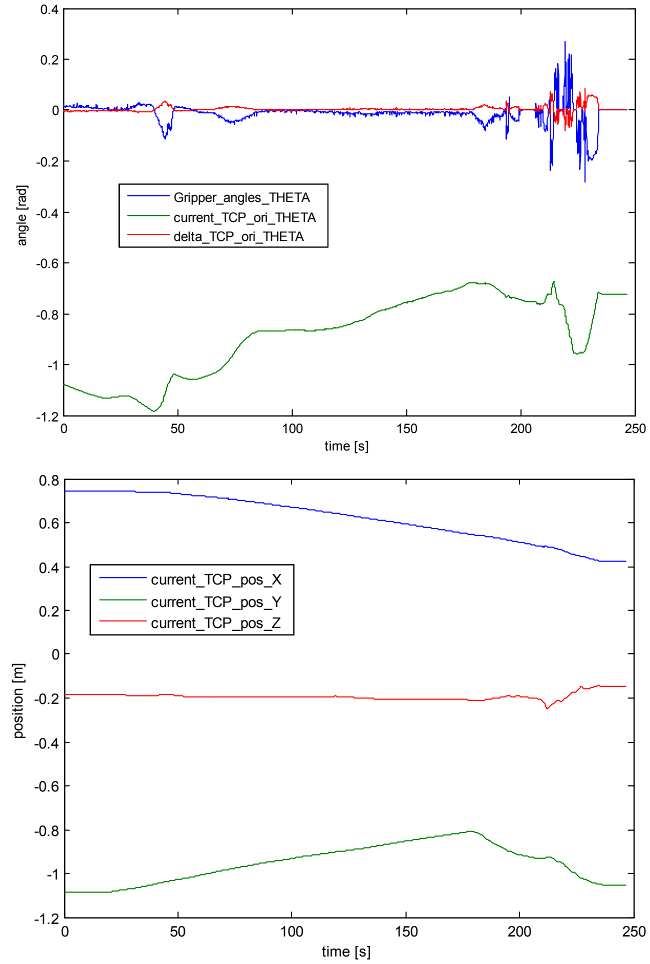

Fig. 10. Opening the door using the matrix sensor only.

Ziegler and Nichols method, the combination of all DOFs could not be controlled properly, and the opening of the door failed. When considering why opening the door with this setup proved to be this difficult, there are three reasons that come to mind. The first one is the tight coupling between robot gripper and the door handle that is completely non-compliant of nature together with the short motion range of the force-torque sensor leads to quick changes in the measured forces, and the second reason being the rather slow control loop of $20ms$ achievable with our manipulator design that exacerbates the first problem, especially when controlling 3 DOFs of orientation at the same time. Lastly, the manipulator's attachment to an immobile base presents a challenge due to the restricted workspace that a robot on a platform or legs does not need to face, and it results in suboptimal arm configurations in the course of the opening.

The next test consisted of evaluating the matrix sensor data and using this as input to the orientation controller. The top graph of Fig. 10 displays the control of the most important gripper angle θ that happened to be the angle around the hinge of the door. The measured angle between gripper and door handle is displayed as a blue line, the resulting gripper orientation adjustment $\Delta\theta$ is shown in red, and the actual gripper orientation is the green line. The bottom graph shows the progression of the robot gripper position. It turned out that this setup worked not too bad, the door could be opened to some extent, but towards the end the situation became unstable. It is noticeable that due to the wealth of information obtained by a total of 112 sensor points, the tactile sensor matrix provides a smoother progression of sensor values than the force-torque sensor that makes it easier for the slow-to-respond robot arm.

The last test with a combination of both sensor types is depicted in Fig. 11. Not unexpectedly, it turned out to be the most successful one. The door could be opened in a smooth, satisfactory manner and with decent speed. The sensor fusion seems to be able to enhance the stability of the orientation control of the gripper and to overcome the shortcomings of the individual sensors. The force-torque sensor contributes a quick responsiveness while the tactile sensor matrix provides a stable sensor signal for a better long-term control.

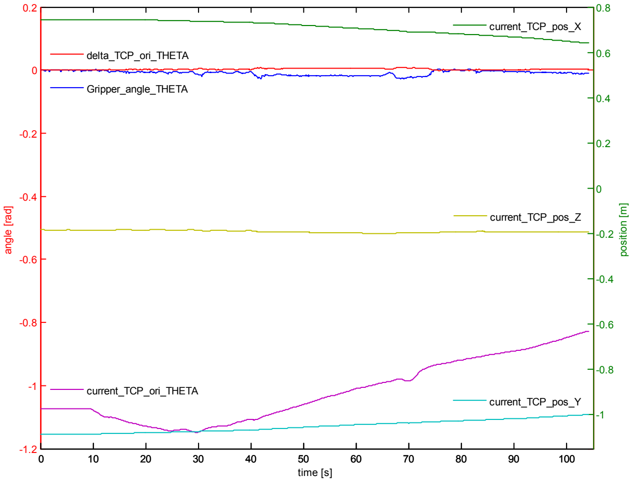

Fig. 11. Opening the door using both sensors.

IX. CONCLUSION

We have presented a multi-sensor based generic approach to opening doors for a dexterous robot. After visually locating and grasping the handle, we strive to open doors without using a model or other prior knowledge of the door geometry, through superior sensor information from both a force-torque sensor in the robot wrist and a tactile sensor matrix in the gripper itself. In the course of the evaluation of our door opening algorithm, it turned out that the combination of both sensors was the most successful way to open the door.

Future work needs to address the fine-tuning of the sensor fusion such that the strengths of each sensor type are optimally leveraged. Also, the possible benefit of creating a model of the door online from the sensor data has to be researched.

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