ASSISTANCE TASK USING A MANIPULATOR ROBOT AND USER KINEMATICS FEEDBACK

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Abstract— This work presents the development of an assistance task performed by an anthropomorphic manipulator robot of five degrees of freedom. The task consists in serving a drink to the users by approaching it to their mouths. While serving the drink, the robot tracks the head movements in order to dynamically adjust the end-effector according to the head position. The planning of the task and modeling of the robot were based on dual quaternion algebra. Since the robot is underactuated for this task, a task-priority based control was implemented such that the control of the end-effector position has higher priority than the orientation control. Experiments were performed in order to test the validity of the approach.

Keywords— Assistance task, human-robot interaction, dual quaternion algebra, task-priority control, Jacobian-based control

1 Introduction

The advances in robotics technology are spreading its areas of application. Robots are now found in many fields of industry, science, and medicine. The development of assistive solutions for disabled individuals through the use of robots is one area that is currently under research. Using robots for the assistance, rehabilitation, or recovering of motor functions of individuals who suffer from this kind of disabilities may help them to improve their lifestyle (Chang et al., 2011; Bó et al., 2011; Vasic & Billard, 2013).

Solutions that helped individuals in the recovery of mobility (Tomari et al., 2012), rehabilitation (Chang et al., 2011), execution of tasks performed with a manipulator robot through a brain interface (Hochberg et al., 2012; Sirvent Blasco et al., 2012), and improvement or recovery of communication skills (Sirvent Blasco et al., 2012; Hwang et al., 2012) have been proposed. All those applications use the best technology available always with the goal of improving the quality of life of impaired individuals, and in a near future, it is expected that they become clinically and commercially available (Wolpaw et al., 2002; Donoghue, 2008; Cecotti, 2011).

Following the same philosophy, this work presents a prototype of a task to assist a user in taking a drink with the help of a manipulator robot. Future developments will be focused on the voluntary activation of this task, and several other ones, using a brain-machine interface.

In this work, the task is performed by a robot with five degrees of freedom and the user kinematics feedback is provided by the Microsoft Kinect® sensor. The robot kinematic model and the rigid motion representation were based on dual quaternion algebra and the control strategy was based on differential inverse kinematics using the Jacobian matrix (Pham et al., 2010; Adorno et al., 2010).

This work represents part of a research that seeks the integration of robotics and biomedical engineering (Lana et al., 2013) for the development of brain-machine interfaces to assist disabled individuals with solutions that are safe (Vasic & Billard, 2013), functional, and easy to use.

The paper is organized as follows: the dual quaternion algebra and their use in the representation of rigid motions are first presented, followed by the model of the manipulator robot described in terms of dual quaternions using the Denavit-Hartenberg (D-H) convention. Section 3 presents the task and the control strategy whereas section 4 reports the experimental results. Finally, the paper is closed with the conclusion and suggestions of future works.

2 Mathematical background

The use of dual quaternions is becoming more widespread in the development of robotics applications. The compact and intuitive representation of rigid motions along with the mathematical properties that allow operations between dual quaternions comprise the advantages for their use (Pham et al., 2010; Adorno, 2011; Leclercq et al., 2013). This section briefly describes the dual quaternion algebra and their use in the representation of rigid motions.

2.1 *Dual quaternion algebra*

A quaternion is a number composed of a real and a imaginary part of the form

$$\boldsymbol{q} = q_1 + q_2\hat{\imath} + q_3\hat{\jmath} + q_4\hat{k},$$

where q_1, q_2, q_3, $q_4 \in \mathbb{R}$ and the imaginary units $\hat{\imath}$, $\hat{\jmath}$, and $\hat{k}$ obey (Kuipers, 2002)

$$\hat{\imath}^2 = \hat{\jmath}^2 = \hat{k}^2 = -1 \text{ and } \hat{\imath}\hat{\jmath}\hat{k} = -1.$$

The dual number is an algebraic expression of the form

$$d = d_{\mathcal{P}} + \varepsilon d_{\mathcal{D}},$$

where $d_{\mathcal{P}}$ (primary part) and $d_{\mathcal{D}}$ (dual part) are two numbers of the same kind, and the dual unit ε obeys (Selig, 2005)

$$\varepsilon \neq 0 \text{ and } \varepsilon^2 = 0.$$

Thus, a dual quaternion is a dual number whose primary and dual parts are quaternions (Selig, 2005)

$$\underline{q} = \underbrace{q_1 + q_2\hat{\imath} + q_3\hat{\jmath} + q_4\hat{k}}_{\boldsymbol{q}_{\mathcal{P}}} + \varepsilon\underbrace{\left(q_5 + q_6\hat{\imath} + q_7\hat{\jmath} + q_8\hat{k}\right)}_{\boldsymbol{q}_{\mathcal{D}}}.$$

We can also define the following operator

$$\operatorname{vec}\left(\underline{q}\right) \triangleq \begin{bmatrix} q_1 & q_2 & \cdots & q_8 \end{bmatrix}^T,$$

which maps coefficients of the dual quaternion into a column vector of eight elements (Adorno, 2011).

2.2 Rigid motions represented by dual quaternions

Dual quaternions are used to represent rigid motions, that is, the position and orientation of a rigid body in a way analogous to homogeneous transformation matrices. The orientation of a rigid body is represented by the unit quaternion

$$\boldsymbol{r} = \cos\left(\frac{\psi}{2}\right) + \sin\left(\frac{\psi}{2}\right)\boldsymbol{n}, \tag{1}$$

which corresponds to a rotation ψ around a rotation axis of unitary norm

$$\boldsymbol{n} = n_x\hat{\imath} + n_y\hat{\jmath} + n_z\hat{k}.$$

On the other hand, the position of a rigid body is represented by the quaternion

$$\boldsymbol{p} = p_x\hat{\imath} + p_y\hat{\jmath} + p_z\hat{k}, \tag{2}$$

where p_x, p_y, and p_z correspond to the position in the x, y, and z axis, respectively.

A unit-norm dual quaternion represents a rigid body motion by combining the position and orientation in the compact expression

$$\underline{x}_1^0 = \boldsymbol{r} + \frac{1}{2}\varepsilon\boldsymbol{p}\boldsymbol{r}, \tag{3}$$

which represents the motion from frame $\mathcal{F}_0$ to frame $\mathcal{F}_1$ (Selig, 2005). The notation used in this paper indicates the current coordinate system in the subscript of the dual quaternion and the reference coordinate system in the superscript. An example of a rigid motion from frame $\mathcal{F}_0$ to frame $\mathcal{F}_1$ is presented in figure 1. The figure shows the displacement $\boldsymbol{p}$ and the rotation ψ around the rotation axis $\boldsymbol{n}$, which is compactly represented by the dual quaternion (3).

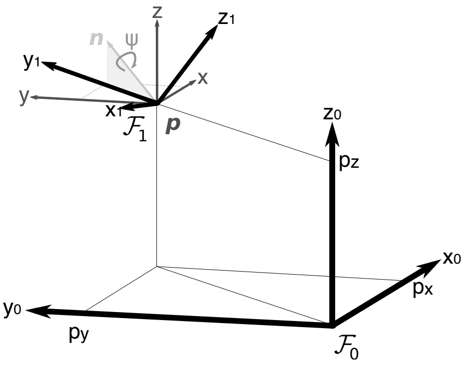

Figure 1: Rigid motion represented by a dual quaternion.

Table 1: D-H model parameters of the AX18 manipulator robot.

Link	d (m)	θ (rad)	a (m)	α (rad)
L_1	0.167	0	0	$-\pi/2$
L_2	0	0	0.159	0
L_3	0	$-\pi/2$	0	$-\pi/2$
V*	0.0815	0	0.02225	0
L_4	0.041	$-\pi/2$	0	$-\pi/2$
L_5	0	0	0	0

* Virtual link: it does not represent a physical link of the robot

2.3 Manipulator robot modeling

One classic approach for modeling serial manipulators is to use the Denavit-Hartenberg (D-H) parameters. The standard D-H convention establishes the relation between two consecutive links using four parameters (Siciliano et al., 2011); that is, a rotation θ around the z axis and a translation d along the z axis, followed by a translation a along the x axis, and finally a rotation α around the x axis. Using dual quaternion algebra, this is represented by (Adorno, 2011)

$$\underline{x}_{L_i} = \boldsymbol{r}_{\theta_i}\underline{p}_{d_i}\underline{p}_{a_i}\boldsymbol{r}_{\alpha_i}, \tag{4}$$

where

$$\begin{aligned} \underline{p}_{d_i} &= 1 + \varepsilon\left(\frac{d_i}{2}\right)\hat{k}, \\ \underline{p}_{a_i} &= 1 + \varepsilon\left(\frac{a_i}{2}\right)\hat{\imath}, \\ \boldsymbol{r}_{\theta_i} &= \cos\left(\frac{\theta_i}{2}\right) + \sin\left(\frac{\theta_i}{2}\right)\hat{k}, \\ \boldsymbol{r}_{\alpha_i} &= \cos\left(\frac{\alpha_i}{2}\right) + \sin\left(\frac{\alpha_i}{2}\right)\hat{\imath}. \end{aligned} \tag{5}$$

The manipulator robot used in this work, the AX18 Smart Robot Arm (CrustCrawler Robotics, Arizona, USA) has five degrees of freedom and a gripper. The D-H parameters of the robot are presented in table 1.

The gripper is represented by the dual quaternion

$$\underline{x}_G = \boldsymbol{r}_G + \frac{1}{2}\varepsilon\boldsymbol{p}_G\boldsymbol{r}_G, \tag{6}$$

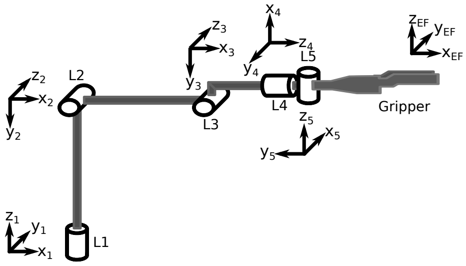

Figure 2: Frames assigned to the CrustCrawler AX18 manipulator robot in order to determine the D-H parameters.

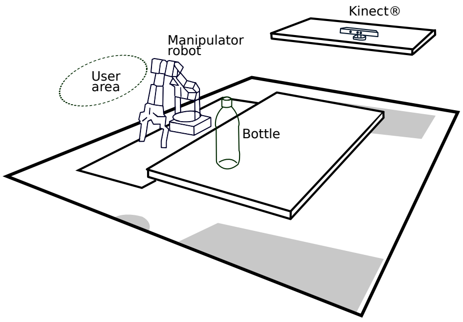

Figure 3: Workspace defined for the assistance task.

where $\boldsymbol{p}_G = -0.17\hat{k}$ and $\boldsymbol{r}_G = \cos(\pi/4) - \sin(\pi/4)\,\hat{k}$. Using (4) and (6) and the D-H parameters of table 1, the forward kinematics model (FKM) is given by

$$\underline{x}_E = \underline{x}_{L_1}\underline{x}_{L_2}\underline{x}_{L_3}\underline{x}_V\underline{x}_{L_4}\underline{x}_{L_5}\underline{x}_G. \tag{7}$$

Figure 2 shows the frames assigned to the CrustCrawler AX18 manipulator robot in order to determine the D-H parameters.

3 Description of the assistance task

The assistance task defined for this work consisted of reaching and grasping a bottle to serve a drink to a person using a manipulator robot. The environment of the task is shown in figure 3. Four components were considered for the task: (1) the user; (2) the manipulator robot; (3) the Microsoft Kinect® sensor; and (4) the bottle containing the drink. The robot base, the Kinect®, and the bottle were maintained in a fixed pose, while the user was able to move within a predefined area. The position of the user was tracked using the Kinect sensor, providing a closed loop at the human-robot interaction level.

In order to establish the geometrical relationship between the Kinect® and the robot, an artificial marker was placed at a known position of the robot base, such that the relation $\underline{x}_{marker}^{robot}$ was known a priori, as shown in figure 4. This way, using the ARToolKit[1] the transformation $\underline{x}_{kinect}^{marker}$ between the marker frame and the Kinect® frame can be found and hence the transformation $\underline{x}_{kinect}^{robot}$ between the Kinect and the robot base is given by

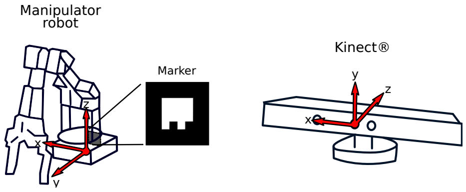

Figure 4: Frames assigned to the robot manipulator base and to the Kinect®. The marker was used to determine the pose between these two coordinates systems.

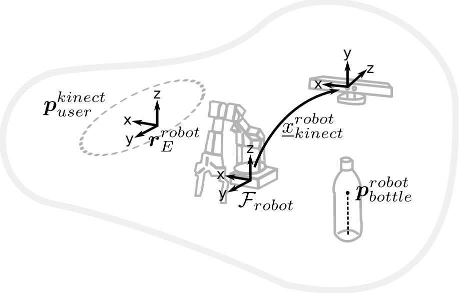

Figure 5: Geometric primitives that define the task.

$$\underline{x}_{kinect}^{robot} = \underline{x}_{marker}^{robot}\underline{x}_{kinect}^{marker}.$$

3.1 Task definition

The assistance task is divided into four stages: (1) the robot, starting from an initial pose, reaches and holds the bottle located at a fixed position on a table; (2) the robot grasps the bottle and brings it close to the user's mouth; (3) the user takes the drink; and (4) the robot places the bottle on the table and returns to its initial pose. For the second stage, the robot receives feedback from the Kinect® about the position of the user.

Some geometric primitives were defined in order to solve the task (figure 5). The initial pose of the bottle was fixed with respect to the robot base and defined a priori. This pose, $\underline{x}_{bottle}^{robot}$, was used as the first desired pose for the gripper; that is,

$$\underline{x}_{d,1}^{robot} \triangleq \underline{x}_{bottle}^{robot}.$$

The pose of the user's head provided by the Kinect® sensor, with respect to the robot base, is given by

$$\underline{x}_{user}^{robot} = \underline{x}_{kinect}^{robot}\left(1 + \frac{1}{2}\varepsilon\boldsymbol{p}_{user}^{kinect}\right). \tag{8}$$

In order to safely serve the drink in the second stage of the task, the next desired pose for the robot was defined as

$$\underline{x}_{d,2}^{robot} \triangleq \underline{x}_{safety}\underline{x}_{user}^{robot}\boldsymbol{r}_{kinect}^{robot*}, \tag{9}$$

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[1] `http://www.ros.org/wiki/artoolkit`

where the safety distance $\underline{x}_{safety}$ was defined as

$$\underline{x}_{safety} \triangleq 1 - \frac{1}{2}\varepsilon\left(0.1\hat{\imath} + 0.05\hat{k}\right)$$

in order to avoid collision between the robot and the user. Since the Kinect® does not provide, in our current implementation, the orientation of the user's head, the term $\boldsymbol{r}_{kinect}^{robot*}$ was used in (9) to make the orientation of the gripper be the same as the one of figure 2. This orientation was fixed given that the users were asked to stay within the area shown in figure 3 and with their mouth aligned with the x axis of the robot base, so they could easily take the drink.

In order to return the bottle onto the table, the third desired pose was defined as $\underline{x}_{d,3}^{robot} \triangleq \underline{x}_{d,1}^{robot}$. In addition, before returning to the initial configuration an intermediate setpoint was defined in order to avoid collision between the robot and the bottle:

$$\underline{x}_{d,4}^{robot} \triangleq \left[1 + \frac{1}{2}\varepsilon\left(0.1\hat{\imath} - 0.1\hat{\jmath} + 0.15\hat{k}\right)\right]\underline{x}_{d,1}^{rob\hat{o}}.$$

Finally, the robot would return to its initial configuration in order to continue another cycle of the assistance task, whenever required.

3.2 Control strategy

The use of dual quaternions allow the simultaneous control of the position and the orientation of a manipulator robot based on the differential forward kinematics model

$$\operatorname{vec}\dot{\underline{x}}_E = \boldsymbol{J}_{\underline{x}}\dot{\boldsymbol{\theta}}, \tag{10}$$

which describes the mapping between the velocity of the task-space variables, given by the first derivative of $\underline{x}_E$ (see (7)), and the joint velocities vector $\dot{\boldsymbol{\theta}}$. It is important to note that the differential FKM can be found for any serial robot by using dual quaternion algebra (Adorno, 2011).

A suitable controller derived from (10) can consider the control of any subset of the end effector pose independently (Adorno et al., 2010). Therefore, given the five degrees of freedom of the AX18 Smart Robot Arm, we decided to prioritize the position control over the orientation control using the task-priority based controller (Liegeois, 1977). In this way, the controller uses three degrees of freedom to control the position (primary task) and the two remaining degrees of freedom are used to control the orientation in the null space of the primary task. Hence, it is expected that the controller will guarantee convergence for the position but there will be a small steady-state error for the orientation. More specifically, this task-priority based discrete control law, using dual quaternion primitives, is given by

$$\begin{aligned}\boldsymbol{\theta}_k = \boldsymbol{\theta}_{k-1} &+ \boldsymbol{J}_{\boldsymbol{p}}^{+}\lambda_p \operatorname{vec}\left(\boldsymbol{p}_d - \boldsymbol{p}_m\right)\\ &+ \boldsymbol{P}\boldsymbol{J}_{\boldsymbol{r}}^{+}\lambda_r \operatorname{vec}\left(\boldsymbol{r}_d - \boldsymbol{r}_m\right),\end{aligned} \tag{11}$$

where $\boldsymbol{J}_{\boldsymbol{p}}^{+}$ is the pseudo-inverse of the position Jacobian, $\boldsymbol{J}_{\boldsymbol{r}}^{+}$ is the pseudo-inverse of the orientation Jacobian, λ_p and λ_r are scalar gains related to the position and the orientation, respectively. The quaternions $\boldsymbol{p}_d$ and $\boldsymbol{p}_m$ are the desired and current positions, respectively, and the unit quaternions $\boldsymbol{r}_d$ and $\boldsymbol{r}_m$ are the desired and current orientations, respectively. Finally,

$$\boldsymbol{P} = \boldsymbol{I} - \boldsymbol{J}_p^{+}\boldsymbol{J}_p \tag{12}$$

is the projection into the nullspace of the position Jacobian, with $\boldsymbol{I}$ being an identity matrix of appropriate dimension. Both position and orientation Jacobians can be found, by using dual quaternion algebra, from the analytical Jacobian $\boldsymbol{J}_{\underline{x}}$ (10) (Adorno et al., 2010). The control law (11) was used throughout the execution of the task and two criteria based on the position error were used to stop the control loop and switch the subtask. First, an error is defined in terms of unit dual quaternions as

$$\begin{aligned}\underline{x}_{error} &= \underline{x}_{d,i}^{robot*}\underline{x}_m^{robot}\\ &= \boldsymbol{r}_{error} + \frac{1}{2}\varepsilon\boldsymbol{p}_{error}\boldsymbol{r}_{error},\end{aligned} \tag{13}$$

for all of the desired poses. Then, if

$$e = \|\boldsymbol{p}_{error}\| < 0.01 \text{ or } \dot{e} < 0.0001$$

the control loop was stopped and the subtask was switched.

4 Results[2]

The execution of the assistance task was implemented in the Matlab® software and tested with five users. Figures 6 and 7 show the geometric parameters for the desired and measured poses of the robot end-effector when reaching the bottle and serving the drink, respectively, for one execution of the task[3]. It can be seen that position converges for all the subtasks, while orientation stabilizes with an offset with respect to the desired values. These results highlight the priority of the position control over the orientation control.

The serving stage was set to last 25 seconds. As shown in figure 7, the controller converged to the desired trajectory even when the user displaced her head. The tracking of the user position provided by the Kinect® sensor improved the performance and experience related to the execution of the task, as reported by the users.

An example of the trajectory calculated by the controller for the drink reaching stage is presented in figure 8. The dual quaternion $\underline{x}_0$ corresponds to the initial end-effector pose and $\underline{x}_m$

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[2] See the accompanying video at `http://www.youtube.com/watch?v=h2AcasjAEzs`

[3] Results for the subtask corresponding to the returning of the bottle were similar to those obtained for the reaching stage, and thus omitted due to lack of space.

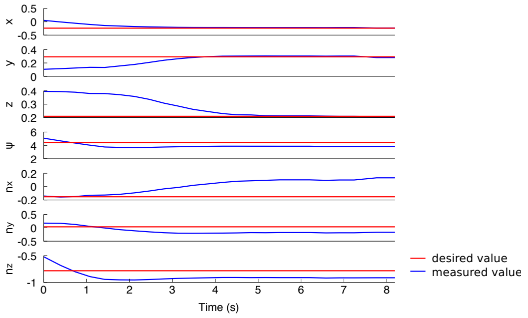

Figure 6: Experimental results for the first stage of the task, bottle reaching.

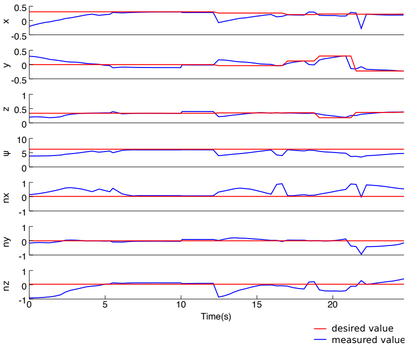

Figure 7: Experimental results for the second stage of the task, drink serving.

correspond to the measured end-effector pose. We note that the position converges to the desired value while the orientation stabilizes in a value close to the desired one. This was expected, since the robot is underactuated and the orientation control was performed with less priority. Remarkably, the grasping of the drink was possible even with the steady-state error for the orientation, as shown in figure 9. Figure 10 shows a sequence of the task execution.

5 Conclusion

This work presented the definition of an assistance task performed by an anthropomorphic manipulator robot based on dual quaternion algebra. Dual quaternions provided an intuitive description of the geometric primitives and were also useful in the design of the task-priority based kinematic controller.

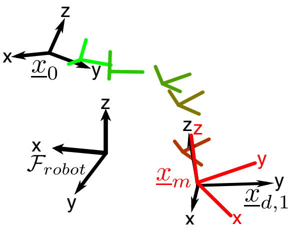

Figure 8: End-effector trajectory for the first stage of the task, bottle reaching.

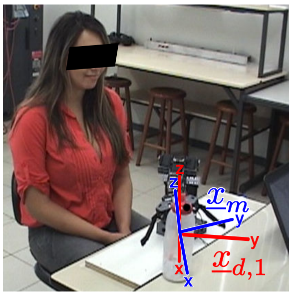
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Figure 9: Final pose $\underline{x}_m$ of the end effector when reaching the bottle. The desired pose corresponds to $\underline{x}_{d,1}$.

The task-priority controller, which was chosen because the robot is underactuated, provided a good behavior at the human-robot interaction level even with the presence of a small steady-state error in the orientation. The experimental results attested the capability of the robot to perform the task in a satisfactory manner.

Future developments will be focused on the implementation of a real-time system, the inclusion of force feedback to maximize safety in situations involving contact, and the use of fully actuated manipulators.

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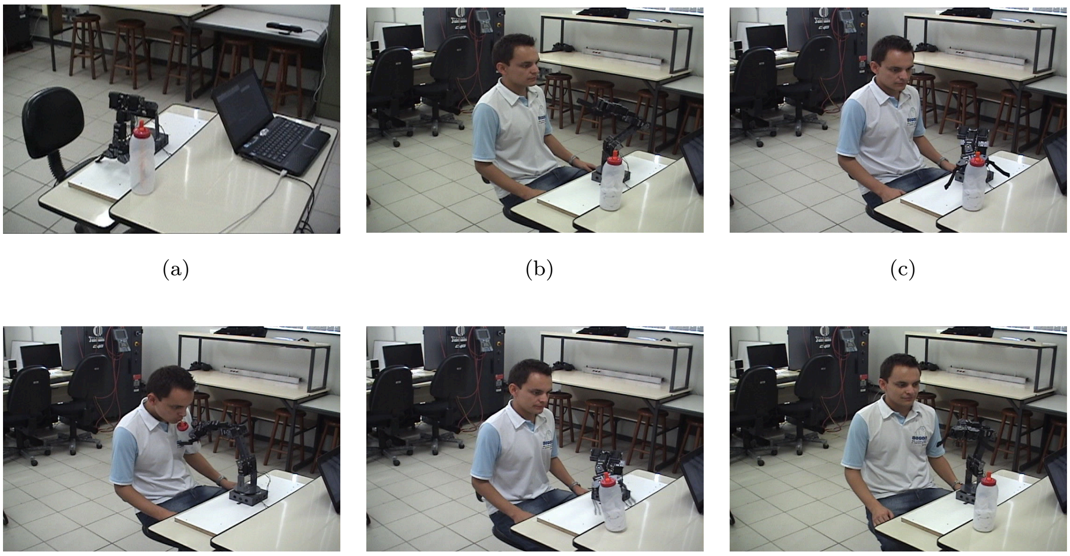
(a) (b) (c)

(d) (e) (f)

Figure 10: Example of one sequence for the task execution: *(a)* the environment of the task, *(b)* the robot at its initial pose, *(c)* the bottle reaching, *(d)* the drink serving, *(e)* the robot returning the bottle to the table, and *(f)* the robot returning to its initial pose.

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