Experiments on Dextrous Manipulation without Prior Object Models [1]

Olac Fuentes Randal C. Nelson
Computer Science Department
University of Rochester
Rochester, New York 14627
{fuentes,nelson}@cs.rochester.edu
http://www.cs.rochester.edu/u/{fuentes,nelson}/

Abstract

In this paper we present a kinematic method for 6-degree-of-freedom manipulation of rigid objects using a dextrous robotic hand. Our method does not require prior models of the objects to be manipulated; all the information needed can be obtained directly from the hand's sensors. The method allows arbitrary (within the robot's physical limits) translations and rotations of the object, and its low computational cost makes real-time performance easy to achieve.

We present experimental results of manipulation using the Utah/MIT hand [1, 2], a 16-DOF dextrous manipulator, and show that with the addition of a Cartesian controller a high degree of accuracy can be attained.

1. Introduction

Most research on dextrous manipulation has relied on the assumption that accurate and complete models of the objects being manipulated are available or can be easily obtained. However, if we want a manipulator to operate in unknown environments and/or manipulate a wide variety of objects, model-based approaches are difficult to apply. Compliant dextrous hands with many degrees of freedom offer a possible solution to this problem, since their redundancy and compliance can be used to achieve stable grasps in the presence of uncertainty.

Due to extensive theoretical studies (see *e.g.* [3, 4, 5]), the mechanics of dextrous manipulation are relatively well-understood. However, few experimental systems for dextrous manipulation have been implemented to date, and most of them have relied on prior information about the objects to be manipulated (*e.g.* [6, 7], [8], [9]). Michelman and Allen [6, 7], presented a method based on hybrid control for dextrous manipulation using the Utah/MIT hand. The system was shown to work for several manipulation tasks, such as removing the top of a child-proof medicine bottle, using a limited amount of prior information about the object. Speeter [8] proposed *motor primitives* for the Utah/MIT hand. Motor primitives are sequences of joint position changes encoding a small functional motion of the hand. Although motor primitives could be combined and generalized to some extent, the fact that they were specific to a particular object made the development of a reasonably useful set of primitives cumbersome.

The method we present in this paper does not rely on *a priori* models. Instead, we show that a wide variety of manipulations can be performed using the hand's sensors as the only source of information about the object's shape and size. We start with the object being stably grasped; the task of the system is to translate and rotate the object while maintaining this stable grasp.

The organization of the remainder of this paper is as follows. Section 2 describes our dextrous manipulation method. Section 3 presents experimental results using the 16 degree-of-freedom Utah/MIT hand [1, 2] showing a quantitative evaluation of the precision that can achieved with the method, and showing how performance can be further improved using a higher-level controller. Section 4 presents conclusions and briefly describes some present and future work.

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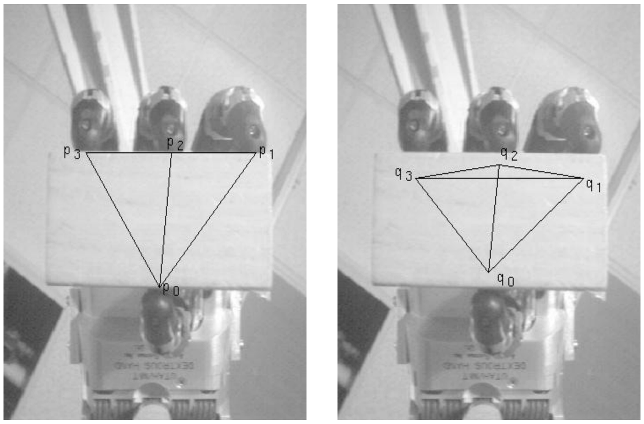
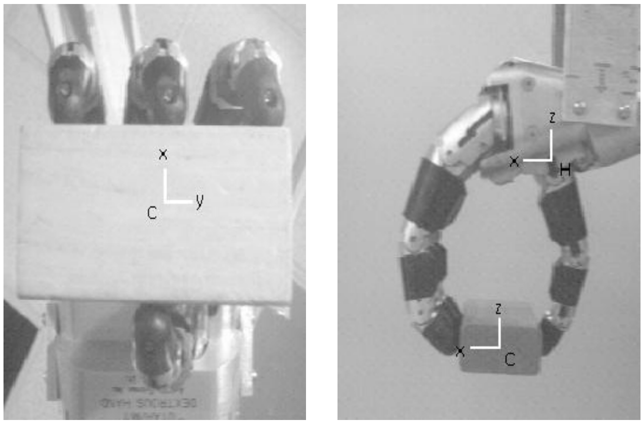


(a) (b)

Figure 1: The contact tetrahedron (a) and the grasp tetrahedron (b).



(a) (b)

Figure 2: The hand-centered reference frame H and the object-centered reference frame C

2. A Non-Model-Based Dextrous Manipulation Strategy

We assume that prior to manipulation the object has been stably grasped. The basic idea of our technique is based on the observation that the commanded fingertip positions or setpoints define a rigid object in three-dimensional space, in this case a (possibly degenerate) tetrahedron. We refer to this object as the *grasp tetrahedron.* The contact points of the fingers on the object define another object that we refer to as the *contact tetrahedron.* Because of the compliant control system, we can model the statics of the situation by regarding each vertex of the contact tetrahedron as being attached to the corresponding vertex of the grasp tetrahedron by a virtual spring. In the case of an object free to move, net wrench is constrained to be zero. Moreover, for a well conditioned grasp, the wrench zero coincides with a deep local minimum of the spring energy function on a manifold defined by the rigid displacements of the grasp tetrahedron with respect to the contact tetrahedron. This means that if we treat the fingertip contacts as fixed points on the object, then the object can be rotated and translated by executing the desired rigid transformation on the grasp tetrahedron. In other words, displace the grasp tetrahedron and the object will follow. Although, due to non-zero finger size and other effects, the assumption of fixed contact points is not strictly correct, our experimental results show that the compliance of the Utah/MIT hand compensates for the errors introduced by the use of this assumption. Somewhat similar approaches have been suggested in [10] and [11].

In more detail, the formulation is as follows. Let ${}^Hp_0, {}^Hp_1, {}^Hp_2$ and ${}^Hp_3$ be the fingertip to object contact points, where ${}^Hp_i$ denotes that p_i is being measured with respect to a hand-centered reference frame H. Let ${}^Hq_0, {}^Hq_1, {}^Hq_2$ and ${}^Hq_3$ be the commanded fingertip positions or setpoints. The tetrahedron ${}^Hp_0, {}^Hp_1, {}^Hp_2 {}^Hp_3$ is the contact tetrahedron. ${}^Hq_0, {}^Hq_1, {}^Hq_2 {}^Hq_3$ is the grasp tetrahedron. The contact and grasp tetrahedra for a sample grasp are shown in figure 1. If the object is stably grasped, the grasp tetrahedron will generally be completely contained in the contact tetrahedron. The locations of the grasp and the contact tetrahedra can be obtained respectively from the measurements of the commanded and actual joint angles and the forward kinematics of the hand.

As noted above, the force applied to the object at any of the contact points is approximately proportional to the difference between the fingertip's commanded and actual positions. If the fingertip positions with respect to the object remain constant, we can apply arbitrary rotations and translations to the object while keeping a constant force applied in every contact point by just rotating and translating the grasp tetrahedron. Formally, we describe the situation as follows.

Let ${}^Hc = [c_x, c_y, c_z]^T$ be the coordinates of the centroid of the grasp tetrahedron with respect to frame H. We define an object-centered frame of reference C, with its axes parallel to H's and with origin at c, as shown in figure 2.

Given the manipulation command $\langle x, y, z, \alpha, \beta, \gamma \rangle$, where x, y and z represent displacements of the object with respect to its initial position and α, β, γ are interpreted as sequential rotations around the x, y and

z axes of C, the resulting setpoints $q'_0, \ldots, q'_3$ are given by:

$$\begin{bmatrix} q'_{ix} \\ q'_{iy} \\ q'_{iz} \\ 1 \end{bmatrix} = T(\langle x, y, z, \alpha, \beta, \gamma \rangle) \begin{bmatrix} q_{ix} - c_x \\ q_{iy} - c_y \\ q_{iz} - c_z \\ 1 \end{bmatrix}$$

Where $T(\langle x, y, z, \alpha, \beta, \gamma \rangle)$ is given by: [1]

$$T = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma & x + c_x \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma & y + c_y \\ -s\beta & c\beta s\gamma & c\beta c\gamma & z + c_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

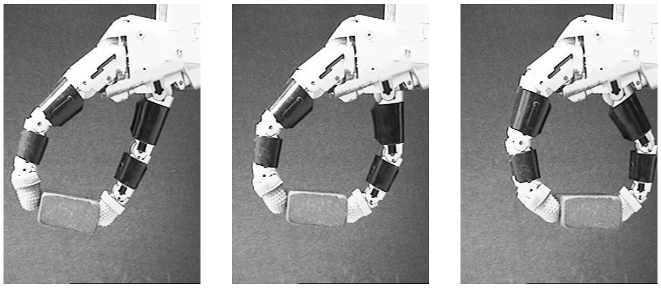


Figure 3: Translation along the x axis

3. Experimental Results

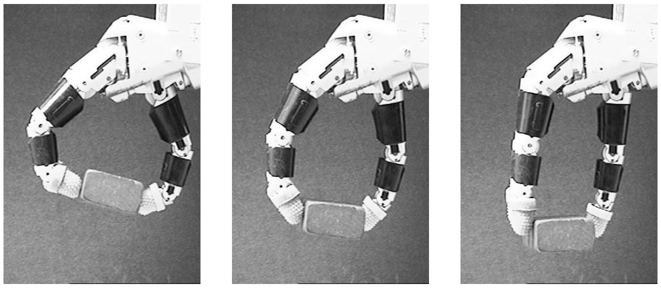


Figure 5: Transalation along the z axis

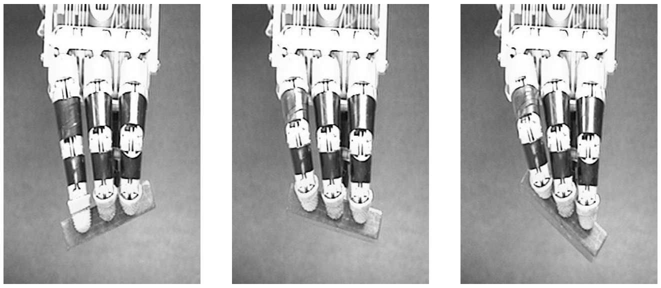


Figure 6: Rotation about the x axis

The algorithm described in the previous section was implemented on the Utah/MIT hand, a 16 degree-of-freedom four-fingered dextrous manipulator. Each joint of the hand is actuated by a pair of pneumatically-driven antagonist tendons. This results in a compliant response, but it also makes reliable and consistent positioning difficult to achieve due to hysteresis and friction effects.

Figures 3 to 8 show the hand manipulating a wooden block. The images show translations along and rotations about the three main axes. Although we only show the results of translations and rotations orthogonal to the main axes, translations and rotations can be performed with respect to any arbitrary axis.

3.1. Performance Evaluation

We evaluated the precision obtained by comparing the commanded and an estimated position and orientation of the object during a manipulation sequence. To estimate the actual configuration of the object we define an object-centered reference frame D from which we can later obtain the estimated $\langle x, y, z, \alpha, \beta, \gamma \rangle$ values. Let $p_0, \ldots, p_3$ be the coordinates of the fingertips, obtained from the sensed joint angles and the forward kinematics

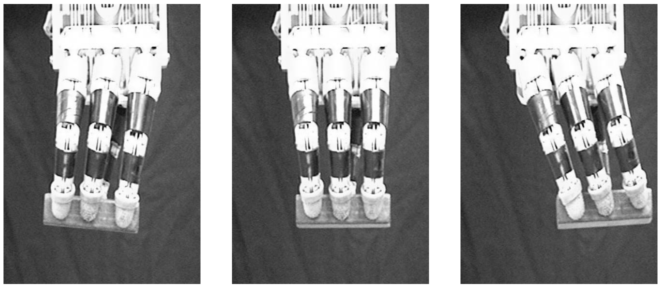


Figure 4: Translation along the y axis

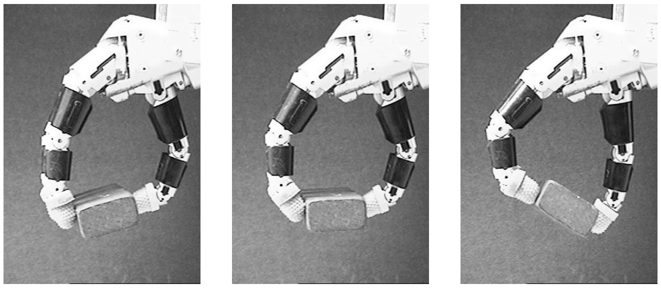


Figure 7: Rotation about the y axis

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[1] we use $c\theta$ and $s\theta$ as shorthand for $cos(\theta)$ and $sin(\theta)$, respectively

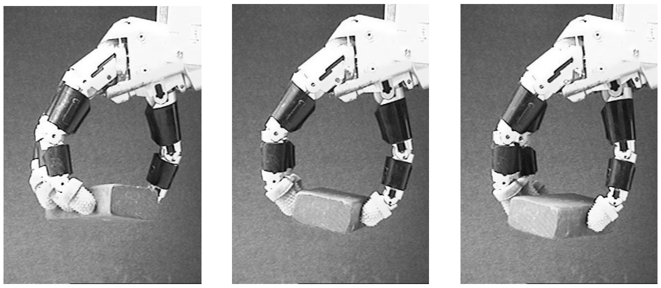

Figure 8: Rotation about the x axis

of the hand. Let d be the centroid of the tetrahedron formed by $p_0, \ldots, p_3$. Let v_{ij} denote the vector joining p_i and p_j. Then ${}^{H}_{D}T$ is given by:

$$
{}^{H}_{D}T = \begin{bmatrix} \frac{v_{02}}{|v_{02}|} & \frac{v_{02} \times v_{31} \times v_{02}}{|v_{02} \times v_{31} \times v_{02}|} & \frac{v_{02} \times v_{31}}{|v_{02} \times v_{31}|} & d \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

That is, the origin of D is the centroid of the contact tetrahedron, the x-axis is parallel to the line joining the fingertips of the thumb and the index finger, the z-axis is perpendicular to the x-axis and to the line joining the fingertips of the index and ring fingers, and the y-axis is perpendicular to the x and z axes.

From ${}^{H}_{D}T$ we get the estimated position and orientation as follows:

$$
x = {}^{H}_{D}T_{14} - c_x, y = {}^{H}_{D}T_{24} - c_y, z = {}^{H}_{D}T_{34} - c_z,
$$

$$
\beta = Atan2(-{}^{H}_{D}T_{31}, \sqrt{{}^{H}_{D}T_{11}^2 + {}^{H}_{D}T_{21}^2}),
$$

$$
\alpha = Atan2({}^{H}_{D}T_{21}/\cos\beta, {}^{H}_{D}T_{11}/\cos\beta),
$$

$$
\gamma = Atan2({}^{H}_{D}T_{32}/\cos\beta, {}^{H}_{D}T_{33}/\cos\beta),
$$

Figure 9 shows a comparison of the estimated and commanded positions in a manipulation sequence using our strategy. The sequence of movements consisted of rotations of 35, -70 and 35 degrees about the x axes, 23 and -46 and 23 degrees about the y axes, and 45, -90 and 45 degrees about the z axis, followed by translations of 20, -40 and 20 millimeters along the x axes, 28, -56 and 28 millimeters along the y axis, and 13, -26 and 13 millimeters along the z axis. These ranges we determined to fall within the physical limit of the hand. For the sequences shown in figure 9, the root-mean-squared error was 3.63 mm for translations and 6.72 degrees for rotations. It can be seen that although the Utah/MIT hand is a relatively imprecise and difficult to control manipulator, due to hysteresis and friction, a fairly good degree of precision can be achieved. In the next subsection we will discuss how we can improve upon this precision by adding a higher-level Cartesian controller.

3.2. Addition of a Cartesian Controller

At the lowest level, each joint in the Utah/MIT hand is controlled using a standard PD controller. In principle the joint errors can be reduced by increasing the gains in these controllers. However, this would also result in a decrease in compliance

A way to reduce position errors while maintaining compliance is to implement a higher-level Cartesian controller to correct errors directly in the 6-dimensional position-orientation space. The estimated errors in $\langle x, y, z, \alpha, \beta, \gamma \rangle$ were fed to a Cartesian PID controller, as shown in figure 10. In the actual implementation we substituted summations for integrals and first differences for derivatives. We performed the same manipulation sequence as in the previous subsection. The resulting improvement in performance is shown in figure 11. For this kind of control, the root-mean-squared errors were reduced to 1.1 mm in positioning and 1.99 degrees in orientation during the sequence.

4. Conclusions and Future Work

We have presented experimental results demonstrating the efficacy of a purely kinematic technique for dextrous manipulation with the Utah/MIT hand. Although the Utah/MIT hand is very difficult to control due to the high dimensionality of its parameter space and the non-rigid nature of its actuators, we have shown that fairly precise manipulation can be performed. We also showed that the addition of a Cartesian controller further improves the precision of the manipulation.

In contrast to most previous approaches to dextrous manipulation, our method is completely model-free, a crucial feature for use in dynamic and unknown environments. The relative low computational cost it requires makes it easy to implement in real-time.

Current and future work includes the application of this method to telemanipulation, where instead of attempting to map the configuration of the teleoperator's hand directly to the robotic hand, the teleoperator uses a polhemus or similar device to command translations and rotations of the object. We are also working on the combination of this dextrous manipulation technique with non-calibrated visual servoing to perform high-precision assembly tasks.

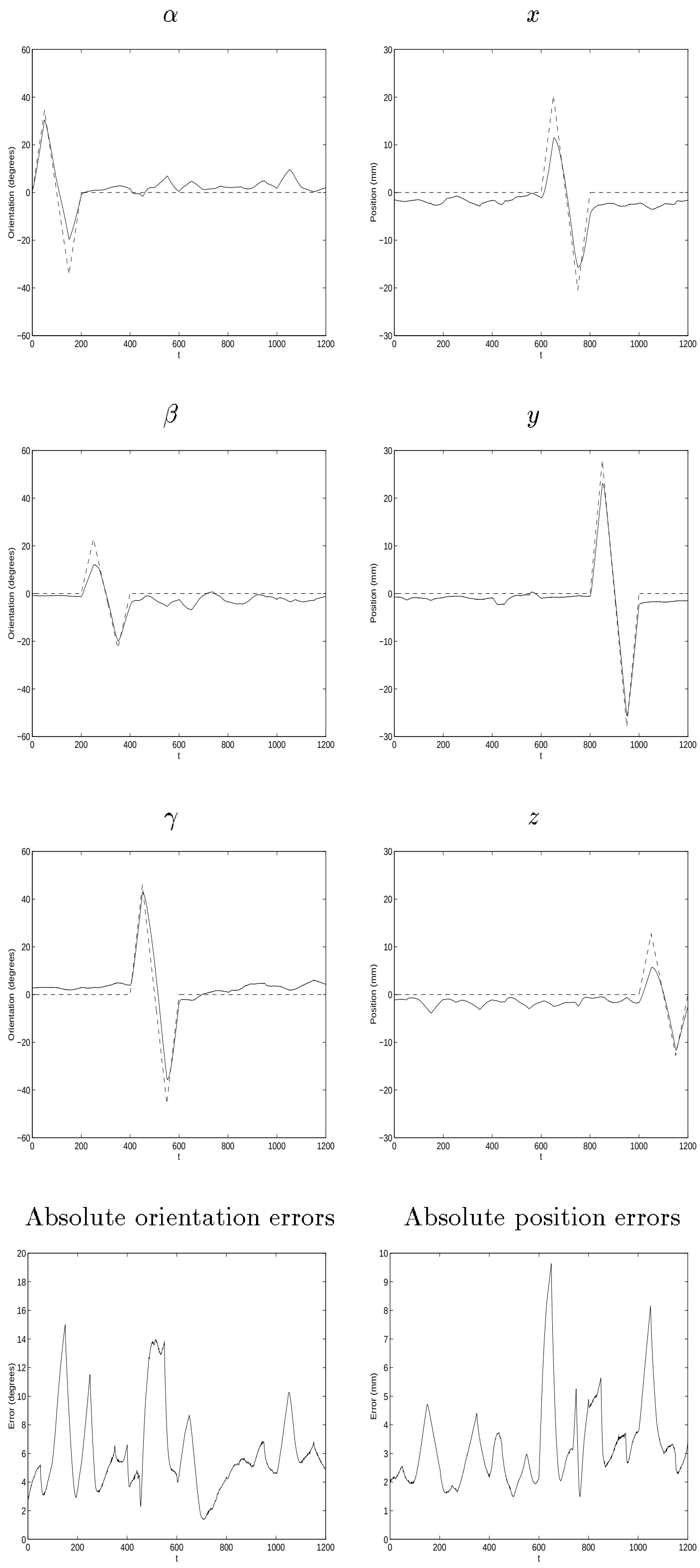

Figure 9: Commanded (dotted lines) and estimated (solid lines) positions and orientations, and estimated errors during a manipulation sequence.

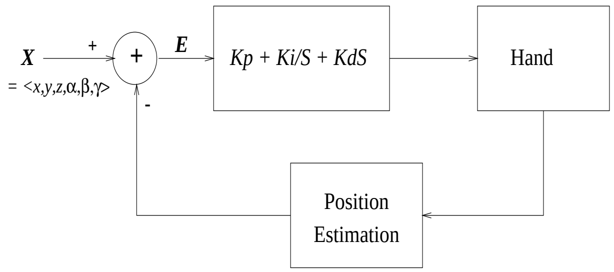

Figure 10: Control system

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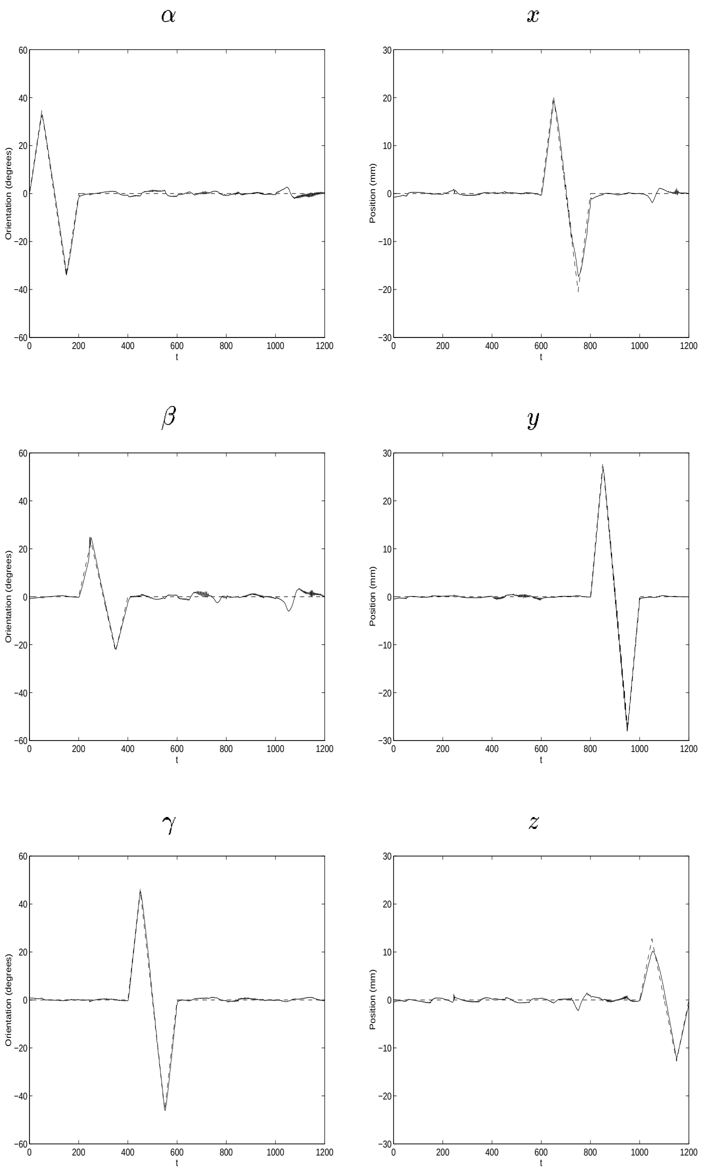

Absolute orientation errors

Absolute position errors

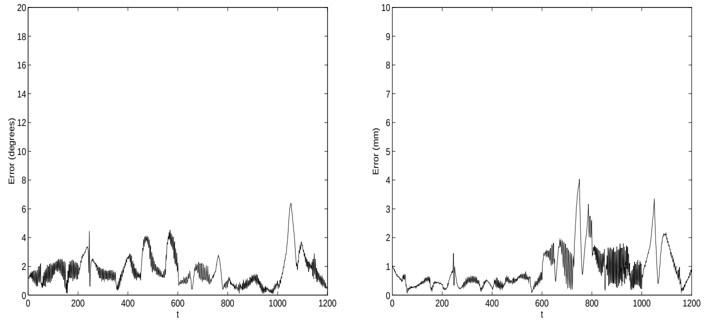

Figure 11: Commanded (dotted lines) and estimated (solid lines) positions and orientations, and estimated errors during a manipulation sequence.

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