UNILATERAL MASTER-SLAVE ROBOT TELEOPERATION BY MEANS OF A USER WEARABLE INTERFACE BASED ON INERTIAL SENSORS

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Abstract: In master - slave teleoperation schemes operated by humans, the interface with which the user interacts plays a key role. In this work an interface based on inertial sensors with applications for unilateral master - slave robotic teleoperation is developed. The interface is composed of two portable inertial sensor units which are placed on the upper and lower arm to obtain acceleration and turning rates. The data is internally processed by a DSP in the sensors which yield real time orientation measurements of the bodies they are attached. Then the 3D wrist human Cartesian trajectory is determined by using kinematic models of the human arm, this trajectory becomes the desired trajectory to the slave robot. Finally by means of a control technique the slave robot is capable to track wrist human movements. For validation purposes a master - slave teleoperation system is implemented with a three degree of freedom (dof) delta configuration parallel robot as slave system. © 2010 IFAC

Keywords: Interface, control, teleoperation, inertial sensors, wearable.

1. INTRODUCTION

Integrating human and robotics machines into a single systems offers multiple opportunities for creating assistive, flexible and robust technologies that can be used in biomedical, industrial, clinical, military and aerospace applications. The applications and possibilities of such systems increase when considering teleoperation, which allows the human and robot system to be at different locations. For this purpose once human motion is captured it is used to design desired trajectories for the slave robot. A human’s ability to perform physical tasks is not limited by intelligence but by physical strength and precision, whereas robotic machines can easily carry out rigorous tasks such as maneuvering heavy objects (Ferreira et. al., 2009). Nonetheless, despite the high dexterity that artificial control algorithms can provide to robots, the performance of naturally algorithms used by humans surpasses those present at robots.

Teleoperation systems are as divers as the technics employed on its control. There exists teleoperated systems that besides the robots dynamics, also the operator arm and the environment dynamics might be included (Speich et al, 2005). Including the four dynamics (operator, master robot, slave robot, environment) results in what is called the
two-port model, which results from an analogy with electric circuits (Hannaford, 2005).

A key point in human - robot teleoperation systems corresponds to the operator interface, in general it is desired that such interface affects the less possible the free of operator movements, but at the same time being capable of determining dynamic aspects of the operator motion.

Several researchs have been conducted to capture and emulate human movement. Although vision based systems can reliably and accurately measure fast human movements if sufficient markers are applied and observed by the distributed cameras, such systems suffer from occlusion, require fast human movements if sufficient markers based systems can reliably and accurately measure accelerations and other variables depending of the instrumentation on board, a tiresome calibration process and intensive computation, among other difficulties. Recently attempts have been done to develop visual based marker-free tracking systems (Wang et. al., 2003), which used conventional cameras and relax some requirements of marker based systems.

In many circumstances, inertial sensor based systems are preferred over other non optical systems, e.g. mechanical, acoustic, radio or microwave systems. Inertial systems produce acceptable accurate measurements of accelerations and other variables depending of the instrumentation on board, are light weight and available for wireless communication. A major drawback on inertial sensors is the presence of drift, nonetheless several works related with filters and sensor fusion to deal with such a problem have been proposed and commercially implemented, see for instance (Yun et. al., 2008) and (Hyde et. al., 2008), even in presence or near of ferromagnetic materials (Roetenberg et. al, 2007).

For example in (Tao et. al., 2007) an inertial tracking systems for monitoring movements of human upper limbs in order to support a home-based rehabilitation scheme was developed. Some others works deal with the human walking pattern acquisition from human models, for example in (Harada et. al., 2009) and (Ferreira et. al., 2009) the authors captured human walking motion to provide motion to a humanoid robot.

The human body can be represented by segments or links connected by revolute joints, if their orientation relative to a fixed reference frame can be determined, then the overall posture of the human subject can accurately be rendered and communicated in real time.

In this work a real time wearable interface for application in teleoperation system is developed. For this purpose human arm movements are measured with a set of two inertial sensors located at the upper and lower arm. Such lower and upper arm trajectories determine the wrist movements, which are transfer to a general n-joint robot manipulator, provided the arm trajectories are inside the robot working space. The inertial sensors communicate with a computer via wireless, using Bluetooth protocol, see Figure 1. This feature allows unrestricted motion of the subject, which is a huge advantage over vision based systems, since commonly required special locations and controlled conditions.

To avoid robot working space singularities, it is considered that the n-joint robot has a working space that entirely covers the working space of the human arm. Notice that this constraint on the working spaces does not imply conditions on the robot architecture (serial or parallel), joint type (revolute, prismatic, etc.), numbers of links or extremities. The imposed condition guarantees that the wrist trajectories are achievable by the robot.

Notice that in general the only constraint on the robot dynamics impose by our proposal, is that the joint velocities and accelerations are such that the robot end effector might track the wrist Cartesian velocities and accelerations.

The end effector of the slave robot tracks the wrist Cartesian motion by means of a PID controller, that is programed at joint robot space. The system is validated through experiments with a delta 3 dof robot manipulator as slave.

![Figure 1. Master-slave teleoperation with an operator wearable interface.](image)

2. HUMAN ARM KINEMATICS AND MOTION ACQUISITION SYSTEM (OPERATOR INTERFACE)

The arm interface is composed of two inertial MTx sensors (Xsens Motion Technology). Each MTx sensor consists of three orthogonally placed piezo-resistive accelerometers (ADXL202E, Analog Devices), three vibrating beam gyroscopes (ENC03J, Murata) and three magneto-resistive sensors (KM51, Philips). The sensors output measurements are considered as raw data for a Kalman filter which determines the orientation...
of the sensor with respect to a general global reference. The orientation data obtained from the inertial sensors is fed to a kinematic model of the arm, which yields the Cartesian position of the arm, and particularly of the wrist. Accordingly to the fabricant the inertial sensors have an angular resolution of 0.05°, a repeatability of 0.2°, a static accuracy of 1°, a dynamic accuracy of 2° RMS and an update rate of up to 120 Hz. The inertial sensors communicate with a computer via Bluetooth or wired devices provided by the manufacturer. The simultaneous use of both inertial sensors is allowed by the XBus master, to which each inertial unit communicates by a wired connection.

The human arm is modeled as two bodies connected by three dof revolute joint or a skeleton (segment) structure, being the upper and lower arm. To each one of this bodies a reference frame is attached as shown in Figure 2, where the global reference system $X_0, Y_0, Z_0$ is located at the shoulder. For the sake of implementation simplicity the upper ($\Sigma_1$) and lower ($\Sigma_2$) reference frames coincide with the local reference frame provided at the MTx inertial units (casing engraved), represented by the boxes on the arm. The location of the sensors are away from the joints to avoid poor rotation estimation. Furthermore the sensors are placed in such a way that the top of the sensors faces away from the trunk when the whole arm is naturally down. The described frame assignation shown in Figure 2 minimizes the number of rotation transformations required by our proposal.

At the horizontal arm position an alignment reset is applied, such reset is provided by the fabricant. This reset aligns all coordinate systems with a single action, and assigns a new global reference system which is constraint to its Z-axis pointing upward, and its X-axis parallel and pointing to the direction of the X-axis of the local reference frame engraved at the sensor box. Once this alignment is conducted both calibrated data and orientation data provided by the sensors are output with respect to the new reference frame. At this points the global reference system $X_0, Y_0, Z_0$ is set exactly as sketched in Figure 3. Such that the orientation of the upper arm (frame $\Sigma_1$) and lower arm (frame $\Sigma_2$) with respect to the fixed global reference $X_0, Y_0, Z_0$ correspond to the orientation output provided by the sensors.

2.1 Calibration procedure

The operator interface is calibrated at the horizontal position shown in Figure 2. At this position the three reference frames (shoulder, upper arm and lower arm) are in principle parallel. Obviously the attaching position of the sensors introduce calibration errors on the parallelism of the reference frames, but such errors are considered as fixed orientation offsets and their effects are minimized by a cautious attaching stage and a reset of the sensors reference frames.

2.2 Wrist Cartesian position

The goal is to transfer wrist Cartesian position trajectories (Point C at Figure 3) to the slave robot end effector, for this purpose the sensor orientation information is considered. The sensors provide orientation measurements in 3 possible representations: Roll-Pitch-Yaw Euler Angles, quaternions and rotation matrix. It is well known that Roll-Pitch-Yaw Euler Angles present singularities at the Pitch angle when it corresponds to $\pm \pi/2$ [rad], thus this output format is avoided. The other two representations are singularity free, nonetheless the rotation matrix possesses more parameters than the quaternions angles (Yun et. al., 2008). The number of parameters of the output format becomes important when reading real time on line data because of processing and data transmission considerations. Therefore the quaternion output representation of the sensors is chosen. Notice that from Figure 3 the X-axis of the sensors is aligned with the longitudinal axis of the upper arm and lower arm, which rather simplifies the kinematic analysis.
Consider two fixed auxiliary systems, one at each rotation point of shoulder and elbow respectively, with the same orientation as the global reference frame \( \Sigma_0 \). Then, after calibration, the sensor output quaternion vector \( q_i = [q_{0i}, q_{1i}, q_{2i}, q_{3i}] \) with \( i = 1, 2 \) denoting the upper and lower arm respectively, represents the orientation of the reference frame (sensor box casing) with respect to the fixed auxiliary frames of shoulder and elbow. So, any vector represented at frames \( \Sigma_1 \) and \( \Sigma_2 \) can be transform to the auxiliary frames at upper and lower arm, and then transform to the global reference frame. For vector transformation purposes, general quaternion transformation (quaternion algebra) or a transformation to rotation matrix and then vector transformations might be applied.

Summarizing there are three sets of reference frames involved in the arm kinematic modeling. The fixed global reference frame \( \Sigma_0 \) located at the shoulder. Two auxiliary frames parallel oriented to the global frame located at the joint of shoulder and elbow. These systems allow determining orientation of the bodies to which are attached. Two sensor reference frames which yield orientation measurements with respect to the auxiliary systems after calibration stage.

Since the X-axis of the sensors box reference frame are aligned with the longitudinal axis of the upper (\( i = 1 \)) and lower arm (\( i = 2 \)), then the vectors \( X_i = [l_{a,i}, 0, 0] \) represent the end point of the upper and lower arm, with \( l_{a,i} \) their corresponding length. Using the sensor output quaternion vector \( q_i \), if follows that vectors of upper and lower arm \( X_i \) might be represented at the fixed auxiliary systems at the rotational joint of shoulder and elbow respectively, their representation in such a systems is denoted by \( X_{a,i} = [x_{a,i}, y_{a,i}, z_{a,i}] \) with:

\[
\begin{align*}
x_{a,i} &= l_{a,i}(2q_{0i}^2 + 2q_{1i}^2 - 1) \\
y_{a,i} &= l_{a,i}(2q_{1i}q_{2i} + 2q_{0i}q_{3i}) \\
z_{a,i} &= l_{a,i}(2q_{1i}q_{3i} - 2q_{0i}q_{2i})
\end{align*}
\]

At this point the vectors \( X_{a,1} \) and \( X_{a,2} \) are represented in parallel oriented systems with respect to global frame \( \Sigma_0 \), thus wrist Cartesian position is given by simple vector sum. Therefore, based on arm length parameters \( l_{a,i} \) and sensor orientation output in quaternion format, the wrist Cartesian position \( X_c \) is given by:

\[
X_c = [x_{a,1} + x_{a,2}, y_{a,1} + y_{a,2}, z_{a,1} + z_{a,2}]
\]

with \( x_{a,i}, y_{a,i} \) and \( z_{a,i} \), \( i = 1, 2 \) given by (1).

3. ROBOT DIRECT AND INVERSE KINEMATIC MODELS

The teleoperation proposal is intended for n-joint general robots, as far as their working space covers the human arm working space. Thus the direct and inverse kinematic models correspond to the general ones presented in literature such as (Spong and Vidyasagar, 1989). The direct kinematics relates the joint robot variable \( q \in \mathbb{R}^n \) and Cartesian effector position \( X \in \mathbb{R}^m \), this is:

\[
X = F_{DK}(q)
\]

Meanwhile, the inverse kinematics, which yields the inverse relationship, is represented by

\[
q = F_{IK}(X)
\]

The inverse kinematics is commonly used for joint trajectory generation and for some control implementations, as it is the case of our proposal.

4. ROBOT CONTROL STRATEGY

Since the goal of this work is to developed a teleoperation systems with a wearable interface rather than a specialized teleoperation controller, for validation purposes a simple joint robot PID control is introduced

\[
\tau_{PID} = K_pe + K_d\dot{e} + K_i\int e \, dt
\]

where \( K_p, K_d, K_i \in \mathbb{R}^{n \times n} \) are the proportional, derivative, and integral diagonal gain matrices, \( e = q_d - q \), denotes the joint robot tracking error, \( \dot{e} = q_d - q \) corresponds to the joint robot velocity error. With \( q_d = F_{IK}(X_c) \) a solution to the inverse kinematics for the desired wrist trajectory \( X_c \) given by (2).

5. EXPERIMENTAL CASE STUDY

The master slave teleoperation system is composed of the designed wearable interface as master system and a 3 dof delta robot presented at Figure 4 as slave system. Because of the physical dimensions and structural constraints of the delta robot, it is only possible to guarantee that the robot working space covers the arm movements on a 3D subspace given by a semi sphere.

5.1 Slave 3 dof delta robot

Consider that a reference frame system parallel to the global reference frame \( \Sigma_0 \) of Figure 2 is located as shown in Figure 4, and three auxiliary system are attached to the actuated joints of the robot. Based on the assigned frame systems the direct and inverse kinematics are obtained by geometrical methods as shown in (Lung-Wen, 1999). For the sake of brevity the kinematic models are skipped but can be consulted in (Lung-Wen, 1999).
Based on the assigned global systems at interface (Figure 3) and delta robot (Figure 4), a rotation of $\pi$ [rad] around X-axis between delta robot Cartesian coordinates and wrist coordinates is required to set the wrist coordinates as desired coordinates for the delta robot. After rotation of the wrist Cartesian coordinates the resulting values are mapped through the inverse kinematics of the delta robot to determine the three desired joint coordinates for the PID control (5).

The delta robot is built with aluminum (alloy 6063 T-5), and has DC brushless servomotors of the brand NICSA, model NC5475 coupled to planetary gearboxes of ratio 90:1, and potentiometers for angular position measuring. The motor characteristics are listed in Table 1.

### Table 1. Servomotors technical data

<table>
<thead>
<tr>
<th>Nominal voltage</th>
<th>24 [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No load speed</td>
<td>2300 [rpm]</td>
</tr>
<tr>
<td>Load speed</td>
<td>3200 [rpm]</td>
</tr>
<tr>
<td>Load current</td>
<td>0.45 [A]</td>
</tr>
<tr>
<td>Maximum torque</td>
<td>150 [mNm]</td>
</tr>
</tbody>
</table>

#### 5.2 Experimental results

The interface acquisition routines and PID controller were programmed in Simulink (Matlab), the controller sampling rate was set as 1 KHz, while the Xsens sensors were working at 100 Hz.

The PID control gains where selected by trial and error methods. The PID gain values for the three dof of the delta robot are given in Table 2.

### Table 2. Cartesian PID control gains

<table>
<thead>
<tr>
<th>i</th>
<th>$K_p$</th>
<th>$K_d$</th>
<th>$K_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0.005</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0.008</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.009</td>
<td>8</td>
</tr>
</tbody>
</table>

At the initial condition the robot is pointing downward, meanwhile after calibration stage the operator moves its arm from calibration position (horizontal arm, Figure 2) to vertical position (pointing downward), at that point the teleoperation task starts. The human wrist trajectory describes the word Juan (see Figure 6), and it is expected the delta slave robot tracks such trajectory. The operator interface is programmed at an independent PC computer which communicates the wrist position through the parallel port to the PC computer that runs the delta robot controller, this computer has a Sensoray 626 acquisition card for interaction with the delta robot and reading of the wrist coordinates, as shown in Figure 5. The communication rate is set as 1 KHz.

Figure 6 shows the trajectories of the slave robot end effector and the wrist desired position. Both systems (operator and slave robot) have a downward position when the teleoperation task starts. The experiments run for about 30 seconds, such that relatively high arm velocities are imposed along the desired trajectory.

The Cartesian tracking errors between wrist and slave robot end effector positions are shown in Figure 7. Notice that from Figures 6 and 7 it is evident that the wrist velocity affects the system response and performance, nonetheless in general the tracking performance is rather acceptable. It is observed that for higher velocities the tracking error increases. This behavior might be due to the sensors sampling rate which is lower than that controller rate. Other possible source of poor performance might be the PID controller which is not highly suitable for tracking purposes.
6. CONCLUSIONS

A teleoperated master slave system with a real time wearable interface based on inertial sensors has been implemented. A simple kinematic model of the human arm allows determining wrist movements which are transfered as desired trajectories to a robot working in master - slave teleoperation. The operator interface is wireless and communicates by Bluetooth protocol, this results in a portable and light operator interface.

The system performance depends on the arm Cartesian and rotation velocities as proven by previous works entitled to human arm characterization by using inertial sensors. Nonetheless there is plenty of room for further improvements, such as velocity and acceleration measurements for advanced controllers and filters implementation. The system nevertheless shows a good behavior and validates the teleoperation philosophy and using of inertial sensors to design wearable interfaces.

7. ACKNOWLEDGMENTS

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REFERENCES


