Wearable interface based on inertial sensors for master-slave robot teleoperation

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***Abstract*— An interface based on inertial sensors with applications for 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 in order to obtain acceleration and turning rates. The data is internally processed by a DSP in the sensors and yields orientation measurements of the bodies they are attached. Thus measurement of the angular position of shoulder and elbow of the operator is done on real time. Then by using kinematic models of the human arm the wrist human Cartesian trajectory is determined. The wrist trajectory is imposed as desired trajectory to a robot system which behaves as slave system. By means of a control technique, in this particular case a standard PID control, the slave robot is capable to track wrist human movements on 3D space. For validation purposes the proposed interface and teleoperation system are implemented with a three degree of freedom (dof) delta configuration parallel robot as slave system. The experiments shows the interface viability and its performance.**

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

I. Introduction

Integrating human and robotics machines into a single system offers multiple opportunities for creating assisted technologies that can be used in biomedical, industrial, clinical and aerospace applications. 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). Moreover, despite the high dexterity that artificial control algorithms can provide to robots, the performance of naturally algorithms used by humans surpasses those presented in robots.

Several researchs have been conducted in order to capture and emulate human movement, which currently is one of the most popular research topics in biomedics and robotic areas. 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, requirement of a fixed or dedicated laboratory setup, a tiresome calibration process and intensive computation, among other difficulties. Recently attempts have been done to develop visual based marker-free tracking systems for human motion capture (Wang et. al., 2003). Such systems are very attractive, because instead of special cameras, they required only conventional cameras. So, marker free systems result cheaper and relax conditions on special and fixed laboratories, however they still shared several limitations of marker based system, such as occlusion and kinematic singularities. Solutions to such problems have been proposed by using inertial sensors based systems, which in general are small or unobtrusive, cheap, portable and easily wearable.

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., 2005) and (Zhou and Hu, 2007) an inertial tracking systems for monitoring movements of human upper limbs in order to support a home-based rehabilitation scheme was developed. The authors used two inertial sensors placed on the upper and lower arms in order to obtain acceleration and turning rates. The main contribution consists in the fusion of vision and inertial sensors to developed a novel tracking prototype to acquire movement from people rehabilitation at home.

Some others works deal with the human walking pattern acquisition from human models, for example in (Harada et. al., 2009) the authors captured human walking motion to provide motion to a humanoid robot. Similarly to this work (Miura et. al., 2009) captures human walking motion where several parameters such as: step length, speed, rotational angle during turn, among others and dynamic balance were considered. All this is to provide motion to an entertainment humanoid to develop walking and turning patterns.

In (Ferreira et. al., 2009) the authors analyzed human gait in the sagittal plain with a video camera to acquire images of a walking person, fitted with a set of white light-emitting diodes (LEDS). And to analyze the stability of the human gait a set of eight force sensors under each foot is used to obtain the center of pressure. Finally the gait is applied to a biped robot.

Accurate real-time tracking of the orientation or pose of human body or in general rigid bodies has enormous application in robotics, aerospace, synthetic reality, teleoperated systems, etc. In the particular case of human body it can be represented by segments or links connected by revolute joints, if the orientation of relative to a fixed reference frame can be determined for each of the links of interest, then the overall posture of the human subject can accurately be rendered and communicated in real time.

As mention the integration of humans and machines into complex systems allows flexible and robust systems. For this purpose once the human motion are captured they are used to design or as direct desired trajectories for the robot system. This action is not other than a teleoperation scheme, particularly a master - slave configuration.

In robotics, a teleoperated system is a robot (Slave robot) operated or controlled at a distance by other system (master), typically another robot or electromechanical system. Master-Slave teleoperation can be divided in two classes, unilateral and bilateral teleoperation. In unilateral teleoperation, the slave robot is receiving information from the master robot or system, but the master system is not receiving information from the slave robot. In bilateral teleoperation, both systems are receiving data from each other. There exist a performance index for teleoperated systems called transparency (Lee, 1998). The less positioning and orientation error in the slave and the better force reflecting to the master, the higher is the transparency of the system.

On the other hand, the problem of teleoperated robots can be studied depending on the the kind of robots, their structural and measuring limitations. When the masterslave robots have the same structure, the teleoperation is called to be with similar or identical robots. In the other case, the teleoperation is called to be with dissimilar or non-identical robots.

Teleoperation systems are as divers as the technics employed on its control. This diversity is due to the broad amount of applications: spacial, military, undersea, medical, etc. 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 major 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 capable of determining dynamic aspects of the operator motion.

In this work a real time wearable interface for application in teleoperaion system is develop. 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 trayectories are inside the robot working space. The inertial sensors communicate with a computer via wireless, using Bluetooth devices provide by the manufacturer. 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 achieved by the robot, thus the robot inverse kinematic problem possesses possible solutions.

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 robot tracks the wrist Cartesian motion by means of a PID controller, that is program at joint robot space. This systems accomplished a real world applications of inertial sensing systems, particularly a master - slave teleoperation task. The integrated teleoperation master - slave system with inertial sensor based operator interface is sketched at Figure 1. The system is validated through experiments with a delta 3 dof robot manipulator.

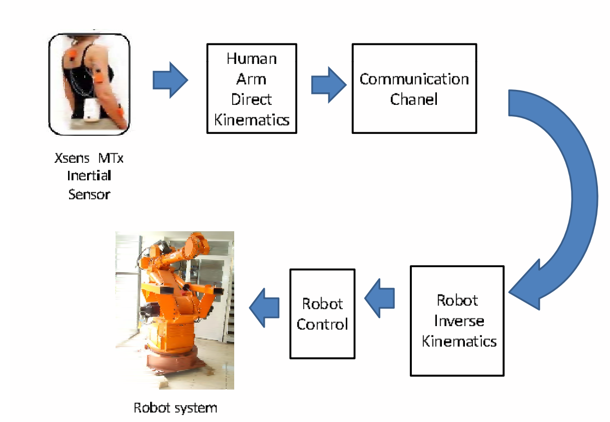

Figure 1. Wearable interface for master-slave teleoperation.

II. Human arm kinematics and motion acquisition system (operator interface)

Sensor attaching and calibration stages, and the reference frames used for arm kinematic modeling are here described.

II-A. *Sensors and reference frame locations*

The arm motion tracking system is composed by two inertial MTx (Xsens Motion Technology, Netherlands). Each MTx sensor consists of three orthogonally placed piezo-resistive accelerometers (ADLX202E, 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 $0{,}05^o$, a repeatibility of $0{,}2^o$, a static accuracy of 1^o, a dynamic accuracy of 2^o RMS and an update rate of up to 120 Hz.

The inertial sensors communicate with a computer via Bluetooth 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 XBus master can communicate with the computer dedicated to data acquisition, both via a wired or wireless connection (Bluetooth protocol). In the validation stage the wireless connection was selected, to allow unconstraint movements during the test. The acquisition frequency of each inertial unit was set to 100 Hz.

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 (frame Σ_1) and lower (frame Σ_2) reference frames coincide with the local reference frame provided at the MTx inertial units (casing engraved), represented by the boxes on the arm. Such that the positions 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.

II-B. *Calibration procedure*

The system composed of the two MTx sensors attached to the human arm 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.

At the horizontal arm position an alignment reset is applied, such reset is provided by the fabricant. This reset

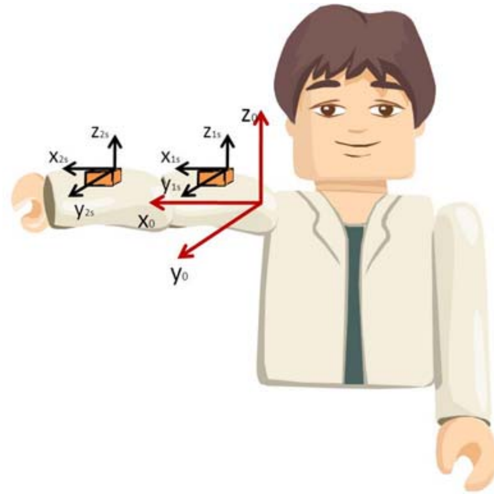

Figure 2. Human arm reference frames and sensor attachments.

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, which corresponds to the global reference system X_0, Y_0, Z_0 exactly as sketched in Figure 3. At this point the orientation of the upper arm (frame Σ_1) and lower arm (frame Σ_2) with respect to the fixed global reference X_0, Y_0, Z_0 correspond to the orientation output provided by the sensors.

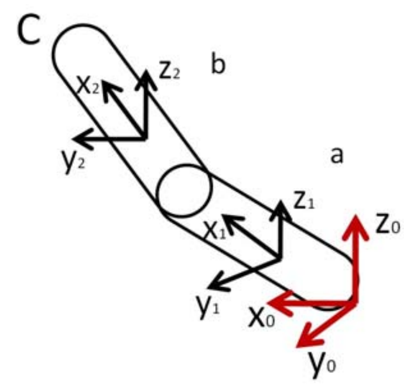

Figure 3. Global reference frame and sensors reference frames.

II-C. *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 Σ_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 Σ_1 and Σ_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 Σ_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 joint of shoulder and elbow, their representation in such a systems is denoted by $X_{a,i} = [x_{a,i}\ y_{a,i}\ z_{a,i}]$ with

$$\begin{aligned} x_{a,i} &= l_{a,i}(2q_{0i}^2 + 2q_{1i}^2 - 1) \\ y_{a,i} &= l_{a,i}(2q_{1i}q_{2i} + 2q_{0i}q_{3i}) \\ z_{a,i} &= l_{a,i}(2q_{1i}q_{3i} - 2q_{0i}q_{2i}) \end{aligned} \tag{1}$$

At this point the vectors $X_{a,1}$ and $X_{a,2}$ are represented in parallel oriented systems with respect to global frame Σ_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

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

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

III. Robot direct and inverse kinematic models

As stated our 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 enf effector position $\mathbf{X} \in \mathbb{R}^m$, this is

$$\mathbf{X} = F_{DK}(q) \tag{3}$$

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

$$q = F_{IK}(\mathbf{X}) \tag{4}$$

The inverse kinematics is commonly used for joint trajectory generation and for some control implementations, as it is the case of our proposal. Notice that the inverse kinematics problem implies, in general, multiple solutions, depending on the robot architecture, thus being the most difficult kinematic model to obtain.

IV. Robot control strategy

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

$$\tau_{PID} = K_p e + K_d \dot{e} + K_i \int e\ dt \tag{5}$$

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

V. Experimental results with a 3 DOF delta robot as slave system

The designed wearable interface is integrated in a robotic teleoperation system with a a 3 dof delta slave robot presented at Figure 4. 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.

V-A. *Delta Robot kinematics and a few technical data*

Consider that a reference frame system parallel to the global reference frame Σ_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 sake of brevity the kinematic models are skipped but can be consulted in (Lung-Wen, 1999).

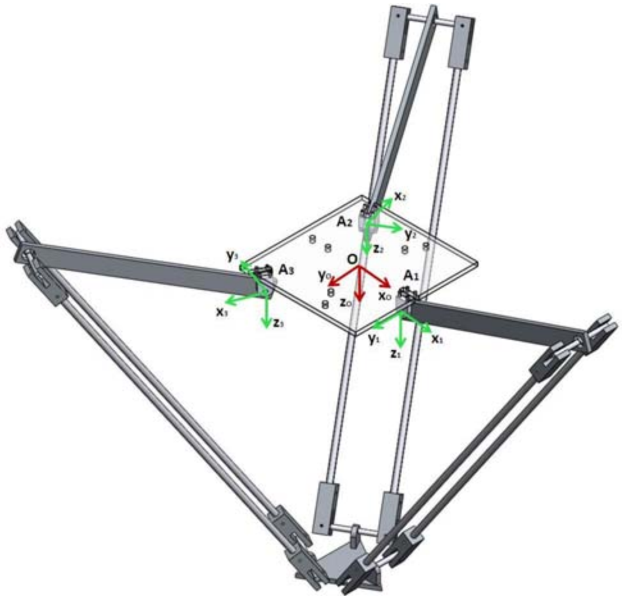

Figure 4. The delta robot and its reference frame systems.

Based on the assigned global systems at interface (Figure 3) and delta robot (Figure 4), a rotation transformation of Pi [rad] around X-axis between delta robot Cartesian coordinates and wrist coordinates is required for considering the wrist coordinates as desired coordinates for the delta robot. After the rotation of the wrist Cartesian coordinates is done, the resulting values are mapped through the inverse kinematics of the delta robot to determine the three desired joint coordinates, which are set as desired variables for the PID control 5.

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

TABLE I
SERVOMOTORS TECHNICAL DATA

Nominal voltage	24 [V]
No load speed	3800 [rpm]
Load speed	3500 [rpm]
Load current	0,45 [A]
Maximum torque	150 [mNm]

V-B. *Experimental results*

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

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 a Table II.

TABLE II
CARTESIAN PID CONTROL GAINS

	K_p	K_d	K_i
i=1	4	0,005	8
i=2	5	0,008	8
i=3	5	0,009	8

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 in a 3D working space, and it is expected the delta slave robot tracks such trajectory. The operator interface is programed 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 5. Teleoperation platform

Figure 6 shows the trajectories of the slave robot end effector and the wrist desired position. As pointed previously 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.

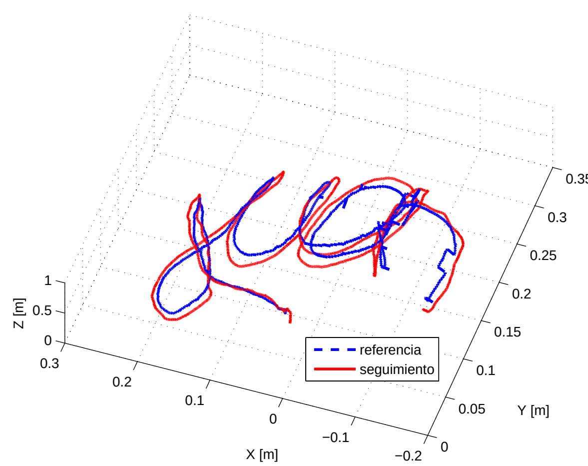

Figure 6. Wrist and End effector Cartesian trajectory positions.

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 that that controller rate. Other possible source of poor performance might be the PID controller which is not highly suitable for tracking purposes.

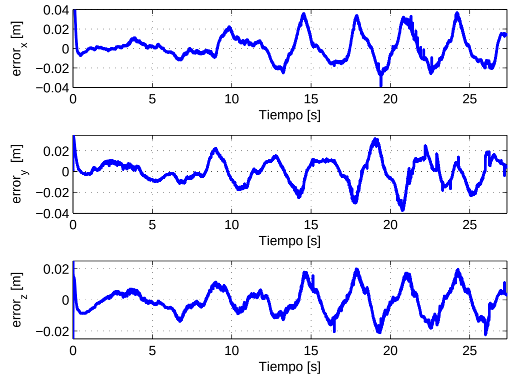

Figure 7. Cartesian tracking errors [m].

The joint input torques, given by controller (5) are shown in Figure 8, notice that the motors are not saturated and the noise level is acceptable.

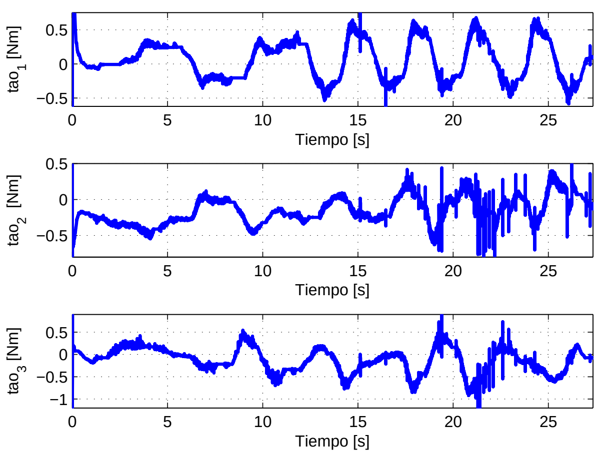

Figure 8. Joint input torques with PID control.

Experiments keeping the arm to a fixed position were also conducted and the regulation Cartesian position errors were about 7 [mm].

VI. Conclusions

A real time wearable interface based on inertial sensors and with applications to teleoperation tasks is developed. 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. This will open further line research of real time applications of inertial sensors.

VII. Acknowledgments

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