Human Motion Mapping to a Robot Arm with Redundancy Resolution

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Abstract In this paper the problem of mapping human arm motion to an anthropomorphic robot arm has been addressed using an Xsens MVN motion capture suite and a 7-DoF KUKA LWR. The desired end-effector trajectories of the robot are reconstructed from the human hand, forearm and upper arm trajectories in the Cartesian space obtained from the motion tracking system by means of human arm biomechanical models and sensor fusion algorithms embedded in the Xsens Technology. The desired pose of the robot is reconstructed taking into account the differences between the robot and human arm kinematics and is obtained by suitably scaling the human arm link dimensions. A Cartesian impedance control is designed to replicate, at the robot side, the human wrist motion and a compliant null-space control strategy is applied to solve kinematic redundancy exploiting the compliant behavior of the elbow to obtain suitable body reconfigurations.

Key words: kinematic model, kinematic redundancy, impedance control

1 Introduction

The development of hardware and software technologies for refining the ability to learn from humans grasping and dynamics manipulation capabilities is of greatest interest in robotics, [4]. A big challenge of humanoid robotics is to provide a robotic arm or a dual-arm system with autonomous and dextrous skills to replicate capacity in performing tasks which are typically executed by humans, [5], [7]. The fields of interest can be in all those applications where

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the robot closely interacts with humans, namely for surgical, industrial and service applications.

Another important issue in unstructured human-shared environment is to achieve a compliant behavior when interaction occurs in order to realize a proper and safe cooperation between humans and robots. This behavior can be imposed in the joint space to ensure safe interaction, [8]. Moreover, the redundant degrees of freedom can be conveniently used to perform some additional tasks besides the main task [3]. These additional tasks can be a given Cartesian position of a point on the body of robot, such as the elbow position, [10]. A compliant behavior in the null space of the main task can be enhanced to manually adjust robot postures to fit into human targeted ones.

The aim of this work is to integrate a robotic platform able to acquire and transfer human body motion to a robotic system. This platform will be used to learn human motion primitives and to achieve a low-dimensional motion manifold. Replication of human body motion is very important to transfer human knowledge and experience to a robot. For accurate motion capturing a sensor technology that use inertial and magnetic measurement units has been used to measure postures of human bodies. The robot arm used for replicating human motion is a 7-DoF KUKA LWR4 arm, [2]. The control of the robot pose is carried out using an impedance strategy in the Cartesian space which uses, as the setpoint for the position, speed and acceleration, the output coming from a second-order filter that processes the signals from Xsens MVN [1]. The redundant degrees of freedom are used to ensure a compliant behavior of the robot elbow in order to reconfigure its position.

2 Experimental Set-up

The Xsens MVN suite is a low-cost motion capture system that does not need cameras, emitters or markers, and it is simple to be used both indoors and outdoors. It consists essentially of 17 MTx inertial and magnetic measurement units and comprises 3D gyroscopes, 3D accelerometers and 3D magnetometers sensors through which it is possible to obtain the position measurement and orientation of parts of the body of the wearer. Two Xbus Masters handle the wireless communication with the PC or laptop and synchronize all sensor sampling. The body worn sensors are positioned in correspondence of the feet, legs, thighs, pelvis, shoulders, sternum, head, arm, forearm and hand. In Figure 1, Xsens MVN is shown and the components used for the developed application are highlighted. The total weight of the system is 1.9Kg. The entire system operates in real-time with a frequency of maximum sampling rate of 120Hz. By means of a dedicated software (MVN Studio Software), the user can easily observe the movements in 3D, record or export them. The system estimates body segment orientation and position changes by integration of gyroscope and accelerometer signals which are continuously updated

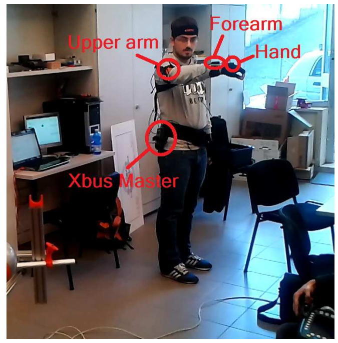

Fig. 1 The Xsens suite worn by the operator is shown. The Xbus Masters and the sensors positioned at the hand, forearm and upperarm are highlighted.

by using a biomechanical model of the human body. This allows for tracking of dynamic motion.

When placing the sensors, the initial pose between the sensor and the relative body segment is unknown. Therefore, a calibration procedure, requiring measures such as the height, the arms length and the foot length of the subject, has to be performed. The subject is asked to stand in an a-priori known pose, the rotation from sensor to body segment is determined by matching the orientation of the sensor in the global frame with the known orientation of each segment in this pose.

The robot used to replicate the human arm motion is the 7-DoF KUKA Lightweight Robot (LWR). The kinematic redundancy, similar to the human arm, allows the elbow motion while maintaining the pose of the hand, see Fig. 2. Moreover, the torque sensors, mounted in all joints, allow detecting contact and collisions for safe human-robot interaction and compliant reaction to applied external forces. Thus, the robot can be also manually guided and programmed [2].

3 Mapping of the Human Arm Motion

The mapping of movements from the human to the robotic arm requires appropriate considerations regarding the differences in the kinematic chain, size of the two arms and joint limits. The motion tracking system does not provide measurements of the joint angles of the human arm in real time, but allows obtaining that information only from the recorded data. Thus, the mapping of the human arm movement should be referred to measurements in the Cartesian space. Since the human arm positions may be out of the workspace of the robot, to generate a suitable setpoint a bounding box has to be considered for safety issues. Further, to limit the speed and have a smooth motion, the signals coming from the Xsens must be processed by means of interpolation and filtering.

The MTx sensors, mounted on the Xsens suite, provide position and orientation (expressed in terms of a quaternion) of the related segments where they are positioned. Because of the difference between the kinematics of the human arm and that of the robot, we made some assumptions to simplify the mapping. It is assumed that the second joint (q_2) of the robot coincides with the spherical joint of the human shoulder. Such assumption is allowed since the axes of the first three joints of the LWR intersect at a single point corresponding to the center of q_2. The same observation can be made for the sixth joint (q_6) identified as the spherical joint of the human wrist. In agreement with this assumption the joints that modify the extension of the robot (distance from the shoulder to the wrist) are joints q_2 and q_4 corresponding to the wrist and the elbow of the human arm respectively. During the motion, the distances between joints q_6 and q_4 (robot's wrist and elbow) as well as the distances between joints q_4 and q_2 (robot's elbow and shoulder) remain constant and correspond to the length of the human forearm and upperarm respectively, see Fig. 2. In order to transfer the movement of an

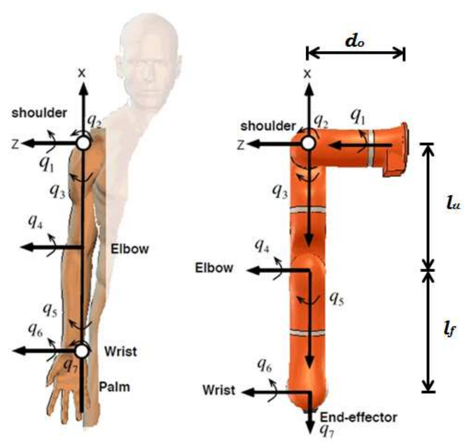

Fig. 2 Human and robot arm comparison, [10].

operator wearing Xsens suite to the robot, the measurements of interest are the position of the hand, forearm and upperarm, $\boldsymbol{x}_h$, $\boldsymbol{x}_f$ and $\boldsymbol{x}_u$ respectively, which are provided by the Xsens and are expressed with respect to the global frame of the motion capture system. Since the robot does mount neither a hand nor any tool, only the desired position of the wrist is mapped, while the orientation of the end effector is controlled to be constant at the initial value. Alternatively, it is also possible to map the orientation by means of the composition of the quaternion related to the hand, forearm and upperarm in the same way as for the position. As already stressed, the kinematics of the human and robot are different also in terms of link dimensions. The position setpoints of the robot are generated by modifying the XSens references on the based of the link lengths of the KUKA robot. To compute the wrist reference position of the robot, the versor of the human forearm and upperarm are obtained and multiplied for the robot forearm and upperarm lenghts, $l_f = 0.39$ [m] and $l_u = 0.40$ [m] respectively. This quantities are summed with the vector linking joint $q2$ to the base of the robot, $\boldsymbol{x}_b = (0 \quad 0 \quad 0.31)^T$, as in the following equation:

$$\boldsymbol{x}_d = \boldsymbol{x}_b + l_u \frac{\boldsymbol{x}_f - \boldsymbol{x}_u}{\|\boldsymbol{x}_f - \boldsymbol{x}_u\|} + l_f \frac{\boldsymbol{x}_h - \boldsymbol{x}_f}{\|\boldsymbol{x}_h - \boldsymbol{x}_f\|}. \tag{1}$$

The global frame of the Xsens has the same orientation of the base frame of the KUKA LWR, thus no further trasformation is needed. A bounding box is applied to the computed desired wrist position to impose limits on the spatial coordinates, $-0.79 \leq x_x \leq -0.45$, $-0.5 \leq x_y \leq 0.5$, $0.15 \leq x_z \leq 0.6$.

The control of the LWR is designed by means of a Cartesian impedance strategy with compliant null space control for redundancy resolution. The desired position, velocity and acceleration are generated by a second-order filter that processes the signals from Xsens MVN. The output signals of the motion tracking system are first modified according to the robot kinematics in such a way as to generate suitable references for the robot wrist and then filtered in such a way to have stable and feasible setpoints. The control purpose is to let the robot following the pose of the human arm and to allow the reconfiguration of the robot body, relying on a compliant behavior in the null-space of the main task.

3.1 Cartesian Impedance Control

The dynamic model of the robot has the form [9]:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{\tau}_f = \boldsymbol{\tau}_c + \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{F}_{ext} \tag{2}$$

where $\boldsymbol{q} \in \mathbb{R}^n$, with $n = 7$, is the vector of joint variables, $\boldsymbol{M}(\boldsymbol{q})$ is the inertia matrix, $\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ is the vector of Coriolis/centrifugal torques, $\boldsymbol{g}(\boldsymbol{q})$ is the vector of gravitational torques, $\boldsymbol{\tau}_f$ is the vector of friction torques, $\boldsymbol{\tau}_c$ is the control torque, $\boldsymbol{J}(\boldsymbol{q})$ is the robot Jacobian, and $\boldsymbol{\tau}_{ext} = \boldsymbol{J}^T \boldsymbol{F}_{ext}$ is the joint torque resulting from external force and torque $\boldsymbol{F}_{ext}$ applied to the end effector, that in this case are null. To design the Cartesian impedance control, it is useful to derive the end-effector dynamics in the operational space [6]:

$$\boldsymbol{\Lambda}(\boldsymbol{q})\ddot{\boldsymbol{x}} + \boldsymbol{\mu}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{x}} + \boldsymbol{F}_g(\boldsymbol{q}) + \boldsymbol{F}_f(\boldsymbol{q}) = \boldsymbol{F}_c + \boldsymbol{F}_{ext} \tag{3}$$

where $\boldsymbol{x}$ is the Cartesian pose vector, $\boldsymbol{\Lambda} = (\boldsymbol{J}\boldsymbol{M}^{-1}\mathbf{J}^{\mathbf{T}})^{-\mathbf{1}}$ is the (6×6) end effector inertia matrix, while $\boldsymbol{\mu}\dot{\boldsymbol{x}} = \boldsymbol{\Lambda}(\boldsymbol{J}\boldsymbol{M}^{-1}\boldsymbol{C} - \dot{\boldsymbol{J}})\dot{\boldsymbol{q}}$, $\boldsymbol{F}_g = \boldsymbol{J}^{\dagger T}\boldsymbol{g}$, $\boldsymbol{F}_f = \boldsymbol{J}^{\dagger T}\boldsymbol{\tau}_f$ and $\boldsymbol{F}_c = \boldsymbol{J}^{\dagger T}\boldsymbol{\tau}_c$ are the forces, reflected at the end effector, corresponding to the non-inertial joint torques in (2). By neglecting the friction and the Coriolis/centrifugal forces and considering that gravity is compensated, the following impedance control guarantees, in absence of external forces exerted at the robot tip, the tracking of the desired end-effector pose trajectory:

$$\boldsymbol{\tau}_{imp} = \boldsymbol{J}^T(\boldsymbol{\Lambda}(\ddot{\boldsymbol{x}}_d - \dot{\boldsymbol{J}}\dot{\boldsymbol{q}}) + \boldsymbol{K}_v\dot{\tilde{\boldsymbol{x}}} + \boldsymbol{K}_p\tilde{\boldsymbol{x}}, \quad (4)$$

with

$$\boldsymbol{K}_v = \begin{pmatrix} 90\boldsymbol{I}_3 & \boldsymbol{O} \\ \boldsymbol{O} & 10\boldsymbol{I}_3 \end{pmatrix}, \qquad \boldsymbol{K}_p = \begin{pmatrix} 2000\boldsymbol{I}_3 & \boldsymbol{O} \\ \boldsymbol{O} & 40\boldsymbol{I}_3 \end{pmatrix}. \quad (5)$$

The impedance gains have been set experimentally. The error between the desired and the effective pose $\tilde{\boldsymbol{x}} = \boldsymbol{x}_d - \boldsymbol{x}_e$ is expressed by means of the position error, $\boldsymbol{p}_d - \boldsymbol{p}_e$, and orientation error expressed in terms of the quaternion $\Delta\boldsymbol{\epsilon}$:

$$\tilde{\boldsymbol{x}} = \begin{pmatrix} \boldsymbol{p}_d - \boldsymbol{p}_e \\ \Delta\boldsymbol{\epsilon} \end{pmatrix}, \qquad \Delta\boldsymbol{\epsilon} = \eta_e\boldsymbol{\epsilon}_d - \eta_d\boldsymbol{\epsilon}_e - \boldsymbol{S}(\boldsymbol{\epsilon}_d)\boldsymbol{\epsilon}_e, \quad (6)$$

where η and $\boldsymbol{\epsilon}$ are the scalar and the vector part of the quaternion and $\boldsymbol{S}(\cdot)$ is the skew-symmetric operator. Snapshots of the experimental results are shown in Fig. 3.

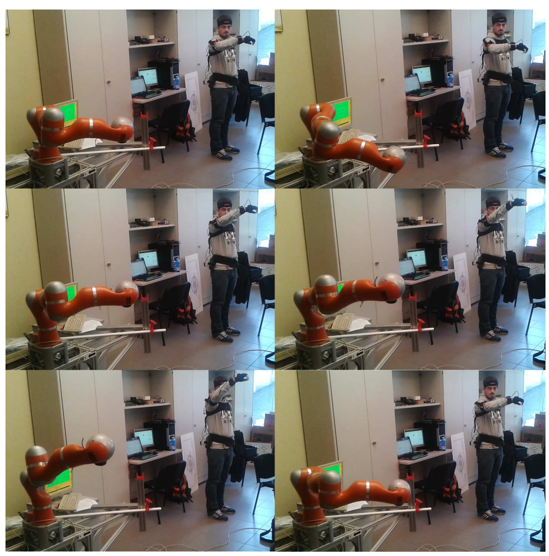

Fig. 3 Snapshots of the experimental set-up during the execution of the motions by the human operator followed by the robot.

3.2 Compliant Null-Space Control for Redundancy Resolution

Equation (3) describes only the end-effector dynamics and does not include the so-called null space dynamics.

In the presence of redundant degrees of freedom, it is possible to impose a secondary task in the null space of the end effector task, as follows

$$\boldsymbol{\tau}_c = \boldsymbol{\tau}_{imp} + (\boldsymbol{I} - \boldsymbol{J}^T \boldsymbol{J}^{\dagger T})(-k_d \dot{\boldsymbol{q}}), \tag{7}$$

where $-k_d \dot{\boldsymbol{q}}$, with $k_d = 0.4\boldsymbol{I}_7$, is a suitable damping torque. In this case the secondary task consists in a possible reconfiguration of the arm obtained by applying forces to the robot's body.

Matrix $\boldsymbol{J}^{\dagger} = \boldsymbol{M}^{-1}\boldsymbol{J}^T[\boldsymbol{J}\boldsymbol{M}^{-1}\boldsymbol{J}^T]^{-1}$ is the dynamically consistent generalized inverse of matrix $\boldsymbol{J}$ [6].

The first image of Fig. 4 represents the configuration assumed by the robot when it is not touched and redundancy is not exploited. In the other two images, two possible configurations, elbow up and elbow down respectively, assumed by the robot, while following the trajectory in the Cartesian space, when complying to external forces exerted on its body are shown.

Fig. 4 From left to right, the first image represents the robot configuration when redundancy is not exploited, the second and the third images represent other two possible configurations, elbow up and elbow down respectively.

4 Conclusion and Future Work

In this work, a kinematic mapping algorithm has been implemented in order to replicate the movements made by a human arm on an anthropomorphic robot arm with seven degrees of freedom.

The desired trajectories are generated in the Cartesian space in terms of position and orientation and are obtained by taking into account the differences between the kinematics of the robot and of the human arm. The control of the robot pose is carried out using an impedance strategy in the Cartesian space which uses, as the setpoint for the position, speed and acceleration, the output coming from a second order filter that processes the signals from Xsens MVN.

Since the robot is kinematically redundant, a compliant null-space control strategy is employed to adjust the configuration of the robot manually in order to generate anthropomorphic configurations.

The objective of this work is to create a robotic platform to learn from human grasping and manipulation tasks. Future work consists on learning primitives of motion in a low-dimensional manifold for a simplified and human-like control of humanoids robots.

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