Abstract—In this paper, a hierarchical control architecture incorporating a novel dual-arm impedance controller is proposed and experimentally evaluated in a valve turning setup. Proposed control architecture incorporates various control/interface modules to render a desired interaction performance in our intrinsically compliant humanoid robot, COMAN: the sensing module provides the manipulation module with the valve coordinates. Consequently, smooth point-to-point and circular trajectories are generated using trajectory generation module and tracked by the implemented arm joint impedance controllers. A desired Cartesian stiffness profile in relative coordinates (between the two hands) is defined and realized by the proposed dual arm impedance controller during rotation of the valve. Experimental results suggest that the proposed COMAN control architecture renders a desirable dual-arm interaction performance while the task is being accomplished.

I. INTRODUCTION

The inevitable nature of catastrophes resulting from the natural processes of the Earth (e.g. earthquakes, flood, etc) and their consequences (e.g. Fukushima disaster), call for the application of robust and effective robotic platforms for an appropriate disaster response. This immediately highlights the requirements for the hardware and the software components to render a desired interaction performance while performing tasks in unstructured and hostile environments [1], [2].

To address this problem, in this work, a control framework incorporating various modules is developed and the achieved interaction performance is experimentally evaluated in a valve turning task. In particular, a novel dual-arm impedance control framework is developed and integrated into the control architecture of our intrinsically compliant robot.

II. INTRINSICALLY COMPLIANT HUMANOID

A. COMAN: COMAN [5] (Fig. 1. A) is a torque controlled robot with 31-DOF, 14 of which are based on Series Elastic Actuation that is used to enhance the physical interaction performance of the robot. The robot has 6 DOFs for each leg, 7 DOFs in each arm, 3 DOFs in the waist, 2 DOFs in the neck, and is equipped with two Pisa/IIT SoftHands (see next section). The passive compliance of the joints are effective to absorb the high bandwidth impacts. Each joint provides position, velocity and torque sensing, while decentralized position and active impedance control are built in each DSP board at 1KHz RT. The robot is equipped with an IMU in the waist and four 6-axes force/torque sensors in the ankles and the forearms. The robot will have a Carnegie Robotics MultiSense S7 sensor1 mounted as a head, but we are currently using a RGB-D camera (Asus Xtion Pro Live) mounted above the torso and two cameras strapped at the forearms for perception.

B. Pisa/IIT SoftHand: The Pisa/IIT SoftHand (Fig. 1. B, [4]) was developed in a partnership between the Centro E. Piaggio of the University of Pisa and the Advanced Robotics department of the Italian Institute of Technology in Genoa, Italy. Using the adaptive synergy approach [6], the anthropomorphic hand was designed with 19 DOFs, 4 on each of 4 fingers, and 3 on the thumb. A soft robotics approach was taken for the rest of the joints by incorporating rolling contact joints with elastic ligaments, which makes it a perfect choice for tasks such as valve turning. The rolling contact joints ensure anatomically correct motion when actuated, but easily disengage on impact to allow safe interaction with humans while preserving the hand. The elastic ligaments also allow deformation while ensuring the hand returns to its original configuration. A single tendon runs through all joints to simultaneously flex and adduct the fingers upon actuation. The hand is actuated by a single

---

1http://carnegierobotics.com/multisense-s7/
DC motor which moves the fingers on the path of the first synergy, allowing the physical hand to mold around the desired object.

C. Robot Interfaces: The robot is controlled using the YARP [7] framework. The low-level library, called Robolli communicates with the DSP boards, while YARP is used for high-level communication between control modules. The DSP boards implement a decentralized joint impedance control running at 1kHz. comanInterface uses the Robolli library to expose the DSP functionalities at the YARP level, where we have access to impedance control, joint configuration, speed and torque measurements, IMU readings and force-torque readings at the ankles and forearms, again at 1kHz. The manipulation module is written using YARP functionalities while kinematic and dynamic model of the robot is developed using idynTree$^2$ and URDF$^3$ libraries.

This module complies to a simple communication protocol to control state transitions in an internal state machine. In particular start and stop commands can be issued on a switch:i port, while by writing Cartesian coordinates on the valve—data:i an external sensing module can provide the manipulation module a relative position/orientation of the valve w.r.t. the waist frame of reference. Lastly, a command:i port accepts manipulation primitives to reach to the object, grasp it, manipulate it (rotate the valve), release it, and disengage.

III. CONTROL ARCHITECTURE

In our control architecture, the valve turning task is broken down into four motion primitives: bimanual reaching (Reach), approaching to/grasping the valve (Grasp), rotating the valve (Rotate) and releasing/moving far from the valve (Disengage). The transition between the phases of the task is achieved using a state machine paradigm and can be controlled/interfered by the user. A joint impedance controller is implemented in both arm joints and the desired joint stiffness values are calculated based on the defined Cartesian stiffness profile, using a conservative congruence transformation $[8]$ (see sections below). The valve data (position and the orientation of the center of rotation, and the valve radius) is sensed using an RGB-D camera, and translated and defined in the torso frame of reference. Smooth Cartesian point-to-point trajectories are generated and a compliant stiffness profile is defined for the reaching phase. Consequently, the arms approach to the valve and grasp it using two SoftHands, mounted at the arm end effectors. While rotating, a relative impedance controller is implemented to realize a compliant profile along the valve radius (to avoid the generation of high interaction forces between the two hands), and a relatively high stiffness profile around the valve center of rotation (to overcome frictional or passive elastic forces in the valve joint).

A. Dual-arm kinematics: Observations on human bimanual coordination suggest that the central nervous system (CNS) stabilizes the first synergy of the two cooperating arms to a larger degree (higher control levels) than if it did for control of each arm joints, separately. Indeed, as regards the human dual-arm activities in its most natural way, two hands cooperate in a way that they form a kinematic chain $[9]$: while the first synergy stabilizes the relative position/orientation of the two hands (as a dominant task requirement), lower hierarchical levels of control stabilize remaining task variables by controlling the redundant degrees of freedom. This promotes the idea of realizing a similar kinematic representation in our dual arm setup. To that end, in our dual arm setup, a relative Jacobian is used which creates a unified, coordinated control between the two arms. Normally, the expression of the relative Jacobian combines the individual Jacobians of each arm, such that the resulting Jacobian maps the joint velocities of the two arms to the relative velocity between the end-effectors $[10]$. This allows users to directly specify the relative trajectory between the two end-effectors such that coordinating the trajectories of the two arms becomes an easy task.

The dual-arm manipulation setup is shown in figure (2). In our setup, $q_G \in \mathbb{R}^{n_A}$ and $\dot{q}_T \in \mathbb{R}^{n_B}$ denote the joint variables of the manipulators $A$ and $B$, respectively. Here, we assume that manipulator $A$ is rigidly holding the object, while manipulator $B$ is executing the defined task with the tool. The position vectors of the origins of gripper frame $(\Sigma_G)$ and the tool frame $(\Sigma_T)$ with respect to the base frames of the two manipulators $(\Sigma_A$ and $\Sigma_B$) are denoted as $\theta_{rg}$ and $\theta_{rt}$, respectively. In addition, the position vectors of the origins of the tool and the object frame with respect to $\Sigma_A$ and $\Sigma_B$ are denoted as $\theta_{obj_T}$ and $\theta_{obj_G}$, respectively. According to $[10]$, the transformation of the joint velocities $\dot{q} = [\dot{q}_G, \dot{q}_T]^T \in \mathbb{R}^n$, onto the task space linear and angular velocities $\nu = [\theta_{obj_T}, \theta_{obj_G}]^T \in \mathbb{R}^6$ is performed by the relative Jacobian, $J_R$, as follows

$$\nu = J_R(q)\dot{q}. \quad (1)$$

with $n = n_A + n_B$, where $n_A$ and $n_B$ denote the number of DoFs of the two manipulators.

B. Relative impedance control of dual-arm: To establish the mapping between the forces acting on the tool frame, $\theta_{obj_T}$, referenced from the object frame, and the required

![Fig. 2: Dual arm manipulation diagram.](http://wiki.iciub.org/codycdox/html/group-iDynTree.html)
joint torques, $\tau$, we can exploit the principle of virtual work. Therefore, we can write
\[ \Delta W_\tau = \tau^T \Delta q, \quad \Delta W_F = \text{obj}_F^T \Delta \text{obj}_X. \] (2)
with $\Delta W_\tau$ and $\Delta W_F$, denoting the work done by the joint torques and displacements, and forces acting on the object and relative displacement of the tool w.r.t. object frame of reference, $\Delta \text{obj}_X$, respectively. By combining the Eqs. (1) and (2), we acquire
\[ \tau = J_R^T(q) \text{obj}_F = J_R^T(q) K_c \Delta \text{obj}_X. \]

with $\Delta \text{obj}_X = \text{obj}_X - \text{obj}_X$. On the other hand, to establish the stiffness mapping between the joint and Cartesian spaces, we employ the following expression [8],
\[ K_J = \frac{\partial \tau}{\partial q} = \frac{\partial (J_R^T(q) K_c \Delta \text{obj}_X)}{\partial q}, \]
The above equation can be written as follows, around the equilibrium position,
\[ K_c = [J_R(q)(K_c - K_g)^{-1} J_R(q)^T]^{-1}, \]
where the diagonal elements of the joint stiffness matrix $K_J \in \mathbb{R}^{n \times n}$ are formed by the diagonal elements of the joint stiffness matrices of the two robots ($K_c$ and $K_g$). Here, we assume that all joint stiffness matrices do not have coupling terms, i.e., they are always of diagonal shape. The stiffness matrix $K_c$ specifies the Cartesian stiffness profile which is defined with respect to $\Sigma_c$, and $K_g = \frac{\partial J_R(q)}{\partial q} \text{obj}_F \in \mathbb{R}^{n \times n}$, captures the effect of geometry in presence of external forces.

A very interesting outcome of the above relation is the definition of the desired Cartesian stiffness (the Cartesian stiffness between $\Sigma_T$ and $\Sigma_{obj}$) in relative coordinates. This means that the need for transferring the configuration-dependent, desired Cartesian stiffness matrices of the two robots with respect to the world frame to the task coordinates is simplified, thanks to the definition of the relative Jacobian.

C. Task Prioritization: To execute the valve turning task in rotation phase, we assume that the gripper hand firmly grasps the valve and dominates the circular motion of the valve around its axis. Consequently, the tool hand follows the imposed circular path and generates additional rotating torques. To achieve this, the task can be decomposed into subtasks with prioritized order of occurrence (multiple prioritization of the task stiffness profile can be realized as proposed in [11]).

An efficient solution for stabilization of the task variables in prioritized order is presented in [12]. Following that, to preserve a desired position of the object w.r.t. the world frame, the first priority subtask is established as follow
\[ \dot{q}_G = J_1^T r_1, \] (4)
where $J_1 \in \mathbb{R}^{6 \times n_A}$ is the first-priority task Jacobian and $r_1 \in \mathbb{R}^6$ is the velocity vector of the origin of the gripper frame. Our secondary subtask establishes the relative movement of the two end effectors and its kinematic relationship is defined by the relative Jacobian of the two arms (Eq. 1). Now, given the two subtasks, we setup the task-priority based kinematic control [12], as follows
\[ \dot{q} = J_1^T r_1 + \tilde{J}_2^T (r_2 - J_2 r_1) + (I - J_1^T J_1)(I - \tilde{J}_2^T \tilde{J}_2) \tilde{\eta}, \] (5)
where $I$ is the identity matrix, $J_2 = J_1, r_2 = v$, and $\tilde{J}_2 = J_2 (I - J_2^T J_2)$. To ensure robustness against kinematic singularities, we use the damped least-squares inverse solution which is defined by $B^+ = B^T (BB^T + \lambda I)^{-1}$, with $\lambda \in \mathbb{R}$ denoting the damping factor. The third term in above equation projects the vector $\tilde{\eta}$, into a subspace which is formed by remaining DoF that do not affect neither one of the subtask variables, and is utilized to avoid the occurrence of joint limits using a potential function as proposed in [13].

IV. Experiments

Two valves with adjustable values of the torsional springs were mounted on a variable height stand (Fig. 1. C). Fig. 3 illustrates different phases of the task execution where a relatively low endpoint stiffness profile was considered for each arm during reaching. After reaching, SoftHands grasp the valve and due to the implemented concept of soft synergies and the existence of passive elasticity in the finger joints, they mold around the valve and take its shape. Once the handle is firmly grasped by the two SoftHands, the user triggers the rotation state. In this phase, the desired diagonal Cartesian stiffness matrix (in relative coordinates) was chosen to overcome the existing frictional and elastic forces around the center of rotation. In the meantime, along $y$ direction (the direction which coincides with the position of the two hands), the stiffness value was set to a lower value to avoid the realization of the high interaction forces. Rotational values of the stiffness matrix were also set to a fixed number. Repetition of the manipulation sequence resulted in the opening of both valves with different radius and friction values. In the meantime, task efficient interaction forces were realized.

V. Conclusion

This work reported on the preliminary experimental results of the implementation of a hierarchical control framework for a compliant humanoid robot. It is worth to note that in our setup, the implementation of the joint impedance control is considered over the joint torque control, due to the improved robustness and stability. Therefore, the realization of the desired Cartesian stiffness matrix is subject to uncertainty. Nonetheless, this error can be reduced by implementing a configuration dependent stiffness (CDS) control [14], and will be explored in future work. In addition, towards the establishment of a whole-body manipulation framework, we will integrate the lower body kinematics/dynamics to possibly avoid any instability caused due to the interaction with the external environment.

Acknowledgment

Authors would like to thank Corrado Pavan and Valerio Varricchio for their support in setting up the pilot interface. This work is supported in part by the European Research...
Fig. 3: Valve turning sequences, starting from the home posture: Reaching, Grasping, Rotating, Releasing, Disengaging. This sequence is repeated until the valve is open.


REFERENCES


