The Role of Impedance Modulation and Redundancy Resolution in Human-Robot Interaction

Fanny Ficuciello, Luigi Villani, Bruno Siciliano

***Abstract*— In this work, redundancy resolution and impedance modulation strategies have been employed to enhance intuitiveness and stability in physical human-robot interaction during co-manipulation tasks. An impedance strategy to control a redundant manipulator is defined in the Cartesian space. Different modulation laws for the impedance parameters are tested in combination with different strategies to solve redundancy. The stability of the coupled human-robot system is guaranteed ensuring that the impedance parameters vary in a range evaluated experimentally. Through an extensive experimental study on a 7-DOF KUKA LWR4 arm, we show that using redundancy to decouple the equivalent inertia at the end-effector enables a more flexible choice of the impedance parameters and improves the performance during manual guidance. Moreover, variable impedance is more performant with respect to constant impedance due to a favourable compromise between accuracy and execution time and the enhanced comfort perceived by humans during manual guidance.**

I. INTRODUCTION

Robots that work close to people in their homes, offices or factories may be employed to support humans in the execution of certain types of tasks requiring intentional physical interaction, like helping in lifting and moving around heavy objects or tools, or performing cooperatively some operation, like assembling. During the execution of these tasks, the human guides the robot by exerting forces on some points of the robots body, often the end effector, which should have a compliant behaviour. To be effective, this behaviour should be changed or adapted according to the task and, possibly, to human intentions.

The most natural and effective way to manage human-robot interaction is to define a desired interaction dynamics using impedance/admittance control strategy [1]. A crucial issue in human-robot cooperative tasks is the selection of the impedance parameters. These can be preset on the basis of the task to be executed, but a more effective solution consists in tuning the impedance behaviour of the end effector on the basis of the inferred human intentions [2], [3].

In implementing fixed or variable impedance control the stability must be guaranteed for all the possible range of variation of the parameters. Stability of human-robot interaction depends on the coupled dynamics of both interacting systems [1], [4] but also on the hardware [3].

Starting from the consideration that instability is likely to occur during interaction when the controller attempts to impose to the robot an impedance dynamics that differs significantly from the intrinsic hardware dynamics, redundancy is exploited to make the robot apparent dynamics at the end effector as close as possible to the desired dynamics.

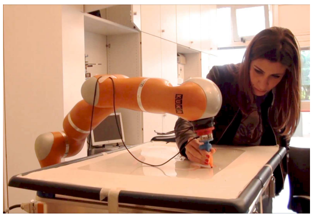

Fig. 1. Snapshot of the co-manipulation task.

This paper aims at contributing to this field by presenting an experimental study on variable impedance control of a redundant manipulator, KUKA LWR4, used for the execution of a drawing task under human guidance.

II. VARIABLE IMPEDANCE WITH REDUNDANCY RESOLUTION

The algorithm considered here relies on impedance control with inertia reshaping [7]. To design the impedance control, it is useful to derive the end-effector dynamics in the operational space [9]. The control strategy is designed to perform tasks in cooperation with humans. The operator interacts with the robot by grasping the end effector and moving it along arbitrary trajectories. It is assumed that only forces can be applied. In order to make the end effector able to follow and adapt to the force exerted by the operator at the tip, the end effector dynamics can be set as a mass-damper system of equation

$$\boldsymbol{\Lambda}_d \ddot{\boldsymbol{x}} + \boldsymbol{D}_d \dot{\boldsymbol{x}} = \boldsymbol{F}_{ext}, \tag{1}$$

where $\boldsymbol{\Lambda}_d$ and $\boldsymbol{D}_d$ are suitable inertia and damping matrices, that are positive definite and are usually set as constant diagonal matrices. The goal of a variable impedance strategy for a co-manipulation task is to vary the damping and mass properties of the robot in order to accommodate the human movement during physical interaction. According to the related results available in literature [3], [2], high impedance parameters are desired when the operator performs fine movements at low velocity while lower values of the parameters should be used for large movements at high velocity. The human perception is mainly influenced by the damping parameter, while, for a given damping, the desired (virtual) mass is crucial for stability.

Therefore, our idea is that of varying the damping according to the absolute value of the end effector Cartesian

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Dipartimento di Ingegneria Elettrica e Tecnologie dell'Informazione, Università degli Studi di Napoli Federico II, via Claudio 21, 80125 Napoli, Italy, email: {fanny.ficuciello, luigi.villani, bruno.siciliano}@unina.it. This research has been partially funded by the EC Seventh Framework Programme (FP7) within SAPHARI project 287513 and RoDyMan project 320992.

velocity in order to improve the performance in terms of execution time and accuracy. Namely, when the velocity is high, the damping force is reduced, so that the operator can move the end effector with minimum effort and the execution time can be reduced; vice versa, at low velocity, the damping force is increased to improve accuracy.

In the presence of redundant degrees of freedom, which is the case considered here, it is possible to assign a secondary task in the null space of the end effector task.

In our application, the human guidance of the end effector involves only the position, which is made compliant by the Cartesian impedance control under the action of the external forces. Thus there are 4 of the 7 degrees of freedom of the robot at disposal for the secondary task. Among the possible redundancy resolution criteria, we have selected and compared two secondary task function inspired to the dynamic conditioning index (DCI), to measure the dynamic isotropy of robot manipulators in joint space [8], and to the kinematic manipulability index.

A. *Stability region*

The stability region in the impedance parameters space could be estimated analytically (see, e.g., [3]). However, many authors have observed that the actual bounds of the stability region are dependent on the robot's hardware and, in the case of interaction with a human operator, also on the impedance of the human arm, which cannot be accurately modelled and evaluated. A further complication here is represented by the null-space stability for the presence of redundant degrees of freedom. Therefore, in this work the stability region has been found experimentally.

A suitable procedure has been set up to find the allowed range of variation of the impedance parameters of (1) so that stability is preserved.

To reduce the number of parameters, the same damping and the same mass has been set along all the directions of the Cartesian space, i.e., $\boldsymbol{D}_d = D\boldsymbol{I}$ and $\boldsymbol{\Lambda}_d = \lambda\boldsymbol{I}$, with $\lambda = \alpha\bar{\lambda}$, being $\bar{\lambda} = 4.2456\,\text{kg}$ the maximum eigenvalue of the end effector inertia in a chosen initial configuration, and $0 < \alpha \leq 1$ a scaling factor. The stability region has been evaluated experimentally by setting a value of damping D in the interval $[5, 60]$ Ns/m and reducing the value of α, starting from $\alpha = 1$, until vibrations can be felt by an operator shaking the end effector in a neighbourhood of the initial configuration.

The results of the experimental procedure are reported in Fig. 2, where the stability region for the parameters D and α is that included between the continuous and the dotted line.

III. EXPERIMENTAL RESULTS

Five different subjects, after some training, have been requested to execute the task. A snapshot of the co-manipulation task is reported in Fig. 1. To evaluate the performance related to redundancy resolution, the methods have been compared using two different impedance laws, one with constant parameters (set as $\lambda = 1.1\,\text{kg}$, $D = 60\,\text{Ns/m}$) and one with variable damping (low constant mass, $\lambda = 1.1\,\text{kg}$). One purpose, relying on a previous study [5] is to analyze if and how redundancy can be used to improve stability and performance. The results show that the use of redundancy to decouple the inertial dynamics of the end effector produces a tangible improvement of performance and enlarge the stability region in the space of the impedance parameters.

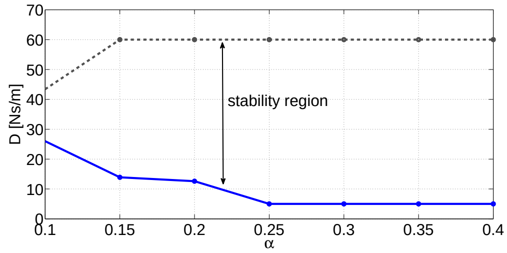

Fig. 2. Range of minimum and maximum allowed damping D for a given scaling factor α of the inertia matrix.

Moreover, starting from previous studies available in litterature [3]), different modulation strategies for the impedance parameters are proposed and tested. The adopted variable impedance law has been compared to the impedance strategy with constant parameters. The experiments demonstrate that the variable impedance performs better than the constant impedance in the sense that it enhances the comfort perceived by humans during manual guidance, and allows reaching a favourable compromise between accuracy and execution time. Regarding the experimental tests, more details are omitted for brevity but these can be further investigated in [6]

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