On the Design and Control of an Empowering Manipulator to Increase the Capabilities of Humans in Industrial Applications

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Empowering robotic solutions are exploited for industrial applications in order to reduce/limit risk factors related to musculoskeletal disorders (MSDs) and to improve the capabilities of humans. This paper aims at proposing both (a) the design and (b) the control of a cooperative manipulator in order to empower humans in onerous industrial tasks execution. (a) a dual driven actuation (DDA) is proposed and described for the shoulder joint of an empowering robotic system. (b) a fuzzy impedance control based approach to assist the human operator while lifting (partially) unknown weight components is proposed. The control method has been validated in a hatrack-like component installation, case-study related to the H2020 CleanSky 2 EURECA project. The proposed application has been shown during the KUKA Innovation Award. As a test platform, a KUKA iiwa 14 R820 has been used.

Keywords: Empowering robotics, mechanical and control design, compliant actuation, cooperative honerous industrial tasks, impedance control.

1. INTRODUCTION

Empowering humans is highly demanded in different areas of robotic research and practice. Industries are one of the key user for the development of such technology, since nowadays many onerous tasks (*e.g.*, lifting/installation of heavy components¹) are still manually made, implying non-ergonomic postures and musculoskeletal disorders.²

1.1. *Empowering Robots Actuation*

Compliant actuation plays a key role in empowering robots design. SEAs³ use a passive mechanical spring in series with a motor. PEAs⁴ differ from

SEAs actuators by using a passive mechanical spring in parallel with a motor, in order to reduce the energy consumption of robotic systems. SEA and PEA combinations are also investigated to exploit their capabilities.⁵ Variable stiffness actuators⁶ are specifically designed for human-robot interaction tasks, consisting of two motors and spring arrangement, allowing to control both displacement and joint stiffness.

1.2. *Empowering Robots Control*

Empowering of humans can be achieved by *programming by demonstration* approaches.⁷ Variable admittance/impedance control scheme are exploited, also estimating the impedance characteristic in real-time.⁸ Moreover, efforts have been made to on-line tuning stiffness/damping parameters avoiding the estimation of the human arm dynamics.⁹ Fuzzy controllers have also been defined,¹⁰ extended such methodologies including neural networks approaches to train the control parameters.¹¹

1.3. *Paper Contribution*

The aim of this paper is (a) to propose a design concept for an empowering cooperative robot and (b) to propose an empowering control approach to assist the human operator during the execution of a honerous task while manipulating (partially) unknown weight components. (a) the proposed mechanism aims at actively assisting the human operator during cooperative tasks while implementing a compliant actuation system. It consists in a Dual Driven Actuation (DDA) architecture, defining a parallel system composed by (i) a serial elastic actuator (SEA) and by (ii) a standard direct actuator. Such solution defines a redundant actuation system, decoupled by the elastic element of (i), capable to manage the energy flow by control. (b) the developed method allows to set in real-time the set-point of the impedance control on the basis of the human's intentions. The proposed method has been validated in an industrial task where a human operator performs the installation of a heavy and bulky component (the installation of a hatrack-like component inside the aircraft cabin, case-study related to the H2020 CleanSky 2 EURECA project) using as a test platform a KUKA iiwa 14 R820.

2. DUAL DRIVEN ACTUATION DESIGN & CONTROL

Figure 2 (a) shows the DDA kinematics with respect to the link side. The torque τ is applied by the motor M_j and can be defined to implement an

Fig. 1. DDA shoulder joint mechanism. (a) concept. (b) mechanical schema.

empowering cooperative controller. The tension T couples the SEA dynamics with the direct actuator dynamics at the joint side and it is a function of the joint position q , of the lumped mass P at the link extremity and of the link side dynamics. α represents the joint position-dependent variable and it can be written as follows:

$$\alpha = \arccos \left(\left(1 - \frac{d_1}{D} \cos(q) \right) \frac{D}{d_2} \right) \quad (1)$$

On the basis of (1), the position x_3 can be written as a function of the joint position q :

$$x_3(q) = -d_3 - d_1 \sin(q) - d_2 \sin \left(\arccos \left(\left(1 - \frac{d_1}{D} \cos(q) \right) \frac{D}{d_2} \right) \right) \quad (2)$$

Figure 2 (b) shows the DDA kinematics with respect to the back side, where the SEA is placed. The position x_2 related to the elastic element of the SEA system is a function of the cable tension T and can be defined as $x_2(T) = -2T/K$. Under the assumption that the mechanism is in its steady state position (*i.e.*, $x_3 = 0$ and $T = 0$, therefore, $x_2 = 0$), the total length L of the cable can be calculated as the sum of the consecutive segments and arcs of circumference (related to the winding on pulleys), resulting in $L = 4h + 3r\pi$. The position x_1 is calculated on the basis of the position x_3 and on the basis of the deformation x_2 of the elastic element. Having that the total length L is constant, it can be written $L = 4h + 3r\pi - 2x_1 + 2x_2(T) + x_3(q)$. The position x_1 can, therefore, be calculated as $x_1 = x_2(T) + x_3(q)/2$. The position x_1 is rigidly connected to the SEA motor M_b . Therefore, defining θ as the motor M_b position it

Fig. 2. (a) the link-side DDA mechanism is shown, highlighting its kinematics. (b) the back-side DDA mechanism is shown, highlighting its kinematics.

results in $\theta = Ix_1$, where I is the transmission ratio.

Position x_1 can be defined in order to impose a target tension T acting on the joint, allowing to compensate for the gravity load on the joint and to assist the joint q positioning. On the basis of Figure 2 (a), the static equilibrium of the system is described by:

$$\tau = Pa_gb \cos(q) - TD \quad (3)$$

where τ is the torque applied by the direct motor M_j and a_g is the gravity acceleration. Since the DDA defines a redundant actuation system (involving two motors, M_b and M_j) with infinite equilibrium solutions for (3), the mechanism energy flow can be managed by control, imposing that the gravitational load is fully compensated by the motor M_b . Therefore, the torque from the motor M_j can be imposed $\tau = 0$ [Nm]. Then, it is possible to calculate the tension T in order to keep the joint in a target position q^d :

$$T = Pa_gb \cos(q^d)/D \quad (4)$$

Substituting (4) in the definition of x_2 , it is possible to calculate the corresponding static deformation x_2^d :

$$x_2^d = -\frac{2Pa_gb \cos(q^d)}{DK} \quad (5)$$

Moreover, from (2), it is possible to calculate the target position x_3^d to be

assumed by x_3 , given a target joint position q^d :

$$\begin{aligned} x_3^d = & -d_3 - d_1 \sin(q^d) \\ & -d_2 \sin\left(\arccos\left(\left(1 - \frac{d_1}{D} \cos(q^d)\right) \frac{D}{d_2}\right)\right) \end{aligned} \quad (6)$$

On the basis of the definition of x_1 , (5) and (6), the proposed control law for the position x_1 , defining the target position x_1^d , can be defined as follows:

$$x_1^d = x_2^d + x_3^d/2 \quad (7)$$

The proposed DDA will be applied at the shoulder joint of a high-payload cooperative robotic device for empowering a human operator in lifting of heavy loads for installation purposes, taking also into account the link-side dynamics for the control purposes. The target manipulator is currently in the design phase within the CleanSky 2 EURECA project.^{12,13}

3. EMPOWERING CONTROL

3.1. Impedance Control

To implement the proposed empowering fuzzy controller, the Cartesian impedance control methodology has to be implemented. It is possible to design the Cartesian impedance control as defined in,¹⁴ obtaining the following six DoFs Cartesian impedance control:

$$\mathbf{M}_r \ddot{\mathbf{x}}_r + \mathbf{D}_r \dot{\mathbf{x}}_r + \mathbf{K}_r \Delta \mathbf{x}_r = \mathbf{f}_r \quad (8)$$

where $\mathbf{M}_r$, $\mathbf{D}_r$, $\mathbf{K}_r$ are the impedance mass, damping and stiffness matrices composed by both the traslational and rotational parts, $\Delta \mathbf{x}_r = \mathbf{x}_r - \mathbf{x}_r^0$ (where $\mathbf{x}_r^0$ is the six DoFs reference for the impedance controller and $\mathbf{x}_r$ is the measured six DoFs robot position), and $\mathbf{f}_r$ is the wrench vector.

3.2. Empowering Fuzzy Control

On the basis of force derivative $\dot{\mathbf{f}}_r$ and velocity $\dot{\mathbf{x}}_r$ signals, the impedance control set-point $\mathbf{x}_r^0$ is on-line calculated to empower humans in honerous tasks. Two fuzzy membership functions have been defined with respect to such signals (Figure 3 (a) and Figure 3 (b)) in order to on-line calculate an assistance level $\mathbf{A}_L$ through the task execution. Considering Figure 3 (a), two states have been defined: *no variation* and *variation*. While in the first state no human intention to move the robot is defined, in the second state the human aims to move the robot. Considering Figure 3 (b), two

Fig. 3. (a) force derivative membership function. (b) velocity membership function.

Fig. 4. Assistant level membership function.

states have been defined: *stop* and *move*. While in the first state the robot is not moving, in the second state the robot is in motion. The assistant level $\mathbf{A}_L$ membership function is defined as in Figure 4, where three levels of assistance have been defined: *none*, *medium* and *high*. The following rules have been implemented to calculate the target assistant level:

$$\left\{ \begin{array}{l} \#1 \text{ If no variation \&\& stop then none} \\ \#2 \text{ If no variation \&\& move then medium} \\ \#3 \text{ If variation \&\& stop then high} \\ \#4 \text{ If variation \&\& move then high} \end{array} \right. \quad (9)$$

Rule #1 aims at impose no-assistance when no force variation, either motion of the robot is observed. Rule #2 aims at impose a medium level of assistance when no force variation is measured but a motion of the robot is observed. Rule #3 and #4 aim at impose a high level of assistance. In #3 the robot is not moving and the human would like to start a motion, while in #4 the robot is already moving and the human would like to modify the robot motion. In both cases, the robot + component inertia have to be compensated with a higher assistance level. The impedance control set-point is then on-line computed as follows:

$$\mathbf{x}_r^0 = \mathbf{x}_r + \mathbf{A}_L \text{sign}(\dot{\mathbf{x}}_r) \quad (10)$$

3.3. Experimental Application

The proposed method has been validated in an industrial task, performing the installation of a heavy and bulky hatrack-like component, case-study re-

lated to the H2020 CleanSky 2 EURECA project. The proposed application has been shown during the KUKA Innovation Award,¹⁵ where the ITIA-CNR MACHAMP team has been selected as a finalist in the competition. Such industrial task is a complete 3-D task. In order to guide the human operator through the installation procedure, a predefined installation path has been defined. The empowering control is applied along the Z Cartesian direction (*i.e.*, gravity direction), while the other traslational and rotational degrees of freedom (DoFs) are constrained to the predefined installation path by the impedance control. The video of the proposed application is available at: <https://www.youtube.com/watch?v=mdYpZZw93YE&t=27s>.

4. CONCLUSIONS

The design and control of a cooperative manipulator in order to empower humans in onerous industrial tasks execution have been proposed. On one hand, the design of a dual driven actuation (DDA) has been described. On the other hand, a fuzzy impedance control based approach to assist the human operator while lifting (partially) unknown weight components has been proposed and tested. Current/future work aims at optimize the design of the proposed actuation and control solutions and perform tests with human operators in order to evaluate the comfort and effectiveness of the proposed design and control approaches. A prototype of the developed DDA and of the cooperative dual arm robotic system will be realized. Empowering control approach will be generalized to the joint space.

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