Robotics and Autonomous Systems 62 (2014) 1827–1836

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Development and control of a series elastic actuator equipped with a semi active friction damper for human friendly robots

Matteo Laffranchi *, Lisha Chen, Navvab Kashiri, Jinoh Lee, Nikos G. Tsagarakis, Darwin G. Caldwell

Department of Advanced Robotics, Fondazione Istituto Italiano di Tecnologia (IIT), Via Morego, 30, Genova 16163, Italy

HIGHLIGHTS

- Whole realization process of a successful implementation of a variable impedance actuator.
- Comprehensive analysis on the effects of compliance and variable physical damping.
- Mechatronic implementation of the variable impedance actuator.
- Introduction of a novel mechanical impedance estimator for measuring physical damping.
- Experimental results validate the analysis and the whole mechatronic system.

ARTICLE INFO

Article history:
Received 1 March 2014
Received in revised form
18 June 2014
Accepted 27 June 2014
Available online 23 July 2014

Keywords:
Robotics
Variable impedance actuation
Compliant actuation
Mechatronics

ABSTRACT

Compliance is increasingly being incorporated in the transmission of robotics actuation systems to cope with unpredictable interactions, improve the robustness of the robot and in some cases its efficiency. However, compliance also introduces some drawbacks as e.g. reduced bandwidth of the controlled system and typically underdamped vibration modes which decrease the accuracy and stability margin of the controlled system. To tackle these issues, variable physical damping has recently been incorporated in such actuation systems. This paper presents the analysis, development, control, identification and experimental evaluation of a novel actuation system which embodies transmission characteristics such as passive compliance and variable physical damping. The first part of this paper introduces an analysis on how these two physical properties affect the performance of the actuation system with the second part analysing the mechatronic design and control in detail. Furthermore, a novel damping estimation method is presented. Results are presented to validate the results obtained in the analysis section advantages gained by employing such actuation approach and to show the effectiveness of the actuation unit in replicating and estimating desired mechanical impedance values.

1. Introduction

The typical actuation approach employed in industrial robots makes use of rigid and non-backdrivable transmissions regulated by high gain controllers to obtain precise positioning. In contrast, there is limited consideration on the adaptability of these machines when dealing with unexpected interactions as such robots work within well-defined and structured environment to eliminate any possibility of unpredicted physical contact with external agents during the execution of the task. However, emerging application domains require direct interaction of the robot with the human/environment and it becomes evident that this typical "stiff" robotic actuation approach has limited performance related to the ability of interaction, robustness and safety, [1]. To deal with these drawbacks, completely different design and control approaches have been introduced which focus on light and compliant structures to lower the output mechanical impedance and control strategies specifically formulated to cope with unexpected interactions [2–14]. In detail, compliance has been identified as a key feature that these robots should incorporate.

However, compliance also introduces some drawbacks, as the induction of oscillatory modes which can dramatically decrease the accuracy of the robot, possibly leading to instability, and the reduction of the maximum bandwidth which can be achieved in the controlled plant, [15]. Taking inspiration from the biomechanical

* Corresponding author. Tel.: +39 010 71781 952.
E-mail addresses: matteo.laffranchi@iit.it (M. Laffranchi), lisha.chen@iit.it (L. Chen), navvab.kashiri@iit.it (N. Kashiri), jinoh.lee@iit.it (J. Lee), nikos.tsagarakis@iit.it (N.G. Tsagarakis), darwin.caldwell@iit.it (D.G. Caldwell).

http://dx.doi.org/10.1016/j.robot.2014.06.007
0921-8890/

structure of mammalians, that exhibit intrinsic compliance in their muscles and tendons, these issues are solved by means of damping which is regulated to improve the system stability and performance [16,17]. This enables the fast, smooth and accurate limb motion typical of mammalians. These works showed that humans vary the level of joint damping during the execution of the task in order to achieve the mentioned behaviour. Therefore, inspired by this, researchers are increasingly incorporating variable physical damping in compliant robotics systems [13,18–20]. This leads to increased stability margins and bandwidth of the controlled system hence facilitating the control of the compliant actuator. In addition, it has been demonstrated that the use of physical damping in the transmission system of a torque controlled actuator can effectively improve its closed-loop performance (bandwidth and accuracy) [13,18,19,21–23].

Dampers can be classified in three main categories (passive, active or semi-active) depending on the amount of power they require to operate. Passive dampers, [24], provide a certain fixed amount of damping and they constitute the simplest solution, however from the robotic perspective they may not be appropriate when energy efficiency is demanded or when a variation of the damping level is required to cope with load/configuration changes. On the other hand, purely active dampers, [25], may require substantial amount of energy to perform their functionality and are valid only within the closed loop bandwidth of the controlled system. Furthermore, compliant actuators which feature low joint physical damping exhibit a marked antiresonance on the motor side either in position/velocity or torque controlled actuators [15], meaning that a solution based on pure active damping will show its limits across resonance as the motor controllability is very low in proximity of this frequency. Differently from active solutions which can be implemented to control both the stiffness and damping components of the mechanical impedance, semi-active devices, [26,27], can only regulate the latter. This class of damping devices typically require much less amount of energy when compared to active solutions still maintaining the versatility of active dampers but in contrast guaranteeing inherent passivity and the reliability of passive devices [28]. A further attractive feature of this class of dampers is that they can be disengaged in particularly risky scenarios to maximize the decoupling effect of compliance. From the above it can be concluded that the use of an actuation approach which can provide both passive compliance and variable physical damping (using e.g. a semi active damper) can form an effective mean for the development of robots which can safely and robustly interact with the environment, still presenting good dynamic performance and accuracy. On the other hand, the implementation of such an approach is not a trivial task, particularly if we consider the high integration density required in robotics systems. In addition to this, also the control architecture becomes much more complex as the number of states and degrees of freedom radically increases when compared to conventional stiff drives where typically one state variable (position/velocity and/or torque) is controlled. Several works have been presented until now on the topic of variable impedance actuation, focusing either on mechatronic design [1–5,7,11–13,19,22,26,29] or on software/control [6,8,10,23,30–35]. In this work, we present a successful implementation case of a variable impedance actuator comprising its whole realization process. We first introduce a study on the effects of transmission compliance and damping on different performance aspects of the actuator including the effect on interaction forces, force/torque exchange and energy consumption. Following that we present the design and mechatronics of the actuator while the last sections of the paper focus on the system identification, impedance estimation, control and experimentation of the actuator. Furthermore, since mechanical impedance needs to be measured to be regulated but no devices to measure this quantity exist, a novel damping estimator is introduced and analysed following an approach that is similar to what has been implemented for measuring variable stiffness [30–33]. The paper is structured as follows: Section 2 analyses the benefits which can be gained by employing the mentioned mechatronic system compared to the usual compliant actuation approach. Motivated by the positive results, Sections 3 and 4 present the design, model and identification of the compliant actuation unit with variable physical damping. The control strategy is presented in Section 5 whereas preliminary results are verified by experiments in Section 6. The conclusions and future work are addressed in Section 7.

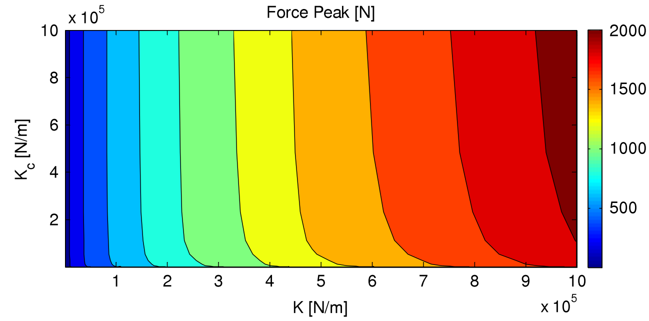

Fig. 1. Peak interaction force generated for different transmission and covering stiffness values K and K_c, respectively. $M_L = 1$ kg and $M_R = 0.5$ kg are the equivalent link and rotor reflected masses.

2. Dynamics of compliant actuators with variable physical damping

2.1. Effects of compliance during interaction

One of the main advantages offered by the introduction of compliance is the improved ability of interaction that is mainly brought by the capability of the system to adapt its configuration to the environment with corresponding reduction of the forces arising from interaction. Compliance can be introduced at two main levels: in the transmission system of the actuator or around the structure of the robot (link). The generated peak force relative to an interaction occurring at a velocity of $\dot{x}_\theta = \dot{x}_q = 2$ m/s in the scenario reported in Fig. 2(a) is shown in Fig. 1 as a function of the transmission and covering stiffness. Fig. 1 shows that interaction forces can be attenuated by the insertion of compliance at both levels. Nevertheless, it can be concluded that compliant coverage is effective for very low stiffness values. This in turn means that the volume of such coverage needs to be substantial to make the overall system capable of withstanding and react in a compliant way to external forces. This, unfortunately, makes this approach impractical [36]. On the other hand, the insertion of compliance at the transmission system has much greater influence on the reduction of the impact forces due to inertia decoupling effect. However, as mentioned in the introduction, this generates several control issues that can be addressed by adopting variable mechanical impedance transmission systems, either regulating the physical stiffness or damping. In this work we consider the latter approach.

2.2. Mechanical model

Consider the equivalent linear model of a general compliant actuation system with variable physical damping, Fig. 2(b). It can be expressed by the following set of dynamic equations:

$$\begin{cases} F_{in} = M_R\ddot{x}_\theta + D\left(\dot{x}_\theta - \dot{x}_q\right) + K\left(x_\theta - x_q\right) \\ F_{out} = M_L\ddot{x}_q - D\left(\dot{x}_\theta - \dot{x}_q\right) - K\left(x_\theta - x_q\right) \end{cases} \tag{1}$$

where $M_L = 1$ and $M_R = 0.5$ kg are the equivalent link and rotor reflected masses, $K = 100$ N/m and D are the joint stiffness and viscous damping, x_θ and x_q are the rotor and link positions, F_{in} and