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Cooperative transport tasks with robots using adaptive non-conventional sliding mode control

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ABSTRACT

This work presents a hybrid position/force control of robots aimed at handling applications using multi-task and sliding mode ideas. The proposed robot control is based on a novel adaptive non-conventional sliding mode control used to robustly satisfy a set of inequality constraints defined to accomplish the cooperative transport task. In particular, these constraints are used to guarantee the reference parameters imposed by the task (e.g., keeping the load at a desired orientation) and to guide the robot using the human operator's forces detected by a force sensor located at the robot tool. Another feature of the proposal is the multi-layered nature of the strategy, where a set of four tasks are defined with different priorities. The effectiveness of the proposed adaptive non-conventional sliding mode control is illustrated by simulation results. Furthermore, the applicability and feasibility of the proposed robot control for transport tasks are substantiated by experimental results using a redundant 7R manipulator.

1. Introduction

Recent advances in technology and robotics are revolutionizing modern society. Robots are becoming more and more present in the form of unmanned aircraft systems, commonly known as drones, driverless cars, robot-assisted surgery and rehabilitation systems, robotic prosthetics and exoskeletons, service robots for personal and domestic use, artificial assistants and smart machines, among others.

Possibly, the manufacturing industry in general has been the most benefited by advances in the fields of robotics, control and sensing, bringing in improvements to production processes as well as worker's ergonomics and job quality. Contrary to the old tendency of developing autonomous systems to replace humans by robotic devices, currently the research is more focused on developing robots to work alongside humans and assist them. The reason is that the combination of human cognitive and sensorimotor skills with the technical capabilities of a robot have proven able to solve, facilitate, improve and/or speed up a large variety of complex tasks that neither humans nor robots could successfully afford to do in solitary (Ansari et al., 2017; Maurtua, Ibarguren, Kildal, Susperregi, & Sierra, 2017; Meziane, Otis, & Ezzaidi, 2017; Mohammed, Schmidt, & Wang, 2017; Tsarouchi, Matthaiakis, Makris, & Chryssolouris, 2017).

A case in point in the manufacturing sector is the manipulation and safe transportation of precarious loads, most notably heavy objects such as car engines, or fragile items such as glass, liquid containers, hazardous materials etc. Moreover, in many cases loads have to be transported and awkwardly deposited in difficult-to-access areas that make it difficult or ergonomically challenging for an operator to keep them in a predetermined position and/or orientation, whilst simultaneously pursuing a higher level assembling or handling assignment. Yet the automatic realization of these type of assignments by a robot is usually discarded due to the limited flexibility afforded by a robot in adapting to changes in the production workspace. Hence, the combination of skillful guidance by the human operator on the one hand, and the sensorimotor stability and strength of the robot on the other can lead to industrially feasible human–robot collaborative solutions for handling applications.

Generally, in this kind of applications guidance for the motion of the manipulator is obtained via a wrist-mounted force sensor which evaluates the forces exerted by the human operators. The most commonly used method to convert these measurements into kinematic instructions to the robot is through compliance control, which establishes a direct relationship between the measured forces and the changes in the robot position (Khan et al., 2017; Nikoleizig, Vick, & Krüger, 2017). Yet other variants and methods can be found in the literature. For instance,

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authors in Jiang et al. (2016) presented a method to determine the compliance controller parameters of the physical model using a particle swarm optimization algorithm for a spinal surgery application. In Li and Ge (2016) a force tracking method under the impedance control framework was extended to also account for uncertain human limb dynamics. An adaptive controller was developed to deal with point-to-point movements, whereas learning and neural network controls were included to generate periodic and arbitrary continuous trajectories respectively. A hierarchical control system was presented in Koustoumpardis, Chatzilygeroudis, Synodinos, and Aspragathos (2016) for the co-manipulation task of folding sheets like fabrics/cloths. The system was based on force and RGB-D feedback at two distinctive control levels. At a higher level, the perception of the human's intention was used to decide on the robot's action, whereas at a lower level the robot reacted to force and RGB-D feedback in following the guidance from the human. In Vogel et al. (2015) a decision-and-control architecture was proposed for hand-arm systems with "soft robotics" capabilities via dedicated human–machine interfaces. The robot was controlled through a multi-priority Cartesian impedance controller, and the behavior extended with collision detection and reflex reactions. The problem of human-directed position/force control of a robot end-effector interacting with an environment given unknown geometry and stiffness was addressed in Lu and Wen (2015). In free space (non-contact) motion, the input was interpreted as a linear velocity command. When contact occurred, a generalized damper-type of impedance control was used for the regulation of force in the constrained direction, while the input from the user would adjust the contact force set point. In Jlassi, Tliba, and Chitour (2014) a mathematical relation between the velocity of the human–robot interaction point and the force applied by the human operator was established using impedance control for handling tasks, where an adjustable force threshold was used to enable the operator to keep authority over the robot motion. An optimal impedance adaptation was investigated in Wang, Li, Ge, Tee, and Lee (2013) for interaction control in constrained motions, which lead to an optimal realization of trajectory tracking and force regulation.

A relevant aspect to be taken into account for human–robot collaboration that directly affects the maneuverability and the human's ergonomics is the compensation of the effort demanded by the human throughout the guidance task. In other words, the manipulator should adapt itself according to the force exerted by the human, causing a greater sensation of freedom of movement and avoiding slow motions. None of the above works deals with this aspect and, to the best of the authors' knowledge, this is the first work that proposes a feasible solution based on an adaptive controller (Chen, Shen, Cao, & Kapoor, 2014; Cong, Chen, & Liu, 2014; Lu, 2009; Monsees & Scherpen, 2002; Plestan, Shtessel, Bregeault, & Poznyak, 2010; Zhu & Khayati, 2017).

Some approaches for human–robot collaborative applications driven by force-control strategies are based on sliding mode control (SMC) theory given its inherent robustness and low computational cost characteristics (Edwards & Spurgeon, 1998). For instance, in Zhou, Zhou, and Ai (2016) a non-singular terminal SMC was developed to ensure trajectory tracking precision for the case of a lower limb rehabilitation parallel robot. The device would adjust the gait trajectory online according to the indications from a human–machine interaction force set-up. In Jin, Zhu, Zhu, Chen, and Zhang (2017) a human–robot interaction controller was introduced for a lower extremity exoskeleton whose aim was to improve tracking performance with the development of a fuzzy SMC that considered system uncertainties. In this way, the controller was able to drive the exoskeleton to shadow the wearer in the presence of weaker interactive driving forces. In Kashiri, Tsagarakis, Van Damme, Vanderborght, and Caldwell (2016) a proxy-based SMC was proposed to obtain effective tracking during normal operations for flexible joint manipulators working close to humans, whilst retaining the ability to recover from positional errors in a smooth and damped manner. In Yun et al. (2016) a robust SMC was proposed that relied on basic information from the human subject (weight, height, age and gender) to handle model uncertainties due to biomechanical variation of patients using an upper limb rehabilitation robot. An SMC consisting of a proportional–integral–derivative sliding surface and a fuzzy hitting control law was developed in Wu, Wang, Du, and Zhu (2015) to guarantee robust tracking performance and reduce the chattering effect for a class of robot-assisted therapeutic exoskeleton. A fuzzy SMC presented in Mitra and Behera (2015) considered a non-linear model for trajectory tracking of micro robots in the human vasculature system. It is worth mentioning that SMC has been recently used in the field of robot force control not only to improve controller robustness but also to improve force estimation by means of a sliding perturbation observer (SPO) in order to avoid the use of expensive force sensors. For examples of this approach, see Rahman and Lee (2013a, b).

One typical problem of SMC is related to the controller switching gain. High values of the switching gain increase the control effort and the *chattering* band, which is a well known issue to be solved in SMC techniques (Kunusch, Puleston, & Mayosky, 2012; Rashid Husain, Noh Ahmad, & Halim Mohd Yatim, 2008; Utkin, 2016). On the contrary, adjusting the switching gain to minimize the control effort and chattering band at a certain operating point may cause the control to become unstable for another operating point. In the specific problem treated in this paper, this issue is present due to changes on the forces exerted by the human operator in order to guide the robot to perform the collaborative transport task.

To overcome this problem, Adaptive SMC (ASMC) solutions have been proposed in the literature, i.e., SMC approaches with an adaptive switching gain (ASG). For instance, in Zhu and Khayati (2017) an ASMC was developed using an integral/exponential adaptation law with boundary-layer in order to reduce the switching gain overestimation while simultaneously speeding up the system response to the uncertainties. In Shen, Wang, Zhu, and Poh (2015) two fault-tolerant control schemes for spacecraft attitude stabilization with external disturbances were proposed, where a fault-tolerant SMC was incorporated with an adaptive technique to accommodate actuator faults in order to relax the required boundary information. In Taleb, Plestan, and Bououlid (2015) a high-order ASMC was proposed based on the concepts of integral sliding mode and real high-order sliding mode detector. For more SMCs with ASG solutions, the reader is referred to Amini, Shahbakhti, Pan, and Hedrick (2017), Begnini, Bertol, and Martins (2017), Bigelow and Kalhor (2017), Chen et al. (2014), Cong et al. (2014), Leung, Zhou, and Su (1991), Lu (2009), Monsees and Scherpen (2002), Plestan et al. (2010), Wheeler, Su, and Stepanenko (1998), Xu (2013), among others.

The approach proposed in this work also exploits SMC so that human operator and robot can cooperatively undertake the transportation of objects, such as the one depicted in Fig. 1, with the aid of force feedback sensing. However, the SMC in this work offers several distinctive features that sets it apart from other works in the literature. In particular, the main contributions and features of the proposed approach are as follows:

- The introduction of inequality constraints within the SMC framework is a key novelty of the proposed method.
- The control strategy relies on a novel adaptive non-conventional SMC regulator to fulfill the inequality constraints.
- The strategy constrains a subset of the robot pose coordinates by prudent reference values imposed by the handling operation, e.g., keeping the load at a desired orientation to prevent spill-offs or to reduce undue stresses that may compromise fragile items as in glass transportation.
- Given the multi-layered nature of the proposed strategy, remaining degrees of freedom in the robot pose are thus left to be guided by the human operator in a lower priority loop using a force sensor located at the robot tool to detect the operator's forces to accomplish the task safely and concurrently. Note that the proposed ASG algorithm is a key advantage in order to adapt the robot control to the changes on the forces exerted by the human operator to guide the robot.