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Research article

Human-robot cooperation for robust surface treatment using non-conventional sliding mode control

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ABSTRACT

This work presents a human-robot closely collaborative solution to cooperatively perform surface treatment tasks such as polishing, grinding, deburring, etc. The method considers two force sensors attached to the manipulator end-effector and tool: one sensor is used to properly accomplish the surface treatment task, while the second one is used by the operator to guide the robot tool. The proposed scheme is based on task priority and adaptive non-conventional sliding mode control. The applicability of the proposed approach is substantiated by experimental results using a redundant 7R manipulator: the Sawyer cobot.

1. Introduction

The automation of industrial processes has generated great improvements in terms of product quality, cost reduction and operator safety and comfort. However, there are currently many industrial processes that are carried out manually due to their complexity. Nowadays robotic manipulators cannot compete with the adaptability of humans and, hence, there is currently a strong tendency to combine robots and humans to collaboratively accomplish complex tasks.

In surface treatment operations the tool has to be in contact with the product surface to apply a specific treatment (polishing, deburring, grinding, etc.) and, hence, the forces exerted by the tool have to be properly controlled and it should be kept perpendicular to the surface to homogenize the pressure on all contact points [1]. Due to the complexity of the shape of the product surfaces, human operators have difficulties in maintaining a constant pressure and tool perpendicularity to the surface at all times. Moreover, when the product to be treated is part of a production line where it is in motion or its morphology is constantly changing, it is difficult for robots to carry out automatic treatment operations efficiently.

To mitigate the drawbacks of both, manual and robotic automatic surface treatment, this work proposes a human-robot closely collaborative solution which adopts the form of a human operator performing the task of “guiding” the tool along the object surface, whilst operating in synergy with a robotic manipulator in charge of automatically maintaining both the tool's pressure on the surface and the tool's perpendicularity to the surface, hence ensuring a flexible surface treatment. For this purpose, this work uses multi-task and a novel adaptive non-conventional sliding mode control (SMC). The SMC is used in this work to benefit from its inherent robustness [2] and low computational cost, i.e., only the first-order kinematics of the robot is required for the proposed approach, as detailed below.

Moreover, the proposed approach resorts to an arrangement with two force sensors to accomplish the collaborative operation: one sensor is used to properly accomplish the surface treatment task, i.e., to attain the desired pressure between the tool and the surface being treated as well as to keep the tool orientation perpendicular to the surface; while the second sensor is used by the operator to guide the robot tool along the surface to be treated. Note that the force sensor used to accomplish the surface treatment cannot be used simultaneously to guide the robot, since the forces exerted by the human operator would represent a disturbance in an underdetermined sensing system that would prevent the satisfactory accomplishment of the surface treatment task. This would be the case for instance should the operator exert a force in the direction away from the surface to be treated larger than the desired pressure for the treatment task. In this troubled scenario the robot would end up moving away from the object to be treated and contact would be lost.

Next, a literature review is presented about the main aspects concerning this work: automatic surface treatment, robot guidance and SMC techniques for robot force control and human-robot collaboration.

Many approaches can be found in literature tackling the problem of *automatic surface treatment* using robot manipulators with force

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feedback. For instance, in Ref. [1] an algorithm was proposed for planning the tool location together with a compliance force control. In Ref. [3] a method for maintaining a constant polishing pressure with a numerical control polishing system was proposed by controlling the force during the process. In Ref. [4] a dual position/force control loop based on fuzzy techniques was presented for robotic grinding applications. In Ref. [5] an analytically force overshoot-free approach based on impedance control was developed to perform force-tracking. In Ref. [6] a sensor-less force control technique was proposed for a parallel machine using the information about trajectories and forces applied by skilled workers.

The *motion guidance* for robot manipulators is typically obtained via a wrist-mounted force sensor which evaluates the forces exerted by the human operator. 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 [7,8]. Yet other variants and methods can be found in the literature. For instance, in Ref. [9] a force tracking method under the impedance control framework was extended to also account for uncertain human limb dynamics. In Ref. [10] a decision-and-control architecture was proposed for hand-arm systems with "soft robotics" capabilities via dedicated human-machine interfaces. In Ref. [11] 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.

Other approaches tackling the problems of robot force control and human-robot collaboration are based on *SMC techniques*. Concretely, in Ref. [12] SMC was used to suppress impact forces when contacting the environment and be able to continue with a stable robot motion. In Ref. [13] a hybrid position/force control scheme was proposed using first- and second-order SMC for position and force control, respectively. In Ref. [14] an impedance control structure was proposed for monitoring the contact force between the end-effector and the environment, and a model-free fuzzy SMC strategy was employed to design the position and force controllers. In Ref. [15], several methods were developed to control a prosthetic hand and the best results in terms of unwanted force overshoot were obtained using a SMC with force, position and velocity feedback. In Ref. [16] a non-singular terminal SMC was developed to ensure trajectory tracking precision for the case of a lower limb rehabilitation parallel robot. In Ref. [17] a proxy-based SMC was proposed to obtain effective tracking during normal operations for flexible joint manipulators working close to humans. In Ref. [18] a robust SMC was proposed that relied on basic information from the human subject to handle model uncertainties due to biomechanical variation of patients using an upper limb rehabilitation robot. An SMC consisting of a PID sliding surface and a fuzzy hitting control law was developed in Ref. [19] to guarantee robust tracking performance and reduce the chattering effect for a class of robot-assisted therapeutic exoskeleton. A fuzzy SMC was presented in Ref. [20] using a non-linear model for trajectory tracking of micro robots in the human vasculature system. Moreover, SMC has been 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 to avoid the use of expensive force sensors, e.g., see Ref. [21]. It is worth mentioning that, currently, SMC is being thoroughly used to control robot systems, see Refs. [22–25] among others.

Recently, a human-robot collaboration aimed at *manual* polishing operations was presented in Ref. [26]. In this application the robot holds the workpiece and the human operator is assumed equipped with an abrasive tool to perform the polishing operation. During this process the robot keeps the workpiece in a *fixed position*, whereas the operator can change its orientation by pushing the robot body, which is detected by a force sensor mounted at the robot wrist. Note that this "static" polishing application is substantially different from the cooperative solution proposed in this work for surface treatment, whereby the robot, not the operator, is in charge of applying the surface treatment with the tool, automatically maintaining both the desired pressure and the perpendicularity of the tool to the surface, whilst the operator's task is to guide the robot tool along the surface to be treated. One of the proposed method's primary virtues is the ability to treat large surfaces, e.g., polishing a car body section, for which the above work is not a fitting solution.

Furthermore, the proposed controller has several distinctive features that sets it apart from other works in the literature. In particular, the combination of two sensors attached to the manipulator end-effector with an adaptive non-conventional SMC framework is a key novelty of the proposal.

The paper is organized as follows: next section introduces some preliminaries, while Section 3 develops the required SMC theory. The proposed method for robotic surface treatment is presented in Section 4. A simulation is presented in Section 5 in order to evaluate the proposed non-conventional SMC and to compare several switching gain laws. The actual implementation of the proposed method is detailed in Section 6, while its effectiveness is substantiated by experimental results in Section 7 using a redundant 7R manipulator: the Rethink Sawyer cobot. Finally, conclusions are drawn in Section 8.

2. Preliminaries

Kinematics. The robot *pose* $\mathbf{p}$ depends on the robot *configuration* $\mathbf{q}$ as follows:

$$\mathbf{p} = \mathbf{l}(\mathbf{q}), \tag{1}$$

where $\mathbf{l}$ is the nonlinear kinematic function of the robot. The first- and second-order kinematics of the pose vector $\mathbf{p}$ result in:

$$\dot{\mathbf{p}} = \frac{\partial \mathbf{l}(\mathbf{q})}{\partial \mathbf{q}}\dot{\mathbf{q}} = \mathbf{J}\dot{\mathbf{q}} \tag{2}$$

$$\ddot{\mathbf{p}} = \mathbf{J}\ddot{\mathbf{q}} + \dot{\mathbf{J}}\dot{\mathbf{q}}, \tag{3}$$

where $\mathbf{J}$ is the Jacobian matrix of the robot.

Robot control. This work assumes the existence of a robot controller in charge of achieving a particular joint acceleration from the commanded vector $\ddot{\mathbf{q}}_c$, and that its dynamics is fast enough compared to that of $\ddot{\mathbf{q}}_c$. Hence, the relationship:

$$\ddot{\mathbf{q}} = \ddot{\mathbf{q}}_c + \mathbf{d}_c \tag{4}$$

holds approximately true, where $\mathbf{d}_c$ represents inaccuracies due to disturbances. Note that the *dynamic model* of the robot system should be taken into account to properly design the mentioned underlying joint controller.

Task-priority scheme. The task-priority strategy [27] allows to tackle several objectives simultaneously assigning an order of priority to each one. Let us consider M tasks which consist in calculating the commanded joint acceleration vector $\ddot{\mathbf{q}}_c$ to fulfill the following equality constraints:

$$\mathbf{A}_i\ddot{\mathbf{q}}_c = \mathbf{b}_i, \quad i = 1, \dots, M, \tag{5}$$

where matrix $\mathbf{A}_i$ and vector $\mathbf{b}_i$ of the ith task are assumed known and index i represents the priority order ($i = 1$ for highest priority). The solution $\ddot{\mathbf{q}}_{c,M}$ that hierarchically minimizes the error of equations in (6)