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Design and control of an end-effector for industrial finishing applications

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ABSTRACT

A strategy to improve industrial finishing applications using commercial robotic arms is presented in this paper. An end-effector is designed and prototyped as the mini manipulator, and is mounted at the end-point of a commercial robotic arm to form a macro-mini manipulator system. The developed end-effector has properties of fast response and high resolution in position control and force control. Position based force/impedance control algorithms of the end-effector are introduced, targeting on applications of polishing and deburring. Experiments are conducted by employing the integrated macro-mini manipulator system and the results are presented.

1. Introduction

Surface finishing, such as polishing and deburring, are common manufacturing processes used to achieve smooth surfaces or edges without significantly altering the profile of the workpieces [MFI, [28]]. Attempts have been made to study these processes which, for satisfactory results, require complex motion control of the polishing/deburring tool which is in continuous contact, and interacts strongly, with the workpiece [6,15,33]. Still mostly done manually by skilled operators, these processes are labor intensive, costly, have low-efficiency and are hazardous due to abrasive dust [22].

Recent years have seen a rapid increase in the number of robot manipulators being used in the manufacturing industry [7,37,39]. Although capable of highly accurate and repeatable motions and working tirelessly on 24/7 shifts [24], their current capabilities are such that they are invariably used for tasks where there is no or minimal contact between the tool (robot end-effector) and the workpiece. For a robot manipulator to perform satisfactorily tasks involving continuous and strong robot/environment interaction, it not only must have position/path control but also good force/compliance control. An external force applied on the end-effector may cause backlash, friction and nonlinear behavior in the manipulator's joints [3,44] and degrade positioning accuracy and control performance of the robot.

At present, only a very small percentage of commercially-available robotic manipulators are able to perform force-controlled tasks. Such robot manipulators usually adopt torque-based force control where the force/torque command is directly applied at the joint actuators [23]. Due to the geometrical structure and large masses of the serial-link industrial manipulator, this control method suffers limitations in bandwidth and stabilities [9]. Typical bandwidth for position control ranges from 10 Hz to 30 Hz [29,34] and for force control about one decade lower [23]. The low bandwidth and stability problems at the tool/workpiece interface resulted in degraded performance when applied for finishing operations where there is continuous contact and strong interaction between the tool and the workpiece [11,36]. In 2012, the International Federation of Robotics reported that only about 0.6% of robot manipulators are used to perform tasks such as polishing and deburring [IFR, [14]].

To improve position/force control bandwidth and accuracy of the robot manipulator, and thereby improve the performance for finishing operations, a macro-mini manipulator configuration has been proposed [36]. Macro-mini manipulator as well has advantages in force control at the end-effector. In general, two primary approaches are used in active force control of robot manipulators, namely, torque-based force control [16] and position-based force control [5]. The former directly applies force/torque command at the robot joint actuators and the latter measures the applied force and converts into position command and feeds into the inner position loop of the robot manipulator. As most of the industrial robots have closed architecture and only take position commands, and it is highly difficult to modify the robot controllers, implementing torque-based force control is not recommended in most of the cases. Whereas the macro-mini system provides possibilities of implementing force control of robot manipulators. With a force/torque sensor mounting on the mini manipulator, measured force readings (the outer force control loop) can be converted into position command and feed into the macro robot's controller (the inner position control loop).

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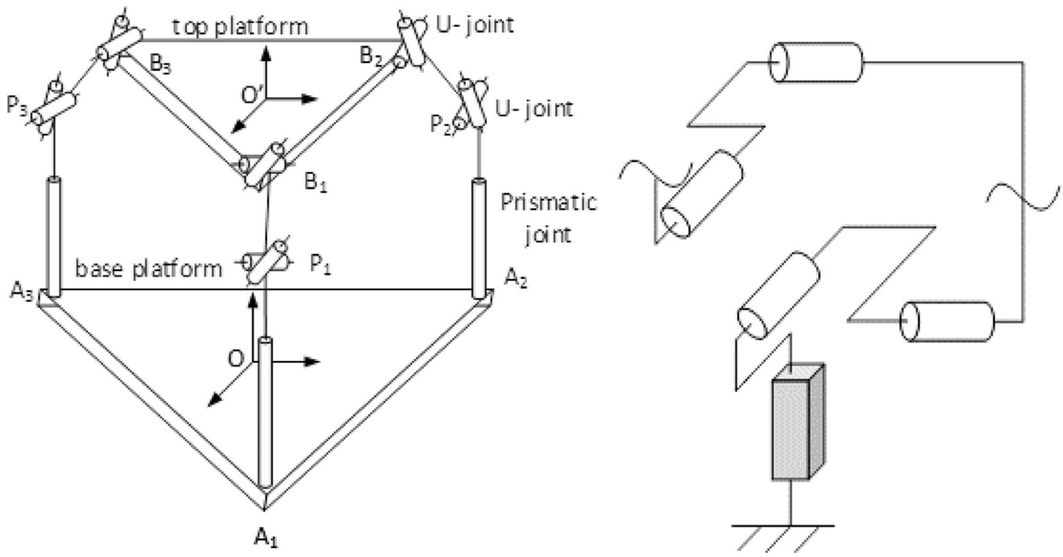

Fig. 1. (a) A 3-PUU Parallel mechanism; (b) one of the limbs of a 3-PUU parallel mechanism.

In addition, if the bandwidth of the inner position control loop is much faster than the outer force control loop, the system has a better performance in rejecting disturbance with larger magnitude compared with torque-based force control approach [4]. A macro-mini manipulator is expected to have a significantly higher bandwidth in position control due to the fast-response and low-inertial mini manipulator. The 6-DOF mini manipulator developed by University of Porto [22] is able to achieve a closed loop bandwidth of 63 Hz (400 rad/s) and the macro-mini manipulator system is shown to have a good position and force tracking performance through experiments.

The objective of our research is to develop an end-effector module as the “mini” in a macro-mini manipulator system for industrial finishing applications such as polishing and deburring. In order to be able to work on large workpieces, the end-effector is mounted in series at the end-point of a position controlled industrial robot. According to the nature of such applications, the end-effector is required to have an accurate and high bandwidth of position and force controlled performance. The controlled parameters, such as desired impedance and force, can be easily modified by users for different applications. Besides, the end-effector should as well fulfil some mechanical properties as a mini manipulator, such as compact in size and light in weight to reduce the effective inertia of the integrated system. In operation, the rough geometry information of the workpiece profile is acquired, and the “macro”, a commercial industrial robot, will follow the geometry under position control. The end-effector, or the mini manipulator, will adjust the overall position and force output of the robot system to achieve better controlled results. In addition, a communication between the end-effector and the macro robot is expected to be established for information exchange. This is to enable the cooperation between the two manipulators. Control methods for the macro-mini manipulator system is needed instead of controlling the macro and mini manipulator individually without putting them to work together as an integrated system.

In this paper, an integrated approach of robotic finishing is presented, which employs a macro-mini manipulator comprises of an industrial robotic arm (macro) and a 3-DOF end-effector module (mini). The mechanical design and basic control of the end-effector has been previously published in [24–26], and based on which, this paper extends the control strategy for the end-effector to achieve a significant improvement in hybrid force/position control performance. We evaluate the developed end-effector by conducting experiments including performing finishing processes on stainless steel workpieces sent in from industry.

This paper is organized as follows. Mechanical design of the end-effector is described in Section 2. Kinematic and workspace analysis of the end-effector is discussed, and a potential polishing/deburring tool is presented in this section as well. Section 3 presents the control of the end-effector. The end-effector is put under position control, impedance control and force control. A communication between the end-effector and the macro robot is established. A mid-ranging method to control the integrated macro-mini manipulator system is proposed in Section 4. In addition to the approach discussed by Schneider et al. [35], the model based mid-ranging control strategy is extended for decoupling the setpoint and the actual output [25]. Controlled performance of the end-effector through experiments is presented and discussed in Section 5. Finally, discussions are presented and conclusions are drawn in Sections 6 and 7.

2. The 3-DOF TPM mini manipulator

In this section, the design and kinematics of a 3-DOF translational parallel mechanism (TPM) to be used as the mini in a macro-mini manipulator system is presented. Important features required of a mini include being small and compact in size and having a high dynamic bandwidth and performance.

In polishing applications, the tool needs to constantly sustain large contact force which typically up to 100 N or more. To deal with such large external forces, a parallel mechanism is preferred with is high stiffness and low inertia [30].

2.1. Mechanical structure of the 3-DOF TPM

Based on feedback from users with experience in industrial polishing and deburring applications, a 3-DOF parallel mechanism with pure translational motions was chosen as the mechanical structure for the mini the end-effector module, as those processes require the tool to maintain a fixed orientation with respect to workpiece and a coupled translational and rotational motion is not desirable. This translational parallel mechanism (TPM) is based on a 3-PUU (Prismatic-Universal-Universal) mechanism as shown in Fig. 1, where the structure of the parallel mechanism is shown on the left and that for one of the individual limbs is shown on the right. The base top platforms are connected by three PUU limbs that are mounted 120° apart about the center.

Chebychev–Grübler–Kutzbach criterion [1] states that for a mechanism that has N links and j joints and with the ith joint having f_i,