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Cost-efficient drilling using industrial robots with high-bandwidth force feedback

Tomas Olsson [a,d,f], Mathias Haage [b], Henrik Kihlman [c,e], Rolf Johansson [a,*], Klas Nilsson [b], Anders Robertsson [a], Mats Björkman [c], Robert Isaksson [c], Gilbert Ossbahr [c], Torgny Brogårdh [d,f]

[a] Department of Automatic Control, Lund University, Box 118, SE-22100 Lund, Sweden
[b] Department of Computer Science, Lund University, SE-22363 Lund, Sweden
[c] Department of Management and Engineering, Linköping University, SE-58183 Linköping, Sweden
[d] ABB Robotics, Department RC, SE-72168 Västerås, Sweden
[e] DELFOi, Sofierogatan 3D, SE-41251 Göteborg, Sweden
[f] ABB Corporate Research, SE-72178 Västerås, Sweden

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ABSTRACT

Here we present a method for high-precision drilling using an industrial robot with high-bandwidth force feedback, which is used for building up pressure to clamp-up an end-effector to the work-piece surface prior to drilling. The focus is to eliminate the sliding movement (skating) of the end-effector during the clamp-up of the end-effector to the work-piece surface, an undesired effect that is due to the comparatively low mechanical stiffness of typical serial industrial robots. This compliance also makes the robot deflect due to the cutting forces, resulting in poor hole position accuracy and to some extent in poor hole quality. Recently, functionality for high-bandwidth force control has found its way into industrial robot control systems. This could potentially open up the possibility for robotic drilling systems with improved performance, using only standard systems without excessive extra hardware and calibration techniques. Instead of automation with expensive fixtures and precise machinery, our approach was to make use of standard low-cost robot equipment in combination with sensor feedback. The resulting sliding suppression control results in greatly improved hole positioning and quality. The conceptual idea behind the force control is useful also in many other robotic applications requiring external sensor feedback control.

1. Introduction

The traditional application areas for industrial robots involve highly repetitive operations such as spot welding. Hence, robotic development has been focused on high precision (repeatability) in repetitive operations. For example, a standard ABB IRB4400 robot for 60 kg payload has a repetitive accuracy of ±0.05 mm. If, however, the same robot is given a new coordinate that it has never visited before, the accuracy is in general around ±3 mm, which is 60 times the size of the repetitive accuracy. Today it is possible to buy the same robot with an option pack that includes calibration for high accuracy. This will improve accuracy to become within ±0.5 mm, which is still 10 times the repetitive accuracy. In addition, this accuracy is only guaranteed under the condition that no unmodeled external forces act on the robot, i.e., only during motion in free space. For contact tasks such as polishing, drilling, and riveting, the effects of the limited mechanical stiffness of the robot must be taken into account in order to maintain the positioning accuracy, which is not feasible unless a detailed model of the particular robot specimen is available.

Systems for automatic drilling have a long history both in industry and the research community. In particular, the use of industrial robots for drilling is interesting due to their flexible programming and the comparatively low cost of industrial robot systems. However, robot drilling is a very challenging task due to the comparatively low mechanical stiffness of the typical serial industrial robots in use today. In general, clamp-up is necessary in robotic drilling to avoid vibration during the drilling process as the drill tool generates vertical, horizontal and axial forces during the cutting process. The compliance makes the robot deflect, sometimes up to several millimeters, due to the externally applied forces during clamp-up and drilling. Due to the bending of the robot links and the elasticity in the gears, the local deflection at the contact point does not necessarily occur in the (axial) direction of the applied force, but may have tangential

* Corresponding author. Tel.: +46 462228791; fax: +46 46138118.
E-mail addresses: Tomas.x.Olsson@se.abb.com (T. Olsson), Mathias.Haage@cs.lth.se (M. Haage), Henrik.Kihlman@delfoi.com (H. Kihlman), Rolf.Johansson@control.lth.se (R. Johansson), Klas.Nilsson@cs.lth.se (K. Nilsson), Anders.Robertsson@control.lth.se (A. Robertsson), Mats.Bjorkman@liu.se (M. Björkman), Gilbert.Ossbahr@liu.se (G. Ossbahr), Torgny.Brogardh@se.abb.com (T. Brogårdh).

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components which are on the same order of magnitude as the axial deflection. This tangential deformation results in poor hole quality and inaccurate positioning. In contrast, aerospace tolerances require drilled holes to be accurate within ±0.2 mm [1].

As for a state-of-the-art comparison on robotic drilling and fastening, we refer to the recently reported robot capability test targeting applications in the aerospace industry with the test robots KUKA KR240, KUKA KR60, ABB IRB7600 and Stäubli RX170 [1]. In this study from Airbus UK, limitations related to static and dynamic deflection, repeatability, absolute accuracy, temperature error, and hysteresis were surveyed, the conclusion being that an absolute accuracy ±0.2 mm was not achievable. Using state-of-the-art anti-skating approaches, Atkinson and co-authors from Boeing-Hawker de Havilland concluded that absolute accuracy remained on the edge of acceptability for aircraft assembly [2].

A drilling process involves moving a drilling end-effector to the correct position of the hole. Prior to drilling, a pressure foot is used to press the parts together in order to avoid burrs entering in between the plates. In addition, the pressure foot assures that the drilling machine is kept stable throughout the drilling cycle. A self-feeding mechanism is normally used to feed the drill through the stack of materials. Automated drilling in the aerospace industry today uses large robots for two major purposes: to handle the large assemblies, and to accurately counter balance the drilling forces involved in the drilling process. There are many different ways to overcome forces in drilling and fastening using industrial robots. One approach is to divide the process in two steps, where in the first step the robot stiffness is mapped by applying forces to the robot TCP and measuring its deflection, while in the second step the robot is adjusted back to the nominal position under load. These compensation values are then applied as a filter to program the robot during process execution [3]. Mapping the robot stiffness in this way can, however, be extremely time consuming. Other methods to solve the skating problem have been tested by using metrology systems to supervise the robot, see for example [4,5,1,6]. In such methods, a metrology system is connected to the robot controller via an external feedback loop to update the nominal position of the robot with measurements in real time. However, using metrology is not a straightforward solution, as the robot will deflect as the pressure foot is engaged.

Common to the traditional approaches is the lack of high-performance sensor feedback to the robot, whereby the robot cannot be updated fast enough to cope with the dynamic process that drilling involve. Robot control systems are traditionally closed, a circumstance which has hampered system integration of manipulators, sensors and other equipment, and such system integration has often been made at an unsuitably high hierarchical level. As a more cost-effective solution, high-bandwidth feedback techniques can be used to control the properties of the drilling process. Research and development on force-controlled drilling has not received as much attention as many other applications of industrial force control, such as assembly, deburring, milling or polishing [7,8]. The reason is probably the difficulties involved in robotic drilling, and the lack of available industrial robot systems with capacity for high-bandwidth force control [9–11]. Some results on force control for special drilling machines have been reported in [12]. Experimental systems for force-controlled robot drilling have been presented in [13], where a force controller with inner position control was used for the drilling thrust force control, and in [14], where an application to bone drilling in orthopedic surgery was presented.

While there exist commercially available products for force control—e.g., from ABB Robotics [15]—none of the available packages include the particular features and/or level of flexibility required for the drilling application, i.e., the ability to redesign the inner-loop servo control for improved disturbance rejection.

1.1. Problem formulation

The purpose of this work is a fully developed industrial prototype of robotic drilling, based on the use of high-performance force/torque control and light-weight industrial robots. The idea presented in this paper is based on applying a dynamically controlled pressure against the work piece with a tripod attached to the drilling tool, while a self-feeding mechanism is used to feed the drill. This setup is as shown in Fig. 1. When used together with a metrology system for absolute accuracy in the initial positioning, the system should be able to satisfy the accuracy requirements of ±0.2 mm, even in the presence of external load during clamp-up or drilling. The method of dynamic sensor-controlled drilling represents a different approach compared to current static (and expensive) systems. The purpose of the force control is threefold: (i) to control the normality to the surface; (ii) to avoid the drilling end-effector sliding on the surface (skating) during the drilling and clamp-up phases; and (iii) to press the parts together so that burrs do not enter in between the plates. The control is accomplished by an open robot controller interface with a sampling rate of 250 Hz—see [7,17]. Further, the system allows for reuse of much of the existing safety and programming functionality of the robot system, with extensions made to allow flexible programming of sensor-based tasks. The off-line programming (OLP) environment DELMIA V5 Robotics was selected for simulation and planning of the drilling process, thereby simplifying robot programming. The robot hole-to-hole programming includes meta-data for the force control in pre-aligning the pressure foot. The force data are included in the robot program with our extension to the ABB Rapid program language called ExtRapid. The goal is to avoid additional force feedback programming after the OLP in DELMIA.

2. System topology

The robot system includes a robot with its controller, two computers and a force/torque sensor. The solution presented in

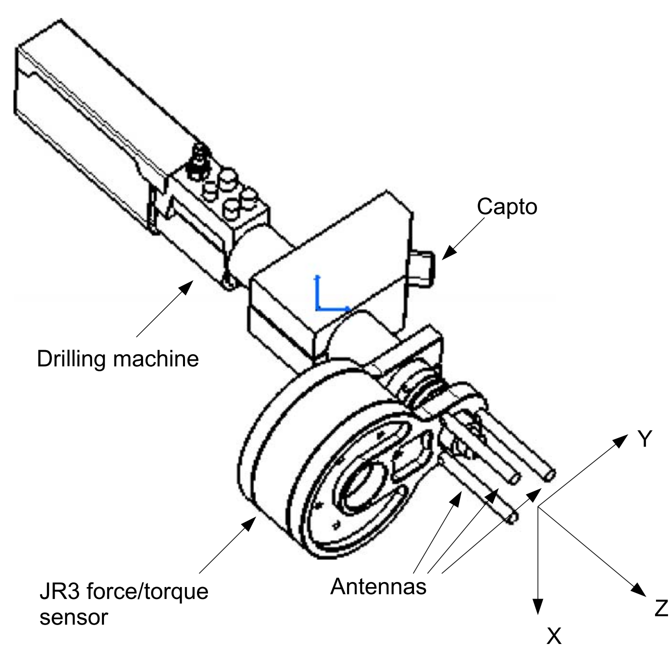

Fig. 1. Overview of the end-effector prototype for the drilling experiments.