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Hard material small-batch industrial machining robot

Alberto Brunete^{a,*}, Ernesto Gambao^a, Jukka Koskinen^b, Tapio Heikkilä^b, Knut Berg Kaldestad^c, Ilya Tyapin^c, Geir Hovland^c, Dragoljub Surdilovic^d, Miguel Hernando^a, Aldo Bottero^e, Stefan Anton^f

^a Centre for Automation and Robotics (CAR UPM-CSIC), Universidad Politecnica de Madrid, Spain

^b VTT - Technical Research Centre of Finland Ltd, Oulu, Finland

^c Faculty of Engineering and Science, University of Agder, Grimstad, Norway

^d Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik IPK, Berlin, Germany

^e Comau s.p.a., Robotics and Automation Products, Italy

^f EasyRob, Germany

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ABSTRACT

Hard materials can be cost effectively machined with standard industrial robots by enhancing current state-of-the-art technologies. It is demonstrated that even hard metals with specific robotics-optimised novel hard-metal tools can be machined by standard industrial robots with an improved position-control approach and enhanced compliance-control functions. It also shows that the novel strategies to compensate for elastic robot errors, based on models and advanced control, as well as the utilisation of new affordable sensors and human-machine interfaces, can considerably improve the robot performance and applicability of robots in machining tasks. In conjunction with the development of safe robots for human-robot collaboration and cooperation, the results of this paper provide a solid background for establishing industrial robots for industrial-machining applications in both small- and medium-size enterprises and large industry. The planned short-term and long-term exploitation of the results should significantly increase the future robot usage in the machining operations.

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1. Introduction

Hard-materials machining has attracted a large amount of attention from advanced industries, in particular, European automotive, aerospace and biomedical industries. However, existing technology has failed to provide these industries with a cost-efficient solution to accommodate small-batch production of large and complex-shaped products.

Until now, only about 3% of overall industrial robots employed in industry are used for machining. This is quite in opposition to the market potential and benefits of industrial-robot-machining applications. It has been widely recognised that inherent 5+ axis machining capability combined with flexibility, large-work envelope and multiple-station capability is a flexible solution that allows users to expand the range of machining applications at a price point competitive to that of employing a traditional CNC (Computer Numeric Control) machine. With the recent dynamic-cost reduction and performance optimisation of modern industrial robots, the price of a comparable robotic solution is typically 1/5–1/3 of the cost of a CNC machine. Integration of two or more robots into flexible multi-stationed and multi-tooled robotic machining

cells may result in significantly lower-cost investments in comparison to employing large-CNC machines.

Based on several studies [1,2], the two underlying technical limitations for the widespread adoption of robotic machining are the insufficient robustness of robotic structures (insufficient precision and stiffness) and lack of efficient programming tools that transfer CAD (Computer-aided design) models into robot motion. Regarding the former, the material removal is one of the least-utilized fields of application within industrial robotics [3]. Waterjet and laser-cutting are commonly robotically controlled, as well as robotic milling of softer materials (wood, urethane, sand-stone, aluminium or cast iron), but not hard materials. Insufficient robot stiffness (approximately up to 100 times less than CNC machines) is commonly identified in the industry as a limiting factor for robot machining of hard materials.

The European project Hephestos, with its focus on developing sophisticated methods in robotic manufacturing, has produced a cost-efficient solution in hard-materials machining for small-batch production of highly customised products through the application of industrial robots. The two main limitations explained previously have been ad-

* Corresponding author.

E-mail addresses: alberto.brunete@upm.es (A. Brunete), ernesto.gambao@upm.es (E. Gambao).

URL: <http://www.hephestosproject.eu/> (E. Gambao)

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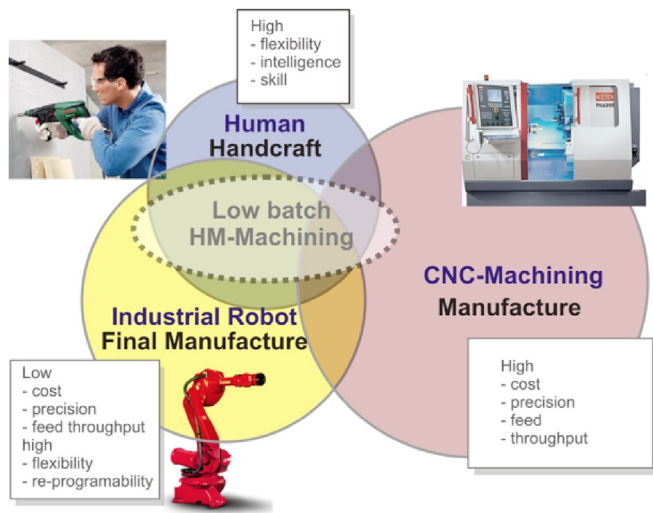


Fig. 1. Shared machining applications and robot-technology positioning.

dressed in Hephestos providing applicable results and a relevant step-change towards industrial applications.

Hephestos has developed a paradigm that shall provide standard industrial robots with break-through techniques in production planning, programming and real-time control systems. Based on established computer-aided-manufacturing frameworks, Hephestos has optimised production planning through the automatic generation of robotic programmes, while considering specific robot signatures, i.e. robot system kinematic and dynamic characteristics, as well as models of processes (e.g. milling, grinding, and polishing), that are essential for the robotic application in hard-material machining. To accommodate small-batch production time scales, real-system data obtained by means of advanced sensor techniques have also been integrated in the planning to improve efficiency.

Human experience and expertise have also been involved in the planning process. For example, real-time strategies based on impedance and force control for the interactions between robot and the cutting of material, which accommodate uncertainties and critical contact effects in hard-metal machining, and various force/impedance machining-control algorithms contribute to confirm high quality and precision in grinding and polishing operations and considerably extend the accuracy limits of the robot. Subsequent re-planning and re-programming also enhance the iterative-machining process through existing sensor technology.

Through this paradigm, Hephestos has combined robotic advantages with the flexibility of human-like strategies of dextrous artisans and workmen to develop a plug-and-play flexible robotic-machining system. In addition, Hephestos has demonstrated benefits of utilisation of flexible and truly open robot control and planning platforms.

The aim of Hephestos is not to compete with or replace general CNC technologies by robots, rather its goal is to identify and demonstrate the position, performance and benefits (Fig. 1) of robot-hard-material machining in the boundary processes shared by manual-work and CNC technology. The focus is on releasing the human-hard work in small-batch machining activities by partial automations using industrial robots, especially by sharing models based on human-robot collaboration and cooperation.

The key innovations of Hephestos, presented in Section 3, improve industrial-robots technology in hard-material machining and establish cost-efficient robotic applications in industry that are of considerable commercial benefits for the European-machining sectors; in addition, they are pertinent and affordable to both small-and-medium enterprises and large-scale producers.

2. State of the art

During the last years, a significant effort has been addressed to solve the mentioned difficulties to apply robots for hard materials machining. Both, the robotic industry and the academic research, have recently proposed different approaches.

To cope with the stiffness and precision barriers for the hard materials robotic machining, the robotic industry has recently adopted several strategies to improve robot structural performance. The parallel link robots (e.g. Fanuc F-200iB) provide substantially more rigidity, however, at considerably smaller work envelopes. Applying closed kinematic chains along serial robotic structures represents a further step to stiffer robot mechanical structures. Almost each robot producer offers recently special robot for pre-machining (e.g. ABB-IRB 6660, KUKA KR-500MT, etc.). Stäubli offers high speed machining robots (HSM) with a Fisher-Precise high speed spindle integrated directly into forearm.

Refining the robot accuracy represents another robot builders approach towards high precision robots. The adopted strategies include calibration, position mastering, and even the usage of new encoder technology in each joint at output shafts to compensate for inaccuracies in the transmission chain. Achievable accuracy is sufficient for some high-precision operations (e.g. drilling and routing in the aerospace industry), but still insufficient for the precision machining. Moreover, all specific robotic systems are considerably more expensive in comparison to standard industrial robots.

To manage the lack of standardized robot programming, in a way that is comparable with the standardization in the CNC world, the robot producers offer recently a wide range of software solutions (e.g. KUKA CAMRob, Motoman standard CNC G-Code Converter, FANUC-Roboguide, etc.) to transfer CAD/CAM generated CNC codes in proprietary robot programs. By this means users can greatly reduce programming time and costs required for programming complex objects shapes. Several SW companies offer specific robot programming add-ons to CAD/CAM tools, such as Robotmaster (Jabez Technologies), Power-Mill (Dellcam), IRBCAM, etc.

However, despite these developments and improvements, hard material robotic machining with conventional robots and control approaches remains so far a challenging problem, especially for small-batch production of complex parts. During hard-material cutting, the position deviations and tool chattering effects result in a not satisfactory quality of the milling surfaces. The finishing of surfaces by using grinding tools to improve the manufacturing quality requires even higher positioning accuracy, which is beyond robot position servo limits.

From academic research, current efforts mainly handle the mentioned practical problems, addressing different integrated approaches based on robot signatures, simulation of the robotic systems and cutting process, various advanced robot control algorithms, as well as high-tech solutions based robot-dynamic motion tracking and real-time correction of the robot poses and high-dynamic compensation on the tools [4–10,12,13].

The integrated machining cell design in conjunction with modular reconfigurable design, robot specific planning that considers real motion limitations and performance, efficient cell alignment methods have been proven in [5] as an competent framework to improve feasibility of the robot machining process.

Compensation for robot positioning errors due to dominant elastic deformation in joints (transmission mechanisms) represents a challenging issue. An off-line model-based approach to predict, analyze and compensate for the elastic robot deformation under cutting process forces in milling applications has been presented in [6]. The real-time control compensation of quasi-static elastic deformations in robot transmissions using force sensing and deviations computations, based on joint elasticity models and Cartesian deformation mapping, has been recently proposed in [7,8]. In the initial experiments the improvement of the milling path roughness accuracy up to 50% was demonstrated.

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