Integrated Design of Robotic Workcells for High Quality Machining

A.O. Andrisano (a), F. Leali (a), M. Pellicciani (a), F. Pini (a), A. Vergnano (a)

(a) Department of Mechanical and Civil Engineering – University of Modena and Reggio Emilia (Italy)

Abstract

Purpose:
Robotic workcells provide high flexibility and reconfigurability, cost effectiveness and user friendly programming for many industrial applications but still lack in accuracy, so important fields of application such as mechanical machining are currently covered by very expensive and rigid systems (machining centers). The present work investigates the possibility to extend the use of industrial robots to perform high quality machining.

Method:
The proposed method is focused on the enhancement of robotic machining accuracy through an integrated design method, based on robotic process simulation and tailored design of mechanical apparatus and software modules for robot control and programming. Advanced techniques for machining strategy validation, automatic robot path generation, workcell calibration, robot code commissioning are concurrently adopted.

Result:
Integrated design tools are fully exploited to define the system behavior, to simulate the whole process, to propose alternative machining set-ups and quickly generate and test parametric programs. The design method is finally applied to design a robotic workcell family for grinding special austenitic manganese steel castings, characterized by severe working conditions as high tool wear, high cutting forces, high vibrations due to surface hardness and non-repetitive shape variations in geometry and features.

Discussion & Conclusion:
Experimental results demonstrate enhanced performance of robotic workcells and final quality, due to minimization of tool vibration, increasing of robot stiffness and higher manufacturing flexibility, thanks to the capability of adapting robot paths to workpieces.

1 Introduction

Industrial robotics represents a key technology for flexible and reconfigurable manufacturing systems and is widely adopted to perform several industrial tasks e.g. material handling, welding, assembly, spray painting or glazing, and machine tending [1].

However, just 3%÷4% of the overall number of industrial robots is employed for mechanical machining [2]. Such field of application is traditionally covered by very expensive and rigid systems as machining centers.

With respect to such manufacturing technologies, industrial robots provide superior dexterity, higher flexibility and reconfigurability and better cost effectiveness but still lack in absolute accuracy and mechanical stiffness [3], [4].

Nowadays, thanks to robust mechanical design methods, advanced controllers, novel simulation technologies, industrial robots offer enhanced performance to quickly bridge the gap against state-of-the-art tool machines, for an effective use in machining.

Machining operations realized by robots can be subdivided, according to scientific literature and industrial standards, in Robotic Finishing and Robotic Machining [2], [5].

In Robotic Finishing robot paths are generally complex and composed by a huge number of target points while speed data are average higher than in Robotic Machining. Contact forces are typically low, so force feedback and tool adaptive control strategies can be chosen to obtain a good quality for surface finishing. Typical examples are: brushing, polishing, de-burring, and de-flashing. Conventional robotic systems are widely used in such applications [6].

In Robotic Machining, on the other hand, typically robot paths are geometrically simple, formed by polylines, arcs, circles and splines as in traditional CNC machining. Speed data are lower than in finishing but contact forces are very high. Low pose accuracy, poor configuration-depending robot stiffness and need for tailored programming strategies are the most important limiting factors for the wide adoption of Robotic Machining in Industry.

Current researches are focusing on different integrated approaches based on robot signatures, robotic machining simulation, robot optic tracking and real-time correction of the end-effector pose, and high dynamic compensation on tools [7]. Such technologies are under investigation and
their development and enabling application in Industry are ambitious goals for engineering researchers.

The present research work is focused on integrating advanced approaches and technologies to develop a novel engineering method for designing robotic machining workcells with enhanced performance. No additional hardware or external devices are adopted, for a quick, cheap and effective technological transfer to Industry.

The method is based on robotic process simulation, tailored design of mechanical apparatus and software modules for robot control, robot code programming and commissioning, and workcell on-line alignment.

1.1 Robot accuracy in machining

Many factors have to be concurrently investigated for enhancing industrial robot positional performance and for extending robot field of application to high quality machining.

Positional performance can be evaluated in terms of resolution, repeatability and accuracy.

Resolution is defined as the smallest incremental robot physical movement.

Repeatability is the measure of the robot ability to move back to the same target position with the same orientation.

Accuracy is defined as the ability of the robot to reach a target position within the 3D space; accuracy can be also divided in absolute accuracy, i.e. the ability to exactly reach a target point in 3D space, and dynamic accuracy, i.e. the ability to follow a path without significant deviations [8].

The most important values used to represent precision performance of manipulators, as specified in the international standard ISO 9283 which sets the performance criteria of industrial manipulators, are pose repeatability and pose accuracy [9]. Current values for industrial robots are repeatability equal to 0,06mm and absolute accuracy equal to ±0,1+0,2mm after calibration [10].

Structural, kinematic and dynamic performance of robotic arms represent the major contributions to the calculation of pose accuracy and repeatability in industrial robots [8].

Robot position and configuration depend both on mechanical and control factors.

Manufacturing and assembly tolerances on robot links introduce variations in their dimensions while the robot controller, set with nominal values, cannot consider the singular difference from one robot to the next.

Other typical mechanical errors, affecting the robot kinematic and dynamic behaviour, are backlashes on gear and belt transmissions, friction on harmonic drives and bearings, and the intrinsic low stiffness, around 1N/mm, of the robotic mechanical chain with respect to conventional tool machines, which have stiffness greater than 50N/mm [2].

Moreover, the difference between the physical joint zero configuration set in the robot controller and the actual joint zero configuration represents another importance source of uncertainty for the definition of an accurate robot pose.

Dynamic errors mainly depend on servo system accuracy, encoder resolution, system inertia and friction, so the robot controller is finally responsible for the trajectory deviation from the nominal value, also due to physical loads acting on the robots (payload, gravity, etc.).

State-of-the-art calibration techniques generally reduce the positional error in robotic applications. A real example of the achieved accuracy after calibration of a 159Kg payload industrial robot manipulator holding full load is: pose accuracy before calibration 3,25mm and 5,43mrad, after complete calibration, 0,29mm and 0,35mrad [9].

In Robotic Machining other source of errors have to be considered, as shown in Fig.1.

Fig. 1 Accuracy in robotic machining.

Robot target points definition, teaching and code generation represent some of the most challenging tasks in robotic machining. A robot machine language, equivalent, for instance, to tool machine ISO G-code, has not been standardized so manual programming is widely diffused, even when a huge number of target points has to be generated. Robot offline programming software arranged with specific machining functions or packages are currently offered by several robot manufactures (e.g. ABB, Fanuc, Motoman, KUKA) to help users. Offline programming (OLP) requires skilled users both in manufacturing engineering and robot programming even if virtual controllers guarantee full correspondence to real robot controllers.

Alignment procedures have to be developed to bridge the gap between robot simulation and real robot behaviour. Robot code has to be finally designed and generate to be modular and easy to (re)use.

Machining strategies have to be optimized to achieve an optimal final quality and saving manufacturing time and costs.

During machining, contact forces between tools and workpieces for both part-in-hand and tool-in-hand robot configurations influence machining quality in terms of accuracy and conformity to geometric dimensions and tolerances. Tools, spindles and machining units have to be carefully selected or designed to offer the optimal dynamic response. Tool dynamic behaviour has to be investigated to minimize robot chattering and robot structure deformation.

Moreover machining parameters have to be carefully chosen [11].

Design of auxiliary equipment is another important factor for achieving high quality machining. Modularity and reconfigurability represent key requirements in robotic workcell design, due to the importance of tailoring the robotic machining approach for each workpiece, generally subjected to geometric and dimensional variability or positioning errors. Devices for tool wear control and part alignment need to be also developed to assure exact reference workframes for high quality machining.

Environmental factors, as temperature variation, cooling and working conditions (swarf and dust aspiration

June 15th – 17th, 2011, Venice, Italy

317 Proceeding of IMProVe 2011
and collection, etc.), are very important to minimize errors during machining [12].

2 Integrated design method

Robotic high quality machining deals with several design factors. Workcell reconfigurability is one of the most important goals to achieve during integrated design because of its deep impact on industry, characterized by a high frequency of changeability on product batches and by the need of saving time and costs without lowering the final quality [13], [14].

Hardware, control and software resources are then concurrently developed to offer high mechatronic performances, tailored for each workpiece or product family [15].

The workcell functional structure and layout design are evaluated starting from the machining cycle, grouping main and auxiliary equipment according to the related process. So workcell configuration results deeply process-dependent, as proposed in Fig. 2.

![Fig. 2 Process-dependent workcell configuration.](image_url)

Integrated design of robotic workcells involves the close integration of different CAE techniques and tools. Offline programming software and CAD need to be effectively integrated in order to obtain a good trade-off between the graphical completeness of simulations and the time needed to generate virtual tests.

Two main approaches can be followed. The first one is based on the use of general purpose software platforms, customized by specific plug-ins oriented to the execution of machining applications. Commercial exemplars are DELMIA Robotics or UGS Tecnomatix. Such tools entail deep knowledge and skilled users because of their complex and articulated structure, so the training is heavy and time consuming. The possible lack of integration between virtual controllers, based on RSS algorithms, and real robot controllers could affect the robotic machining accuracy.

The second approach deals with the use of proprietary offline programming software, developed by robot manufacturers to generate a virtual copy of the robot controller so that full compatibility is guaranteed. Such tools are generally easier to use than software platforms and offer a superior integration with the robotic process. On the other hand, users need a good experience in robot programming to really exploit their potentialities.

The developed integrated design approach is focused on solving three main issues:

1) definition of a common reference reconfigurable workcell structure;
2) definition of the end-user working procedure for the introduction of new batches;
3) definition of part-dependent hardware apparatus and software code.

In the first phase, the functional structure of the workcell is defined and its general layout is roughly modelled by 3D CAD tools.

In the second phase, the method requires the definition of the end-user procedure for robot programming and workcell reconfiguration for every new workpiece. OLP software need to be adopted for evaluating robot reachability, detecting possible collisions and robot singularities. Moreover, cycle time estimation can be performed for cost calculation and process balancing. The number of target points which compose each machining path has to be calculated to respect cycle time, machining tolerances and communication limits given by the robot controller, so several iterative tests are needed to find a good compromise.

For the definition of part-dependent hardware apparatus and software code OLP software functions were exploited to reproduce the same nested architecture of the real workcell in the 3D CAD system. Furthermore, thanks to the software capability in associating the OLP and 3D CAD environments, 3D models are kept updated, so alternative machining configurations can be tested, in order to evaluate different tools, strategies or even to verify the process in different tool wear conditions.

2.1 Alignment of the reference frames

Workcell alignment covers a fundamental importance in robotic high quality machining. Such phase consists in the accurate alignment between the virtual and the real robot reference frames which define the position of every target point with respect to the robot world reference system.

The most important frames in robot machining are tool frames, defining the real position of tools, and workpiece frames, defining the real position of the workpiece.

Alignment is generally performed though a manual procedures which involves the manual displacement and measure of the robot end-effector poses for given target points. Vision systems and sensors are used to enhance the accuracy and automate the alignment procedure. Moreover, on-line alignment is required to periodically adjust reference frame position, to consider the progressive wear of machining tools and the possible variation in the workpiece geometry, due to successive passes of the tools. On-line alignment represent the key factor in robotic high quality machining, so particular attention has been paid in developing a novel flexible and reconfigurable integrated procedure.

3 Experimental validation

The proposed method was adopted to design robotic workcells for machining and finishing operations on cast parts made of special steel in harsh working conditions and under a high final quality demand. In such kind of applications, pre-machining operations represent an important part of the overall production cost [2].
Workpieces, also named hammers, are consumable components for crushing machines and are used to smash inert for infrastructure and civil buildings or for recycling purposes. To increase their life cycle in such heavy working conditions, hammers are made of a special metal alloy, with high wear resistance, known as Hadfield steel. This alloy steel has an austenitic structure with about 13% manganese. It provides high impact strength and resistance to abrasion, with hardness in the range 500-700HV [16]. Figure 3 illustrates some cast parts used in smashing machines and propose their manual machining. The hammer is the part positioned in the middle upper part of the figure.

Today, industrial robot manufacturers produce 6-axes robots capable of performing machining, thanks to their stiff structure and robust components. Also industrial robot payloads are increasing, up to value of 1200kg. In the present case-study the workcell is equipped with a M-900iA/600 FANUC robot with 600kg payload (Fig. 5), performing machining through a part-in-hand strategy.

Due to the complex shapes and the high material strength, hammer machining (face milling) is usually manually performed but working conditions are particularly heavy and safety is not guaranteed because of hot and dangerous sparks, fine metal powders, heavy and bulky tools, repetitive movements, considerable reaction forces and heavy weights which also hamper to achieve a good and constant quality on workpieces. Robotic machining guarantees labour wellness and cost effective production, thanks to the robot flexibility and small ratio between cost and work volume [2], [5] but the heavy weight of hammers, up to 130Kg, and the high material hardness, represent difficult challenges also for heavy industrial robots. In add, the payload limits require a very careful robot selection.

The definition of the reconfigurable workcell reference structure was performed by 3D CAD Solidworks®. Thanks to such approach, it was also possible to easily define different workcells as configuration variants. Each configuration could be automatically selected according to the workcell designer needs.

The definition of the end user working procedure for the introduction of new batches was a complex task. In order to directly program the robot and analyze its behaviour, the proprietary OLP software FANUC Roboguide® with base package Handling Tool was adopted. Within the Roboguide® environment it was possible to evaluate several specific solution for robotic machining, such as properly sized fingers of the gripper and jigs, with respect to the position and geometry of features to be machined, and also to evaluate the system layout to avoid collisions and robot singularities during the process. OLP Roboguide® software and Solidworks® were finally associated to automatically exchange CAD data (Fig. 6).
The definition of part-dependent hardware apparatus and software code, of primary importance, was obtained developing an original strategy aimed to solve accuracy problems in robotic machining. The programming strategy and the robot reference frames alignment were mainly investigated to enhance robotic machining accuracy without adding external hardware or tailored mechatronic devices.

Special strategies for offline programming and alignment operation were developed. The manual robot teaching strategy commonly adopted in Industry for hammers is a fast method but did not reach the required tolerance and cannot guarantee the quality steadiness. Such limits were overcome thanks to the OLP, through the definition of target points disposed on the theoretical final surface of the model with mathematical precision, the experimental analysis of velocities and accelerations, the minimization of the robot chattering and the development of an original on-line alignment strategy.

Due to the high mechanical properties of the material, special attention was paid to the definition of the machining strategy. A modular and parametric software routine was developed to manage the iteration of the paths in function of the cutting depth and of the deviation of workpiece shape by the ideal CAD geometry.

Machining parameters, e.g. robot acceleration and velocity, were also considered in order to find the best trade-off between final quality and cycle time. Fig. 7 shows the software interface adopted to optimize the robot behavior.

Several contact sensors arranged inside the workcell performed the workpiece measurement in specific control points, while a software procedure received and processed the point data to detect the flatness error on the surface. The error value was used to adaptively define the number of the path reiterations.

Software and hardware solution were integrated to finally solve the on-line alignment issue. The sensor-based measuring system was also adopted to perform the part frame alignment. As in tool machining a preliminary definition of workpiece alignment was performed through a tailored fixture, in order to execute the first machining operation for the creation of reference planes. Then the on-line alignment procedure was performed starting from the measure of the workpieces and the identification of the surface shapes.

The same approach was proposed to define the tool frames positions. The tool units were equipped with laser sensors for non contact measuring, so it was possible to perform the tool presetting and also measure the tool wear, without spindle rest or speed reduction. Figure 8 presents the original integrated on-line procedure.

Thanks to the method proposed the part quality was significantly enhanced with respect to the manual machining: the measured value of the planarity was between 0.3mm and 0.8mm. Compared to the manual process, the robot machining was a slower process, taking 10 minutes instead of 8 minutes, but the final quality was greater and more constant. Moreover, thanks to the OLP approach, the workcell reconfiguration at the batch change required only the 20% of the time needed to manually teach a new robot program of complex workpieces.

4 Discussion and Conclusion

The present research work proposes an original integrated design method for robotic machining workcells. The overall workcell design process results efficient and enables a fast system reconfiguration, guaranteeing workcell safety and reliability. The integration of different techniques exploits both the potentialities of robot off-line programming and 3D
CAD/CAE simulation, allowing the evaluation of alternative design solutions and working scenarios, to deliver an optimized system with enhanced machining accuracy, even without external devices and expensive advanced technologies.

Due to the importance of the robot workcell alignment for high quality machining, great attention has been paid to defining on-line software procedures applied to tailored robot measuring system for an effective use of OLP to reach the tolerance conformity and the final quality.

The method has been successfully followed in a real case-study, characterized by heavy machining conditions due to hard material, big dimensions and weight. The present case-study represents one of the first robotic high quality machining applications in Italy.

The ongoing research work will investigate engineering methods and techniques to further enhance robot accuracy in machining. The next goal is to make this technology suitable for other application fields, like machining operation for automotive, aerospace or for other cast parts with even smaller geometrical and shape tolerances.

Acknowledgement

The authors want to express their gratitude to L. Passoni, L. Ferrari and D. Passoni, from SIR S.p.A. (Modena, Italy), for their technical and managerial contribution to the project, and FAR S.p.A. (Udine, Italy) for supporting the experimental tests.

The research work has been realized with the sustain of the "Interdepartmental Centre for Applied Research and Services in the Field of Advanced Mechanics and Engine Design - INTERMECH-MO.RE.", supported by the European funds POR FESR 2007-2013 for the Emilia-Romagna region.

References