Robotic machining: Status, challenges and future trends

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***Abstract*— Robotic machining is considered a viable replacement for large, fixed single-process machines like computer numerical control (CNC) machining and drilling units. Robotic machining is attracting intensive research interests in recent years due to its high efficiency, flexibility, and low cost. However, its industrial adoption is still extremely limited. This paper systematically reviewed the status of major robotic machining processes, including milling, drilling, polishing, and finishing. The key focus was to identify the challenges of robotics machining that derive from low stiffness, poor positional accuracy, and current approaches to over these challenges. The paper concluded with future research trends and the potential of robotic machining.**

Keywords*— *Robotic Machining; Error compensation; Stiffness

I. INTRODUCTION

Robotics and Automation are important industrial digitalization technologies for developing smart and flexible manufacturing capabilities in smart manufacturing. According to the International Federation of Robotics 384,000, robots were implemented in 2020 and are estimated to increase steadily above 500,000 by 2024 [1]. These robots have been used for picking and placing, assembly, palletizing, material handling, and many other applications. Although only 1.4% of industrial robots (IRs) were used for machining -mechanical cutting, deburring, milling, and polishing, robotic machining is a growing field. From an academic point of view, scholars have been interested in IRs as they are cheap, flexible, mechanical machines that are reprogrammable [2]. They are applicable in a range of industries that require repetitive, dangerous, or adaptable manufacturing processes. and attracting researchers to study the field has resulted in a yearly increase in journal papers as shown in Fig 1. The terms "Robotic/Robot machining" were searched on Elsevier's ScienceDirect in the "Title, abstract or author-specified keywords" box. All documents with the mentioned phrases in the title between 2010 and 2022 have been considered.

Moreover, there have been a few prominent projects; HEPHESTOS [3], [4] which aimed to cut harder materials through robot programming and real-time control system, and COMET [5], [6] used increased real-time positional accuracy, improve programming and simulations to ensure first-time accuracy and real-time reactions to in-process changes both projects funded by the EU.

This paper will perform a systematic review of robotic machining by looking at its status - what is achievable and what is out of reach-, the challenges that are currently being faced by scholars and the future objectives, where robotic machining going and what must be achieved to reach key industries. In the first section, this paper will look at the status of robotic machining in terms of robotic milling, grinding, drilling, polishing, and finishing, a dive into the potential applications and benefits of each process. The second section will investigate the challenges that derive from the low stiffness found in robots that require extra attention to make robotic machining tangible for high-precision applications. The final stage will look at the future trends that should be improved to enhance robotic machining.

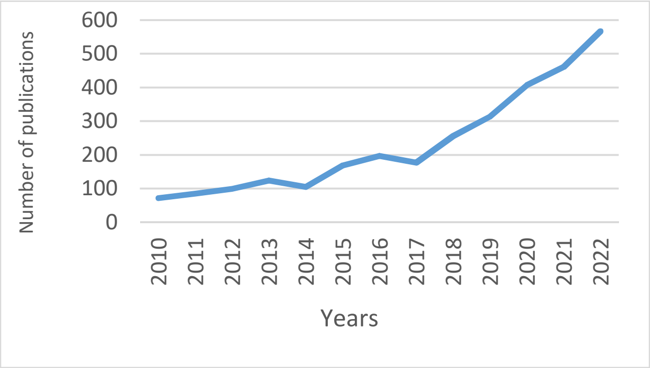

Figure 1 Robotic machining publications from 2010 to 2022 according to Elsevier, ScienceDirect.

II. STATUS

Robotic machining can be classified into robotic milling, grinding, drilling, polishing, and finishing. Table 1 summarizes their current application, work materials, and attainable accuracy. There has been a lack of integration into the industry due to the limited machining accuracy [7].

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Table 1 Robotic machining and its process capabilities. Milling [8], [9], Drilling [10], [11], Grinding [12], [13], [14] and Polishing [15], [16].

	Milling	Drilling	Grinding	Polishing
Current application	Aerospace, Automotive, Marine, High performance, Energy	Aerospace, Marine, Energy, High performance	Aerospace, energy, automobile, and rail transit industries	Die, Aerospace, Automotive,
Workpiece	Aluminium, CFRP, Steel	Aluminium, CFRP, Titanium, Steel	Aluminium, Inconel, Steel	Aluminium, Steel, Inconel
Accuracy (µm)	100-400.	60-400.	5-60.	<10

A. *Robotic milling*

Robotic milling has potential applications in wind power, aerospace, automobiles, and other high-end industries. Wang, et al, [17] describe the wide application of IRs as an “inevitable trend”. Robotic milling is compared to CNC as Robotic machining outperforms CNC machine tools in several distinct aspects however the low stiffness and low frequency are hindering the use and promotion of IRs in milling [17]. IRs low stiffness, posture-dependent characteristics, and various configuration changes result in poor efficiency, accuracy, and consistency. Despite these disadvantages, there are some huge benefits like the high adaptability of robots to new processes, flexibility due to the large work envelope and low initial investment compared to CNC machines. Zhu, et al, [18] have identified compensation, chatter, robot stiffness, machining dynamics, and posture as the biggest challenges within robotic machining. A typical Robotic milling work cell can be seen in Figure 2 ‘A’ [9].

Klimchik, et al, [19] developed an error compensation method that helped to create a machining accuracy on a KR270, 0.06mm of deviation at 100N of force this is better than the KR360 which gives 0.07 machining accuracy at 100N. The gap is exceptionally low however increases at 2000N to 1.17mm on the KR270 and 1.42mm on the KR360. Looking at the circularity maps the KR270 has a smaller ρmin 0.84mm whereas KR270 is 1.02mm this is like the KR100 which has a ρmin of 1.03mm and has comparable results at 100-1000N of force. This data was generated from milling 60mm circular groves on numerous different workpiece locations and various cutting depths (4-10mm) [19]. This provides a good analysis of different robots comparing the most efficient based on price, payload, work envelope and circularity. The joint compliances for different-sized robots can also be seen in Figure 3 [19]. This data shows that just because the robot is larger with higher payloads it will not necessarily be the most efficient for machining. In this case, the KR100 has a similar performance to the KR270.
Schneider, et al, [8] analysed the error sources, amplitudes, and frequencies to compensate for the errors found in robotic machining. Using online compensation methods one utilizing laser tracking and the other performing dynamic compensation. The two online compensation method boasts 100µm accuracy in machining a 70mm circle on a steel workpiece. This is extremely impressive to produce a high-accuracy component on as hard material as ST-37 Steel [8]. This method has been cited in Table 1.

As seen in Table 1 Liao, et al, [9] optimized the robotic posture to improve machining quality due to the low stiffness of IRs. A novel stiffness index was created considering the robot's rotational deformation. Followed by an optimization model, posture, and workpiece optimization -the final setup can be seen in Figure 2 ‘A’ [9] based on the set covering problem. Finally, a machining accuracy of 172µm was achieved [9].

B. *Robotic drilling*

Robotic drilling has been used in the aerospace industry for years for large components made of anything from Carbon fibre-reinforced plastic (CFRP) to aluminium or titanium. The low stiffness present in IRs has made large-hole drilling using CNC or automated drilling units. The aerospace industry is looking to move away from large singular process machines in favour of robotic systems. In a conference paper by Brownbill, et al [10] holes 25mm to 32mm were drilled in a titanium substrate, this was done in research conditions the setup for this can be found in Figure 2 ‘B’ [10]. Robotic drilling is the most advanced robotic machining process with holes around 15.88mm drilled on aluminium workpieces using a robotic drilling setup in the industry [10]. This method was stated in Table 1 helping to contribute to the general state of the research being done. Frommknecht, et al, [11] multi-sensor drilling method with increased 6D pose accuracy achieving less than 100µm of error and 0.2º of perpendicularly [11].
Jiao, et al, [20] performed an off-line programming drilling solution for drilling countersunk holes, this method was based on increasing kinematics and stiffness performance. Jiao, et al, [20] states off-line programming’s basic functions cannot achieve high machining precision and quality [20]. The stiffness was significantly increased from 2700 to 5500 k/N/mm however the paper does not discuss accuracy improvements from drilling tests that were completed.

C. *Robotic grinding*

Grinding is typically used for complex freeform components, adding the flexibility of a serial robot can further increase the complexity of the task applicable. Robotic grinding is an efficient and intelligent machining method for complex components. A robotic grinding cell can be seen in Figure 2 ‘C’ [21]. Researchers in robotic grinding have been concentrating on two extremes, one end has investigated small-scale complex surfaces and the other has targeted efficient grinding of large-scale components [22]. A lot of research has been concentrated on this.

Accuracy control is a major challenge in robotic grinding it requires efficient and accurate calibration of robotic grinding is required for high-performance robotic machining of complex components. Some major difficulties have been identified in robotic machining; positioning accuracy can be as poor as 1mm before error compensation with an average force of 20.4N (discusses Error compensation further in section III Challenges) [23]. Compliance control can ensure a contact state with constant positive pressure and further control of machining allowances, the system calibration error and elastic deformation at the tool-workpiece level in robotic grinding directly influence geometrical accuracy [24].

The following grinding techniques were used in Table 1 to populate the robotic grinding review- Robotic belt grinding provided a machining accuracy of around 60µm using an Aluminium alloy workpiece [12]. This system was set up with a robot holding the workpiece and manoeuvring it around the belt grinder [12]. Chen, et al, [13] performed a force variation analysis, it is challenging to maintain constant force which results in varying surface roughness and material removal depths. Chen, et al, [13] were looking to improve the variation. Using a machine learning algorithm, the maximum errors for surface roughness is between 0.38-0.42µm predicted and actual values and material removal depth vary between 59-52µm predicted and actual values a maximum of 15% variation between the model and actual values [13].

D. Robotic polishing

Polishing is a robotic machining method that reduces residual errors on the surface of the workpiece using mechanical and/or chemical processes. Polishing machines have high precision and are expensive and fixed once built, like the structure of a CNC machine [25]. An image of a robotic polishing set-up can be seen in Figure 3 'D' this is a generic setup which allows quick tool changeover. Over the past few years, broader interest has been placed on polishing as robots have been involved. Robots are described as a key element in achieving manufacturing competitiveness within polishing, particularly if they are collaborative robots (Cobot) [26].

Most finishing techniques are time and resource-consuming, having a significant impact on the overall manufacturing cost. Robot-based solutions have been developed in the last decade to provide automation of complex surface finishing operations [26]. Several robot-assisted polishing techniques have been used like small tool polishing (STP), Bonnet polishing (BP), Fluid jet polishing (FJP), Magnetorheological finishing (MRF), Rigid comfortable (RC), and many others. Robotic polishing's force directly affects the material removal rate [25]. Robotic finishing is limited to the positional accuracy of the robot which sits around 100µm, this can be improved using auxiliary units or error compensation methods to achieve greater positional accuracy. As seen in Table 1 MRF can achieve a surface finish of 0.022µm [15].

Two main control methods are being used to ensure uniform polishing of complex surfaces, passive and active control. Passive compliance control uses auxiliary compliance mechanisms like dampers and springs to ensure natural compliance with external forces. This method depends on the EE and polishing tools [25]. Active compliance is based on position control, the robot can use position control and use force feedback information to adopt certain control strategies to actively control the force [25].

Robotic machining is a highly beneficial subtractive manufacturing method, with great industrial benefits like flexibility, cost-effectiveness, and versatility hence a large amount of interest from many different researchers Verl, et al, [2], Chen, et al, [27] & Kim, et al, [7]. However, despite these benefits, there are several challenges found in serial robots that hinder their application insufficient rigidity, poor accuracy, and complex programming [28].

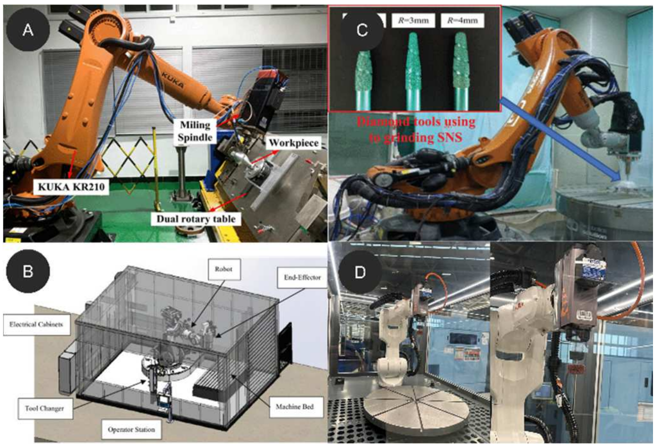
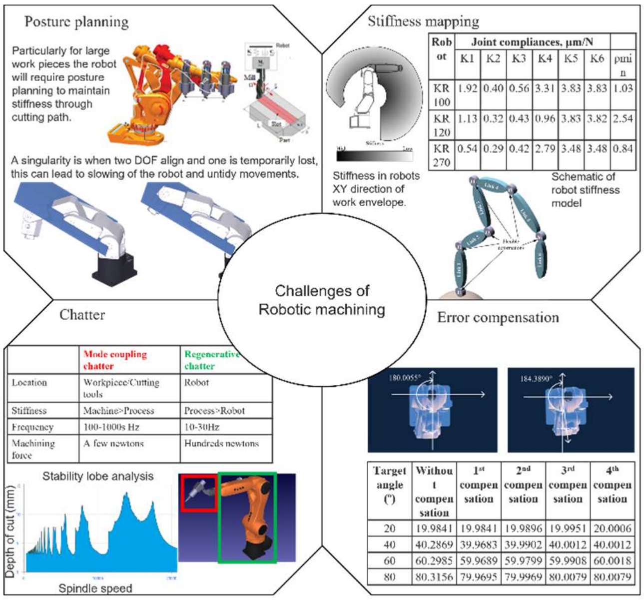


Figure 2 Robotic Milling A [9] and Drilling B [10], Grinding C [21] and Flexible robotic machining setup with Polishing tool D.

III. CHALLENGES



Particularly for large work pieces the robot will require posture planning to maintain stiffness through cutting path.

A singularity is when two DOF align and one is temporarily lost, this can lead to slowing of the robot and untidy movements.

Robot	Joint compliances, µm/N						
	K1	K2	K3	K4	K5	K6	ρmin
KR 100	1.92	0.40	0.56	3.31	3.83	3.83	1.03
KR 120	1.13	0.32	0.43	0.96	3.83	3.82	2.54
KR 270	0.54	0.29	0.42	2.79	3.48	3.48	0.84

	Mode coupling chatter	Regenerative chatter
Location	Workpiece/Cutting tools	Robot
Stiffness	Machine>Process	Process>Robot
Frequency	100-1000s Hz	10-30Hz
Machining force	A few newtons	Hundreds newtons

Target angle (°)	Without compensation	1st compensation	2nd compensation	3rd compensation	4th compensation
20	19.9841	19.9841	19.9896	19.9951	20.0006
40	40.2869	39.9683	39.9902	40.0012	40.0012
60	60.2985	59.9689	59.9799	59.9908	60.0018
80	80.3156	79.9695	79.9969	80.0079	80.0079

Figure 3 Major aspects that require overcoming; Posture planning; Posture planning [21], Singularity avoidance [29]; Stiffness, stiffness in X-Y [30], Joint compliances [19], Stiffness schematic [31]; Chatter attenuation, Chatter source, Stability lobe analysis, Key chatter types [32]; Error compensation, Angle error and compensation [33].

Robotic machining currently has many benefits compared to CNC machining. However, it has main drawbacks that derive from low stiffness, typically IRs have between 0.5N-1/µm whereas CNC machines are typically larger than 50N/µm [34]. Stiffness performance describes the robots and their joint resistance to defections inflicted by external forces [35]. The low stiffness in robotic machining results in several challenges that were commonly researched by researchers. Measures have been used to overcome these challenges including posture planning, stiffness, error compensation and chatter attenuation.

Posture planning can be used to help improve stiffness thus increasing machining accuracy. Using different postures will result in changes in stiffness, scholars have researched Various stiffness-based posture plans, and it can be particularly challenging with large or complex 3D surfaces. Posture planning is also good practice within robotics when avoiding singularities as seen in Fig.3 [29]. Another good practice for robotic machining is the use of functional redundancy [36]. This utilizes the 6th axis of the robot when performing 5-axis machining and helps to increase the robot's stiffness as seen in Figure 3 by Qi, et al, [21].

Stiffness as mentioned is a challenging area in robotics, this requires a good understanding of what is required and what stiffness is available within the robot being used. The most common method to understand the stiffness of a robot is stiffness maps as seen in Fig. 3 a stiffness map showing the stiffness of a robot in the XY direction throughout its work envelope provides the stiffness (N/µm) found at different locations [30]. A source of low stiffness can be seen in Fig. 3 Klimchick, et al, [19] monitored the stiffness in different KUKA robots under different external forces to monitor joint compliance.

Chatter is the effect of vibrations between the workpiece and the cutting tool, chatter can be better understood through an understanding of the robot, base, and cutting tool's natural frequencies. Yuan has characterized mode coupling and Regenerative chatter, et al, [32]. There are effective methods to help reduce chatter a stability lobe analysis can be seen in Fig. 3, this considers the natural frequencies of the machine, tool, and base. These in turn create a graph of the ideal spindle speeds and cutting depth depending on the material.

Error compensation is a real-time method that reduces errors found in the system typically located in positional inaccuracies. A good diagram by Tyapin, et al, [37] has been created showing the desired cutting path compared to the actual cutting path due to the external cutting forces deforming the joint, cutting tool, links, and base.

A. *Posture planning*

Posture planning- Robot dynamics and posture planning are the "two of the most essential fields in robotics" according to Wang, et al, [17]. Low stiffness can be improved through posture optimization. In a study by Liao, et al, [38] a workpiece region-based toolpath generation method is proposed to improve the robot stiffness index. A posture optimization model was proposed to gain the correct posture of the robot at the cutting point while considering functional redundancy and orientation of the tool axis to gain the expected robot posture with the highest stiffness. Toolpaths can require undesirable posture changes on complex surfaces a posture-based surface sub-section method is proposed in the study [38]. This method can group cutting sections with similar postures and helps to reduce the variation between the expected postures and increase the stiffness through ideal joint configurations and obtain higher surface finishing. This is an advanced posture planning method compared to others that have been researched boasting better balance between stiffness, force, and machining accuracy.

B. *Stiffness*

One of the most common methods to improve accuracy due to poor stiffness is stiffness mapping. When machining for a high-precision application it is important to understand the stiffness of the IR to predict the offset that will be inflicted by low stiffness and take measures to improve accuracy when machining. Several standard modelling methods are used in stiffness mapping. Finite element analysis (FEA) is typically the most accurate method although this results in lengthy computational simulations, Virtual Joint method (VJM) a highly utilized method by scholars, describes joints as virtual springs and assumes no deformation on the spring accuracy has been increasing by considering the working conditions of the robot.

FEA is typically the most accurate stiffness mapping method however the calculation time reduces the commonality of the method. This is due to the multi-directional deformations and multiple degrees of freedom available. The accuracy of the FEA model depends on the CAD model, boundary conditions, and mesh refinement. These also affect the computational time [39]. To reduce deviations from the desired trajectory Xu, et al, [35] proposed a novel process of using an FEA stiffness model that considers the link, joint, link weight, and gravity compensator. In this case, it was used to verify a VJM. The method requires static equilibrium calculations of the substructure, and a map showing linear and angular deflections between the joints, links, and EE. A stiffness model is then produced through joint and link compliances. This experiment used a KR500 IR, this method found gravity induces large deflections at extended postures. The link weights cause up to 9mm of linear deflection when the arm is extended positions and ±0.2deg in angular deflections [35], these large deviations are undesirable for machining therefore the work envelope will be under-utilized unless compensation methods are used.

C. *Chatter*

Chatter has been a highly researched area within machining long before robotic machining, chatter leads to low machining accuracy, poor surface quality, tool wear, and low production rates. The chatter mechanisms of robots are vastly different from CNC, and it is easy for mode coupling chatter and regenerative chatter to occur [17]. Regenerative chatter is a self-excited vibration caused by variations in cutting forces and influenced by changes in cutting depth due to the displacement in trajectories [40]. Mode coupling chatter is also a self-excited vibration caused by concurrent vibrations of different amplitudes and phases; the vibration derives from the cutting force whereas the chatter frequency comes from the robot's natural frequency [17].

Celikag, et al, [40] is one of many scholars that have attempted to make improvements and reduce the effects of chatter in robotic milling. Using continuous posture reconfiguration and varied functional redundancies creates a dynamic system to reduce chatter in the machining operation. A vibration test on the cutting path using the structural modes was found to be highly dependent on the posture of the robot resulting in significant changes in the magnitude and frequency of the modes [40].

Cordes, et al, [41] did a chatter stability study on the dynamics of robotic milling. The structural dynamics of the articulated manipulator with spindle and tool are modelled and the dynamic milling forces are applied to the structure. The stability of the system was analysed using frequency domain methods. The stability charts are experimentally validated using Aluminium and Titanium workpieces [41]. Posture-dependent modes of the robot structure are low frequencies and damped out by the high-speed spindle speeds during the machining process. The pose-independent spindle modes cause chatter in high-speed milling by analytically predicting stable depths of cuts and spindle speeds robotic milling of Aluminium parts. At lower cutting speeds high-frequency tool and spindle, modes are damped out by the milling process and the robot's low structural modes cause chatter. The robotic system shows structural mode coupling due to the kinematic configuration [41].

D. *Error compensation*

Using several methods to improve accuracy the End Effector (EE), increase joint positioning, posture, force, and about any aspect of robotic machining can be improved through error compensation. To improve positional accuracy a digital twin-driven positional error compensation method was proposed by Wu, et al, [33] this method used an attitude sensor on the base joint to provide an online compensation method that would feedback rotational joint error and reconfigure the angle to improve the accuracy providing greater positional accuracy of the EE [33].

Lin, Et al, [42] used a real-time path plan correction approach. Joint positional errors (JPEs) are the source of the errors they originate from motors and links have been identified as the main source of deformations when performing machining tasks. To correct the trajectory of the EE the actual position of the links must be predicted, and the dynamics of the robot, joint flexibility dynamics, and disturbance dynamics are considered. The proposed method showed over 80% path accuracy improvement for a material removal process (grinding) [42].

Li and Zhao, [43] researched the kinematic parameters and positional accuracy of the EE that are affected by temperature [43]. A thermal distribution model and deformation model were made to calculate the positional error depending on the temperature at different gears and ambient temperature. The actual working space is measured using a laser tracker and platinum resistance temperature sensors. The laser tracker monitors the positional accuracy at arbitrary positions after temperature compensation accuracy is 83μm compared to 186μm before compensation [43]. The results were almost identical for the first hour this suggests the error occurs due to motor temperature creating unwanted joint errors. The variety of different methods used and their main purpose shows how vast a subject error compensation is a highly beneficial and well-used method to minimize the effects of errors suffered by IRs.

IV. FUTURE TRENDS AND CONCLUSION

Robotic machining still requires research and development to ensure suitability across high precision and high-performance applications, whether this be milling or finishing some broad areas require improvements. The main robotic machining aspects that require improvement have been summarised as follows.

Machining results in external forces affecting the joints, links, and tooling thus reducing the absolute accuracy of the robot, sensors, simulations, algorithms, and many other external tools can be utilized to calculate, predict, and compensate for the errors caused by machining however this is challenging, and further research should be done to provide solutions that further increase the machining accuracy of the robotic machining.

Further understanding of regenerative chatter and mode coupling chatter within the robotic machining and frequencies both affecting robotic machining can be used to further understand the robot's machining capabilities and where the ideal conditions are. Using tap testing to create a stability lobe analysis gives an understanding of the ideal spindle speed and depth of cut on a specified material. This can help reduce the potential effect of regenerative chatter within a robotic machining process increasing finishing and surface integrity.

Robotic machining has potential high-performance applications in numerous industries for in-situ repairs, to be moved around a facility to large and heavy workpieces as well as provide a flexible amount of tasks that increase the cost efficiency of the robot.

DATA STATEMENT

All data are provided in full in the reference section of this paper.

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