Issues and Challenges in Robotic Trimming of CFRP

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Abstract: Thanks to their adaptability, programmability, high dexterity and good maneuverability, industrial robots offer more cutting-edge and lower-cost than machine tools to bring molded Carbon Fibre Reinforced Polymers (CFRPs) parts to their final shapes and sizes. However, the quality of CFRP parts obtained with robotic machining must be comparable to that obtained with a CNC machine. In addition, the robot itself has to be very stiff and accurate to provide the same consistency and accuracy as their machine tool counterparts. If the robot is not sufficiently stiff, chatter, overall vibrations and deviations in shape and position of the workpieces will occur. Furthermore, during robotic machining of Carbon Fibre Reinforced Polymer, the anisotropic and highly abrasive nature of CFRPs combined with the higher cutting forces and the lower stiffness of the robot, lead to numerous machining problems. Therefore, robotic machining of CFRPs stills a big challenge and need further research. In this position paper, a methodology has been developed and implemented to identify, understand and quantify the machining errors that can alter parts accuracy during high speed robotic trimming of CFRPs.

1 INTRODUCTION

Compared to machine tool, the industrial robot, thanks to its adaptability, programmability, high dexterity and good manoeuvrability, offers cutting-edge and low cost solutions to bring the moulded CFRP parts to their final shapes and sizes. It has indeed already been introduced to many industrial applications, including welding, painting and assembly, and has produced excellent results. It is relatively cheaper in terms of cost as compared to the machine tool, is flexible, and has a large working envelope. Nevertheless, current industrial robot still cannot provide the same consistency and accuracy as their machine tool counterparts. The most essential sources of errors hindering the use of industrial robots for machining applications are related to manufacturing tolerances, joint friction, servo errors, thermal effects, as well as flexibilities in the drives and joints. Because of these flexibilities, the robot end-effector will vibrate along the desired trajectory and deflects due to the cutting forces. These flexibilities not only limit the accuracy but also the dynamic performance of the robot.

The successful fulfillment of manufacturing orders requires high performance industrial robots. However, since very limited information on robot performance can be obtained from robot manufacturers, its assessment in terms of accuracy and repeatability has become increasingly important, especially in the aerospace sector. High accuracy trajectory performance is also a requirement in many industrial applications, and should be provided by the robot controller.

Many research works deal with positioning performance in terms of type and magnitude of typical errors. Muelaner et al. (Muelaner, 2010) used a FARO Laser Tracker to assess the repeatability of a large KUKA KR240 industrial serial robot and found that it is no more than 10 micrometers, when short periods of time are considered. The validity of such results is, however, questionable since the repeatability of the FARO Laser Tracker (ADM only) itself is approximately 8 micrometers at 2 m.

To evaluate the backlash error type, which is one of the most important source of errors affecting the performance of industrial robots, Slamani et al. (Slamani, 2012a) proposed an experimental approach using a laser interferometer measurement instrument. The effects of backlash error are assessed statically by experiments conducted on horizontal and vertical paths. Following statistical analyses, they found that backlash is highly dependent on both robot configuration and Tool Center Point (TCP) speed, but remains nearly unaffected by changes in payload. Ruderman et al.

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(Ruderman, 2009) present an approach to the modeling and identification of elastic robot joints with hysteresis and backlash. The distributed model parameters are identified from the experimental data obtained from internal system signals and an external angular encoder mounted on the second joint of a six-axis industrial robot. However, the static assessment technique does not consider the real mode of operation of the robot.

We know that in many automated manufacturing systems, higher speed is a key to productivity enhancement. High accuracy trajectory performance is also a requirement in many industrial robot operations, and should be provided by the servo mechanism. A major problem with the servo systems of industrial robots is contour error, which occurs during curve tracking (Slamani, 2012b, Brogardh, 2009). A desired curve is the shortest distance between the actual trajectory and that of the reference command. When the robot speed is relatively low, the contour error caused by the servo system is usually acceptable. However, once high speed and high accuracy are demanded, as in water jet cutting, laser cutting, gluing, dispensing, and deburring, for example, contour errors will have a significant effect (Brogardh, 2009), and hence the need to improve the performance of contouring control by decreasing or eliminating contour errors as much as possible. There are two commonly used methods for achieving this. One is to design advanced controllers, and the other is path pre-compensation.

With respect to the control field, a large amount of work has been done on trajectory planning, feedback control, system compensation, and feedforward control (Lambrechts et al. 2005, Hakvoort et al. 2008). Koch et al. (Koch et al. 2011) have presented an algorithm to adjust the position and orientation of the tool by predictive vision-based control, which compensates for system delays caused by the robot dynamics and the vision sensor.

Dynamic errors are generally manifested in the form of overshooting, rounding-off, and vibration (Kataoka et al. 2011). In the case of vibration, a well-planned trajectory guarantees good path tracking, and generates less excitement of the robot's mechanical structure and servo control system, and so this source of error can be avoided (Olabi et al. 2010, Shimada, 95). Friction is one of the major limitations in performing high precision manipulation tasks, as it affects both static and dynamic contouring performance and may cause instability when coupled with position or force feedback control (Lischinsky et al. 1997). Tracking error is most likely to occur in circular arcs and corners. When a circular arc path is ordered, the radius of the actual path is smaller than that of the ordered path because of a delayed servo response in each axis. Without appropriate command system capability and correct servo tuning, moving around a corner at high TCP speed and acceleration actually creates and aggravates errors.

Robotic machining has become a very important tool in the industry. Many research studies have been done in recent years, and have shown that industrial robots achieve remarkable success in many machining applications such as polishing, grinding, deburring, and milling (Shirase et al. 1996, Dumas et al. 2011, Leali et al. 2014). On the other hand, precision machining applications require high performance and precision, e.g. accuracy and repeatability, of the industrial robot.

In the aerospace sector, the demand for lighter aircraft components with high mechanical and physical properties has increased the popularity of Carbon Fibre Reinforced Polymers (CFRP). CFRP parts are usually produced by moulding or near net shape processing. In most applications, however, trimming, milling, and drilling are still required to bring CFRP parts to their final shapes and sizes. For these machining operations, industrial robots represent a cost-saving and flexible alternative compared to standard machine tools. However, during robotic machining of CFRP, the anisotropic and highly abrasive nature of this material combined with the higher cutting forces and the lower stiffness of the robot, lead to high levels of vibrations. This in turn results in numerous machining problems, such as rapid tool wear, fibre pull-out, fibre fracture, delamination, trajectory deviation, poor quality, and in some cases, rejection of machined parts.

The main objectives of this work regard a better understanding of the errors sources that can deteriorate parts accuracy during high-speed robotic trimming of CFRP.

2 METHODOLOGY

Tests were performed using a six-axis KUKA KR 500-2 MT industrial robot mounted on a 13-foot linear rail and manipulating a heavy spindle HSD Mechatronic ES 789 delivering spindle speeds of up to 26000 rpm (Fig. 1). The robot could handle a payload of 500 kg.

Because the industrial robot has heterogeneous stiffness within its working envelope and the compliance error is highly depending on the manipulator configuration during trimming, two configurations (placements) were tested in this study. The two placements were obtained by moving the robot base on the linear axis while maintaining the same trimming position in the two-axis positioning table. A first placement noted “operation OP1” with a relatively stretched configuration is shown in Figure 2a. The trimming direction in the OP1 is parallel to the linear axis and Y-axis of the cell. A second placement noted “operation OP2” with a relatively folded configuration is shown in Figure 2b. The trimming direction of OP2 is perpendicular to the linear axis and parallel to the X-axis of the cell. For a given position, the distance between the robot base and the tool is 2669 mm for OP1 and 1816 mm for OP2.

The laminates for the machining tests were prepared in a controlled aeronautical environment using pre-impregnated technology. The stacks were autoclave-cured, and the plies were oriented such as to ensure that the laminate had quasi-isotropic properties. The 24-ply laminate was 3.68 mm thick, with a fibre volume fraction of 64 %.

Before starting the first trimming test, the laminates were pre-drilled for tightening on a machining fixture, as shown in Figure 3. The pre-drilling was necessary for screwing the laminate to the fixture, to facilitate the smooth entry of the cutter in the laminate and to avoid the transient vibrations and reached a constant TCP speed when detouring each slot using different cutting conditions. The aluminum back plating system (Fig. 3), which uses 49 screws and a torque wrench to secure the laminate, was designed to trim 84 slots on two placements of the robot (OP1 and OP2) and under different cutting conditions. A total of 42 slots along the Y-axis of the cell during the OP1 operation and 42 slots along the X-axis of the cell during the OP2 operation were trimmed. As shown in Table 1, different combinations of cutting parameters were tested for the OP1 and OP2 operations, respectively. The subassembly (laminate and back plate) was tightened to a three-axis Kistler 9255B type dynamometer table. The assembly was subsequently installed on the two-axis positioning table KUKA DKP-400 (Fig. 1), located in the working space of the robot. The positioning table and the linear axis supporting the robot were static during the trimming tests. The tool used to trim the coupons was a 3/8 inch diameter PCD end mill with two straight flutes, having a 20° rake angle, a 10° relief angle and a 5 µm cutting edge radius. The cutter was inspected prior to the machining operation.

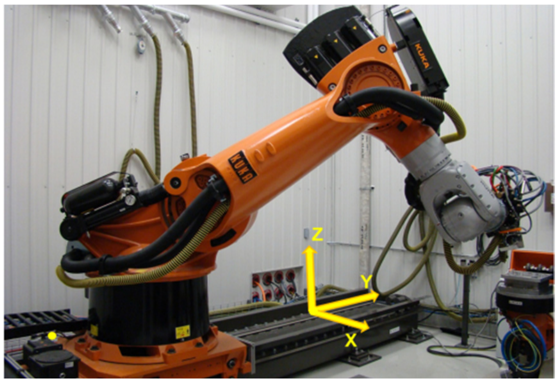
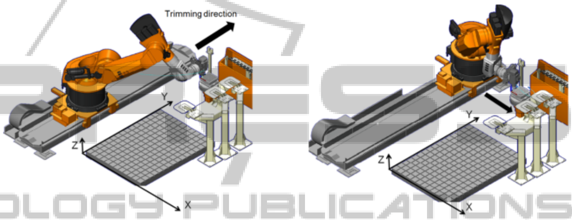


Figure 1: Photo of the six-axis KUKA KR 500-2 MT industrial robot.



a) Operation OP1 b) Operation OP2

Figure 2: Robot configurations during the operation OP1and OP2.

a) Rough part before trimming b) Finished part after trimming of the 84 slots

Figure 3: State of the part before and after trimming.

Table 1: Cutting conditions of the robotic trimming tests.

Speed m/min	Feed mm/rev	Speed m/min	Feed mm/rev	Speed m/min	Feed mm/rev
200	0.2540	400	0.2540	600	0.2540
200	0.3048	400	0.3048	600	0.3048
200	0.3556	400	0.3556	600	0.3556
200	0.4064	400	0.4064	600	0.4064
200	0.4572	400	0.4572	600	0.4572
300	0.2540	500	0.2540	650	0.2540
300	0.3048	500	0.3048	650	0.3048
300	0.3556	500	0.3556	650	0.3556
300	0.4064	500	0.4064	650	0.4064
300	0.4572	500	0.4572	650	0.4572

3 RESULTS AND DISCUSSION

The machinability of CFRPs in high speed robotic end milling was evaluated via parameters such as cutting forces, delamination, profile deviation and dimensional error. The knowledge of the cutting forces during robotic trimming processes is of great importance, it is considered as the most important indicator of machining condition. Usually, in robotic machining this force causes essential deflections that decrease the quality of the part.

Specimens were trimmed under different cutting conditions, and the cutting forces were measured in the x, y, and z directions with a 3-axis dynamometer table. The cutting force data were then recorded for further analysis and evaluation. Figures 4 and 5 express the evolution of resultant cutting forces versus TCP speed (feed rate) and cutting speed for the OP1 and OP2 operations respectively. According to these figures, it can be seen that the cutting force increases as the TCP speed increases. This is explained by the fact that when the TCP speed increases, the laminate resists more to the rupture and requires larger efforts. Hence the cutting force increases as the TCP speed increases. On the other hand, Figures 4 and 5 show that there is no much effect of cutting speed on cutting force.

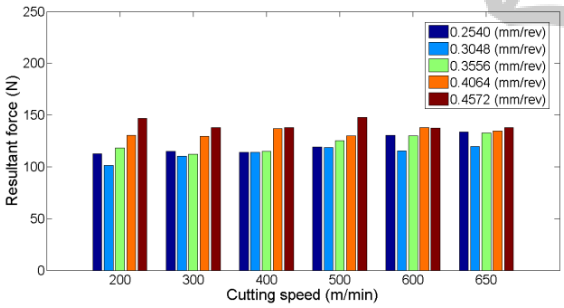


Figure 4: Resultant cutting force as function of cutting speed and TCP speed for the OP1 operation.

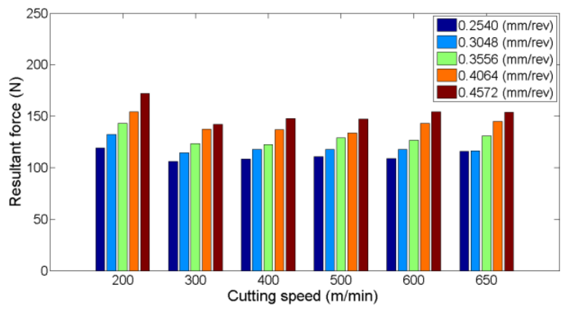


Figure 5: Resultant cutting force as function of cutting speed and TCP speed for the OP2 operation.

The most important type of edge surface damages during trimming of CFRP is delamination (Sheikh-Ahmad, 2009). This damage is caused by the absence of support from the adjacent plies during trimming. So the delamination is usually found on the top and the bottom of the surface plies. Figure 6 shows the delamination of type I of the surface areas where some ply fibers are missing. The maximum value of delamination measured in this case was 4.8 mm (#19 in Fig. 6). Figure 7 shows the delamination of type II where some of the uncut fibers overhung from the trimmed edge. The value of delamination in this case was 1.4 mm (#5 in Fig. 7). A combination of both type I, and type II delamination was also observed in these tests (Fig. 8). The measured delamination values were 0.65 mm, 0.7 mm and 0.45 mm for #5, #6 and #7 respectively (Fig. 8).

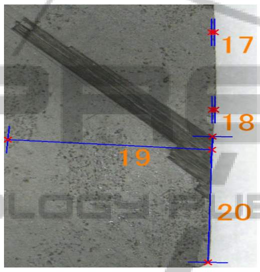


Figure 6: Type I delamination.

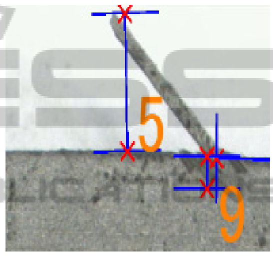


Figure 7: Type II delamination.

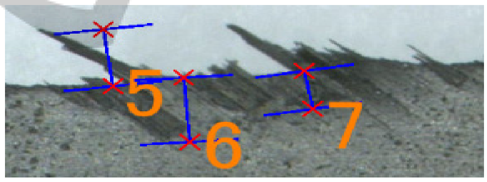


Figure 8: Type I/II delamination.

During the trimming operations, when the robot controller attempts to move the tool along the nominal tool path, the actual profile usually deviates from the programmed one. This deviation is due to the combined effects of the robot errors and the machining process errors. Figures 9 to 12 show some trajectory deviations for different cutting conditions. We can observe from these figures that the machining error consists in material undercuts for the whole profiles having magnitudes of 0.32 mm, 0.435 mm, 0.45 mm and 1.02 mm (Fig. 9 to 12). The figures also show that the trajectory deviations are strongly affected by the cutting conditions. This is shown by different wavy paths that are clearly visible for each cutting condition.

Figure 9: Trajectory deviations for OP1 operation at TCP speed of 0.3048 mm/rev and speed of 400 m/min.

Figure 10: Trajectory deviations for OP1 operation at TCP speed of 0.2540 mm/rev and speed of 600 m/min.

Figure 11: Trajectory deviations for OP1 operation at TCP speed of 0.2540 mm/rev and speed of 650 m/min.

Figure 12: Trajectory deviations for OP1 operation at TCP speed of 0.4572 mm/rev and speed of 650 m/min.

At high cutting conditions, dynamic errors become a significant source of errors, which affect the path accuracy. This is manifested through high amplitude vibrations along the trimmed path. This behaviour is explained by the variations of the cutting force during machining and the poor rigidity resulting from flexibility in the joints, which induces vibrations in the end-effector. It is important to note that the dynamic performance of an industrial robot is even less homogeneous than its static performance. Obviously, the less the main joints (especially joint 1) are displaced, the better the dynamic performance of the robot.

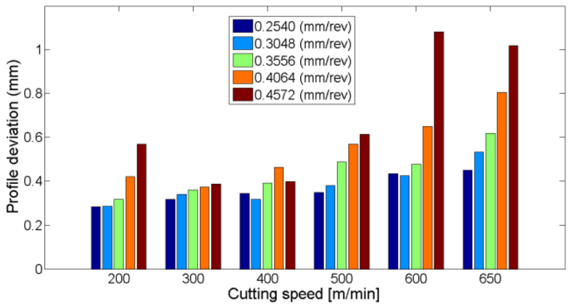


Figure 13: Profile error as a function of the cutting speed and TCP speed for OP1.

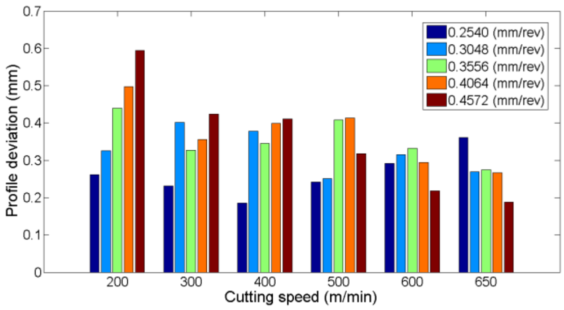


Figure 14: Profile error as a function of the cutting speed and TCP speed for OP2.

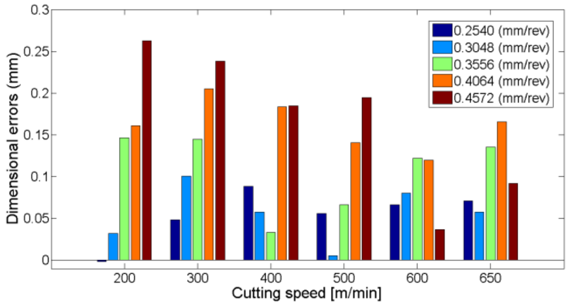


Figure 15: Dimensional error as function of the cutting speed and TCP speed for OP1.

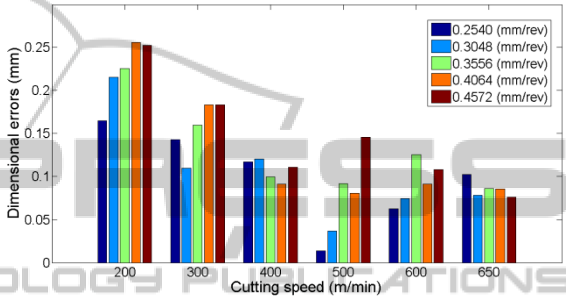


Figure 16: Dimensional error as function of the cutting speed and TCP speed for OP2.

For further analysis of the machining errors, each trimmed slot was inspected with a Mitutoyo CRYSTA coordinate measuring machine. The profile deviations and dimensional errors for each cutting condition were calculated and the results are plotted in Figures 13 to 16.

Figures 13 and 14 show the profile deviation as a function of the cutting speed and TCP speed for the OP1 and OP2 configurations, respectively. The results show that the profile deviations for the OP2 (with relatively folded configuration) are much better than for OP1. They vary from 0.3 mm to 1.15 mm and from 0.2 mm to 0.6 mm for the OP1 and OP2, configuration respectively. They also show that generally, the profile deviations for the OP1 configuration slightly increases with an increase in the TCP speed and cutting speed. Conversely, for the OP2 configuration, the results show that overall; the profile deviations increase with an increase in the TCP speed and slightly decrease with an increase in cutting speed.

4 CONCLUSIONS

In this paper, the sources of error in high speed robotic trimming of CFRP are investigated. The most important sources were identified and quantified. In the light of the experimental results presented, the following conclusions can be drawn:

- The cutting forces proved to be more sensitive to the TCP speed than it is for the cutting speed; they increased as the TCP speed increased.
- Results show that during high speed robotic trimming, inaccuracies of the serial robot kinematic, the mechanical compliance of the robot and the effective process forces are leading to large trajectory deviations which leads to profile errors and dimensional errors.
- Results show also that trajectory deviations and delamination are the main sources of error affecting the accuracy of CFRP parts.
- The robot configuration, which is optimally suited to perform the trimming task, is reached by using a relatively folded configuration and a minimal displacement of the joint 1.

During high-speed robotic trimming of CFRP, the higher cutting forces and the lower stiffness of the robot, lead to high levels of vibrations. Regenerative vibrations create chatter. Chatter not only limits the productivity of cutting processes, but also causes delamination, poor surface finish, reduces geometrical accuracy and in some cases, rejection of machined parts. As future work, it would be interesting to study the relationship between cutting conditions and chatter, chatter and delamination, chatter and tool wear and finally chatter and surface roughness. A study on the stability lobes for the prediction of chatter formation could be also interesting.

On the other hand, results show that trajectory deviations are the most sources of error affecting the accuracy of CFRP parts. To reduce the effect of trajectory deviations, it might be interesting to propose compensation strategies for this error.

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