23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

ROBOTIC SYSTEM WITH FORCE CONTROL FOR DRILLING OPERATIONS

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Abstract. *This paper presents the study and test of a force control strategy for drilling operations with a robotic manipulator. This subject has important industrial and medical applications. Drilling in aircraft fuselages and in surgeries are improved if a precise control strategy is adopted. In this work, it is used an interactive control with force feedback. This force control strategy is embedded in an industrial robotic controller present on the market. It was developed to general machining processes and can be extended to drilling processes, if a correct programming is done. With specific routines, experimental trials and data analysis, it is possible to evaluate the use of the force control and discern its advantages and limitations in drilling operations. High precision drilling is a difficult assignment and requires specific investigation. Slight displacements inside the workpiece can occur, resulting in drilling uncertain in specimens with small dimensions. The implemented force control in drilling demonstrates to be a good method to avoid the risks of failure in the material during the drilling process.*

Keywords: *drilling with robots, robotic machining, force control.*

1. INTRODUCTION

Robotic manipulators have been developed quickly and they are applied in multiple applications. They are typically used in industries, even though they are present in other non-industrial fields. One usual application is in the field of machining operations. Polishing, milling and grinding are examples of them. They request a high power and a good precision of the manipulators. However, industrial robots present limitations in tasks that involve force contact coupled with the low dimensional precision. Isaksson (2009) asserts that one of the main limitations is the low mechanical stiffness of robotic manipulators. During a machining operation, the lack of stiffness can lead to imprecisions or, in severe situations, damages in the workpiece or in some equipment used in the process.

On the other hand, robots have advantages, as high flexibility and large workspace. Thus, even if it has structural limitations, some solutions appear to minimize the stiffness problem. One possible solution is the adoption of force control strategies (Johansson *et al.*, 2004). Two options can be used to control the robot, the passive or the active force control.

In the first case, it is necessary to use auxiliary equipment, as springs and dampers in the robot end effector. However, the active force control guarantees major flexibility, using the controller parameters to complete the robot tasks (Lopes and Almeida, 2007). The second option appears to be appropriated for industrial manipulators. However, elaborating an algorithm for them is a difficult assignment, because industrial robots are generally locked to changings in their controllers.

With a view to solve this problem, some enterprises offer a machining package to their robotic controllers (Robotiq, 2015). The packages are actually used in some industrial machining operations, but they are not regularly used in drilling. In fact, drilling is a very difficult task to be force controlled (Groth, 2015). Although there are difficulties related to drilling with robots, the operation is being adopted in manufacture industries, as in aircraft fuselages, or in surgical robotics (Manufacturing Engineers, 2013; Wall, *et al.*, 2008). In all cases, these operations can be improved with the use of force-controlled systems.

1.1 Drilling parameters

As mentioned, drilling with robots is an important but difficult task, especially when a force control strategy is used. Therefore, it is necessary to understand the machining operations and the importance of the torque and force contact on them. According to Diniz, *et al.* (1999), to know the behavior and the order of magnitude of mechanical stress is fundamental. The dimensioning of the machine tool, the capacity of precision and other parameters of the procedure depend of this knowledge. Undoubtedly, the power involved in a polishing or in a turning operation is different. In this case, the difference is due to the quantity of removed material. In addition, there are some methods to determine power and forces in machining. In this article, an empirical method is used, *i.e.*, some coefficients are obtained with experiments and they are used to establish the main equations.

It is well known that machining operations are a combination of two movements. Figure 1 shows them in the case of drilling, that is the focus of this work. The motion in feed direction is responsible for the thrust force (vertical drill press) (F_v [N]). It is required for positioning the twist drill in the workpiece surface. In addition, the tool rotation is the responsible for the cutting movement. The tangential cutting force (F_t [N]), the torque required (M [Nm]) and the power for machining (P_m [W]) are obtained with the Eqs. (1), (2) and (3) (Ahmad, 2009).

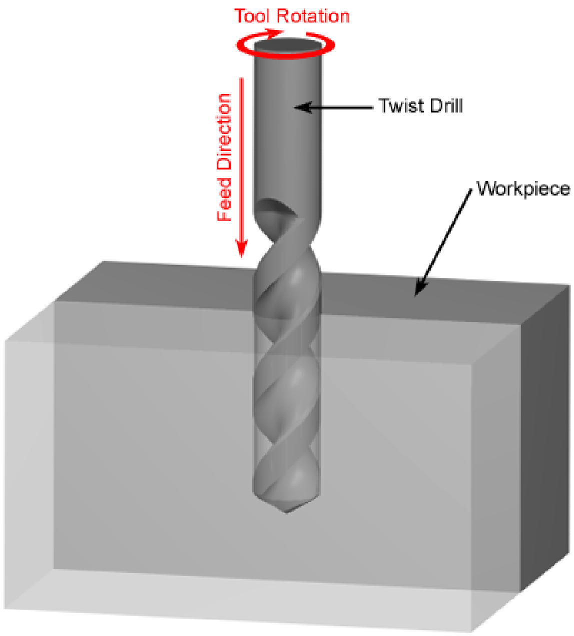


Figure 1. Scheme of movements in a drilling operation (CustomPartNet, 2007)

$$F_t = f\, D\, u_s / 2T \tag{1}$$

$$M = F_t\, D / 2 \tag{2}$$

$$P_m = 2\pi\, M\, N / 60 \tag{3}$$

Where N [rpm] is the spindle speed, D [mm] is the drill diameter, f [mm/s] is the feed rate, T [-] is the number of flutes in a twist drill and u_s [Ns/mm²] is the specific cutting energy. It is possible to perceive that there are geometric, operational and material parameters involved in the process of obtaining F_t. However, the values in Eqs. (1), (2) and (3) are found only for the rotational movement, *i.e.*, for the machine tool spin. The linear movement, in feed direction, is related to the robot arm and its joints. It depends of the capacity of the manipulator, normally given on its datasheet.

The thrust force, in opposition to the tangential cutting force, does not have significant dependence of many operational or material parameters (Diniz *et al.*, 1999). Hence, it is possible to control this force without substantial modifications in the process. The advantage to control Fv is related to the stiffness of the manipulator. It makes the robot less susceptive to failure in positioning. However, it is necessary to distinguish that the thrust force is different in three moments: during the first contact with the surface, in the beginning of the drilling process and during the removal of material (Rios, 2014). This fact should be remembered during the programming of the robot. If the thrust force is high in the first contact, damages can occur in the tool and in the workpiece. If it is low during the removal of material, the task might not be finished. It is also necessary to perceive that the power related to the feed motion is normally smaller than the power in cutting process. As a result, it is possible to understand the use of a standard industrial robot in drilling operations.

With a detail study of force control, it is possible to understand how to proceed in novel situations. An application of this theme is the use of robots in surgeries. The possibility of integrate force control has many advantages, as to provide safety in interaction with humans (Haidegger *et al.*, 2009). However, manipulators with force control for surgeries usually are not present in the hospitals, but only in research laboratories (Zemiti et al., 2007). It means that force control is not commonly used and the principal reason is the difficulty to create systems that can provide a good accuracy in positioning coupled to precision in force control.

1.2 Force control strategy

The choice of a force control strategy, *i.e.*, a solution based on force control to solve problems related to drilling with robots, depends on many parameters. As stated, considering an industrial manipulator, active force control strategies are the best options to assurance the flexibility of the system. However, the active force control can be subdivided in other kinds of control, as hybrid position/force control, hybrid impedance control, explicit force control, etc. (Haidegger et al., 2009). Consequently, many techniques and algorithms are being developed to solve the force control problem, using theories of robust, adaptive and intelligent control, or combining them with classical methods. However, definitive solutions are not found, particularly in drilling operations.

The cause of this problem is that many functions are required for a robot controlled in force. Isaksson (2009), referring to aircraft industries, affirms that if a low contact force is maintained, the risk of sliding is minimized. Another task is related to drilling two connected workpieces. In other cases, there is a risk of appearing a fail named delamination, which is the main failure cause when drilling composites (Cantwell & Morton, 1991). In addition, there are complex surfaces that need a flexible and force-controlled machining process such as finishing operations (Viana, 2012). As a result, the first problem to address when developing a force control strategy is selecting the type of application of the robot.

On the other hand, the previous selection of a specific application limits the possibility of use of a force control strategy. Moreover, due the complexity of the problem, many authors try to simplify the problem. Lafortune (2011) uses a control strategy created by the enterprise ABB, called Machining Force Control Pressure, to control an ABB robot with force feedback during deburring operations. By changing internal parameters in the software used to control the robot, he studied and found some solutions for general deburring situations.

On this paper, the ABB force control strategy used is the Machining Force Control Pressure (FC Pressure). The strategy consists in controlling the manipulator in position and speed while it approaches to the workpiece surface. When the robot is near the surface, a command is given and the robot end effector starts to search for the workpiece. Later, when the first contact force is identified, the force control is activated and the manipulator continues its task under force control. The robot keeps a constant contact force (Fv) against the workpiece during all process. At the end of the procedure, the force control is deactivated and the robot is again position and speed controlled.

Theoretically, in usual machining operations, if a minimal contact force is maintained, the robot can complete its task in one o more paths. However, in drilling operations, some forces appear during the process, because of the chip formation (Toenshoff & Denkena, 2013). It makes the process more difficult and uncertain and limits the use of ABB force control strategy in drilling operations. At the same time, there are advantages in using this strategy. A benefit is the possibility of combine the use of an industrial robot, recognized by its good accuracy, with an active force control ready available. Another advantage is related to the implementation costs, avoiding the need to implement specific mechanical systems to the operation. Therefore, to succeed the procedure of adopting a force controlled drilling process, detailed studies are necessary. Here, the force control uses the ABB robot controller and its available software.

2. EXPERIMENTAL EVALUATION

In this section, the equipment and software used in the experimental work is presented Two experiments are described and the obtained results presented. The first is related to the precision of the drill in force controlled movements. The second analysis is complementary to the first one and consists in a brief experimental study about displacements in the workpiece during a robotic drilling. Throughout the analysis some discussions are presented with a view to understand the process and its characteristics.

The machine tool used in this work is an electrical spindle model PDS XLC-070, which has a power for machining (Pm) of 2.2 KW. The manipulator is an ABB IRB 2400, with a handling capacity of 20 Kg and a total supplementary load of 12 Kg. The feedback sensor is an ATI Delta 330-30, used to acquire force and torque in three orthogonal directions. The sensor is installed between the manipulator end effector and the spindle. The machined material is a piece of wood. The tool is a helical HSS twist drill with 6 mm of diameter (D) and two flutes (T).

The software used to program the robot is the ABB RobotStudio. The robot controller uses a high-level programming language, called RAPID. The software in the controller is the ABB RobotWare. In Fig. 2 it is possible to observe the robotic cell used in the experiments (a) and its virtual copy created in the ABB RobotStudio (b). The virtual cell is used to simulate the process, to check the behavior of the programmed path and to verify the functionality of the data acquisition subroutine.

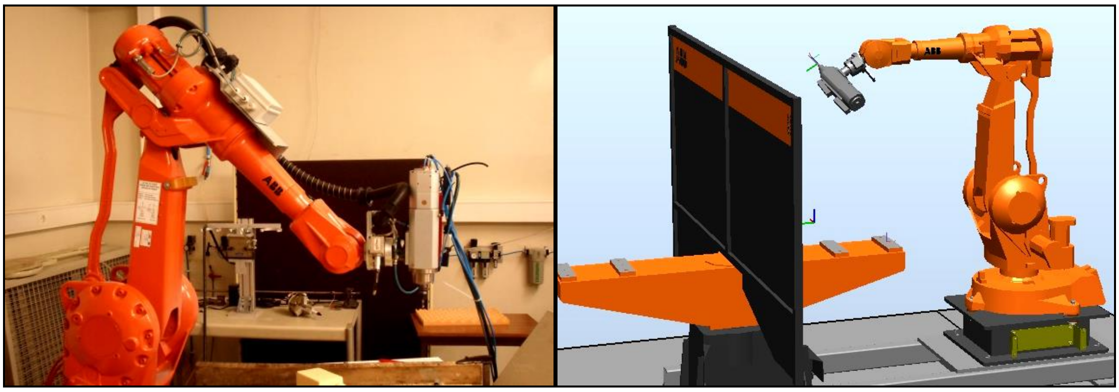
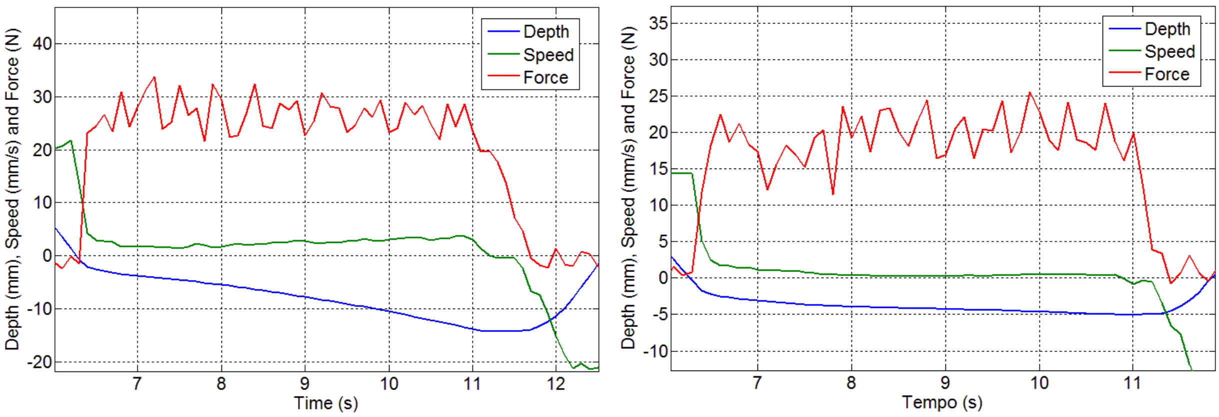

(a) (b)

Figure 2. a) Real robotic cell; b) Virtual robotic cell

Initially, a set of drillings paths were programmed and implemented without force control. The objective is to have some data to compare with the force-controlled paths. The planned depth for the drill is 18 mm, the spindle speed (N) is 5000 rpm and the machining speed (feed velocity) is 5 mm/s. Blind holes were successful done in the initial tests. In these cases, the measured force necessary to finish the drilling was approximately 40 N during major part of the process.

The drilling operations with FC Pressure were initially set up to limit the force in drilling direction to 30 N and 20 N, as exposed in Fig. 3, (a) and (b) respectively. A particular caution in the first contact with the surface is required. The force has to be limited to lower levels because the FC Pressure turns off the position control while the tool is searching for the surface. It also happens during the entire drilling process. If the force control is active, the position control is inactive. That is the reason for not achieving the drill depth of 18 mm. The FC Pressure always stops the position control in the direction of the movement.



(a) (b)

Figure 3. a) Force control limitation set to 30 N; b) Force control limitation set to 20 N

Figure 3 also shows that the drill depth reached in the process is different in each test. When the limitation of force is 30 N, the depth is 14 mm. In the other case, the depth is only 5 mm. It would be a serious problem. This is due to the fact that the force control is only active for a few seconds. This time depends on the robot programming. Position and speed are specified to the robot controller, as in a path without force control. The controller internally makes a mathematical operation and finds the time necessary to finish the process. When the time finishes, the force control is turned off, independently of the position. In Fig. 3 both drills where force-controlled during the same time. Nevertheless, in case (b) the depth is reduced because the force applied during the process is minor.

This implicit calculation could be observed only after many experiments, by changing drilling parameters, as depth, feed rate and contact force, and internal parameters of the robot controller, as force change and damping tune. Unfortunately, it is a common problem when using a high-level language to programming a robot. With a view to obtain better results, a new test was made. In this case, by reducing the robot path velocity (feed velocity) to 2.5 mm/s. The force limit is fixed in 30 N. With this setting, the robot can be force-controlled during more time and, as a consequence, achieves a higher drill depth.

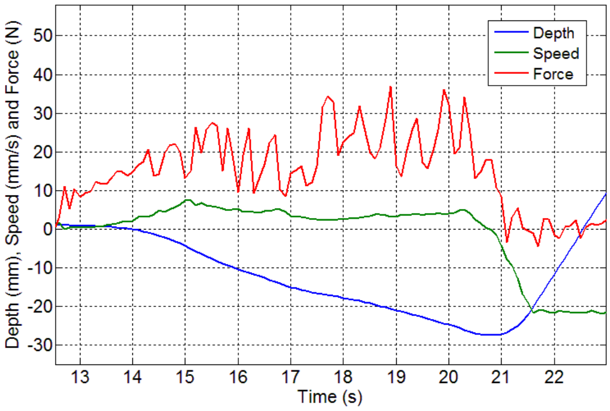


Figure 4. Force control limitation set to 30 N and reduced speed

Figure 4 shows the result of the new analysis. The drill depth is approximately 27 mm, more than the 18 mm previously programmed when not using force control. In fact, a reduction in robot end effector speed increased the time of activity of the FC Pressure. As the robot is under force control, no position control is active, resulting in a drill depth that is dependent on the time under force control. However, the new the result is better than the other one. In a drilling process that requests a through hole, the used strategy can be adopted, enabling to drill the hole while not exceeding a defined drill force. According to Fig. 4, during the drill operation, the drill force was able to be kept under the specified value of 30 N.

One more experiment was made to evaluate the control strategy and the robot behavior. Considering the linear movement in drilling as a movement in z-axis, it is possible to verify the behavior of the system in a xy-plane parallel to the workpiece surface. Movements in this plane should not appear during the whole process. However, Fig. 5 illustrates displacements around the point (x, y) = (0, 0), where (x, y) is the tool tip position in a plane orthogonal to the drilling direction. The point varies with time, *i.e.*, it changes for each position in z-axis during the drilling process. Vibrations cause some small displacements and generate errors in data acquisition. Severe displacements in the tool tip can appear in the first contact with the surface or during the process, affecting the final quality of the drilling. Consequently, a force limitation can be used to minimize this problem (Isakson, 2009).

Figure 5(a) indicates a point with a displacement of 0.1 mm in y-axis. It occurs exactly during the first contact between the twist drill and the workpiece. It happened in a drilling without force control. The value presents a contrast with the medium values acquired during the hole drilling process, which are around 0.01 mm. Moreover, the robot position repeatability is 0.06 mm. It indicates that a displacement of 0.1 mm is a high value. A different result is achieved when the drill is made using force control strategy. Figure 5(b) shows a displacement of the twist drill when the first contact force is limited to 10 N in the beginning and 20 N during the process. It is about 0.06 mm. In fact, the force control can reduce the sliding of the tool tip in the beginning of a drilling operation.

However, Fig. 5(b) shows another displacement in y-axis when the twist drill is inside the workpiece. The unconformity in this case is higher, approximately 0.17 mm. Similar displacement occur in Fig 5(c), that is related to the trial with reduced speed. In both cases, the displacements occurs when the twist drill is in the deepest point of the drill, in z-axis. There are two possible reasons for this problem. The first one can be due to the transition between force control and position control in the end of the process. The second possibility is related to the change in robot trajectory, that occurs when the manipulator stops and inverts its movement, in the opposite direction.

To verify the reason and the behavior of the displacements inside the workpiece, tests with position-controlled paths were carried out. In this case, the workpiece is not used and no force control is used. It is verified that the same displacement in xy-plane is present, evidencing that the problem is not related to the force control neither to the contact between the twist drill and the workpiece. Figure 5(d) shows the results for this test. If it occurs both in force-controlled and in position-controlled paths, there is an external reason for this. The problem can be related to the tool change device that uses pneumatic connection between the spindle and the robot end effector, which does not have a high rigidity. Moreover, the displacement value is high in some experiments and low other experiments, randomly. In Fig. 5(a) the value can be considered low, approximately 0.05 mm.

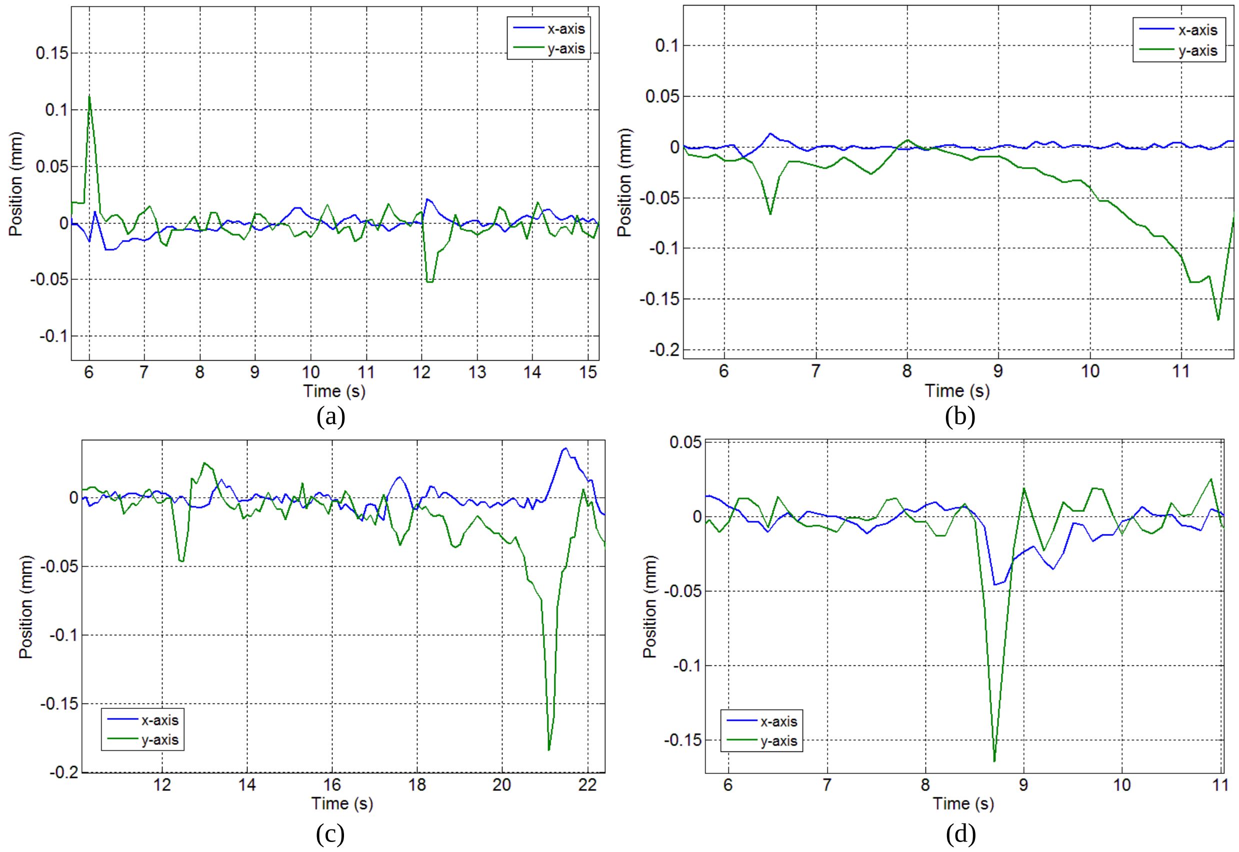


Figure 5. a) Displacements in drilling position without force control; b) Displacements in drilling position with force limitation set to 20 N; c) Displacements in drilling position with force limitation set to 30 N and reduced speed; d) Displacements in position without drilling material

Another problem related to the precision is the drilling operation of very small diameters. The value of 0.17 mm can be considered high if the twist drill diameter is 1 mm, for instance. The scheme in Fig. 6 illustrates the cited diameter and the influence of a displacement of 0.17 mm. It is possible to perceive that an operation with a very small diameter is impracticable in this case. The high imprecision can cause damages to the tool and inaccuracies in the drills. However, if there are no displacements inside the workpiece during the drill, the force control can improve the operation, minimizing the sliding effect and allowing the operations safe even with small diameters. Figure 6 also shows that, for larger diameters, the influence of the same dislocation of 0.17 mm becomes proportionally smaller.

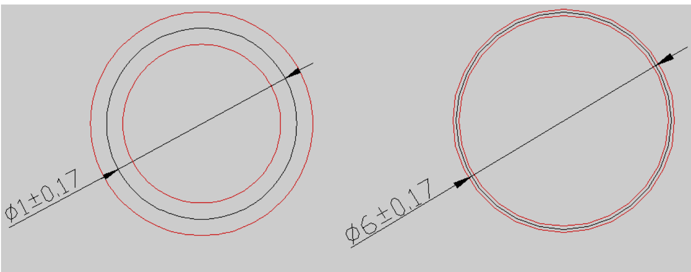


Figure 6. Influence of the dislocation in two different drill diameters

3. CONCLUSION

The use of a force control strategy (FC Pressure), available in an industrial robot controller, for drilling applications was presented. It was possible to produce drills with good quality and assuring the control of thrust force during the drill process. However, the FC Pressure control is limited as it cannot guarantee the programmed depth in blind drills. In case of through holes, the strategy should be tested before, to assurance that minimal time and force limitation are sufficient to conduct the operation correctly. Additionally, the FC Pressure is also capable to reduce the sliding during the first contact between the twist drill and the workpiece.

About drilling with high precision, a particular attention is necessary. The drilling operation of a wood workpiece presented only problems related to the diameter of the drill and the risks of small displacements on the tool tip. However, the process in medicine and aircraft industries has different exigencies. A future development of the force control feedback should be able to explore its use in drilling composites, complex surfaces, low and high density materials or even bones in orthopedic surgeries.

Other drilling control strategies to overcome some of the limitations found should involve the use of active force control with position feedback

4. ACKNOWLEDGEMENTS

The authors would like to thank CNPq, Capes and University of Porto for their support in this work.

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