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Pressure based approach for Automated Fiber Placement (AFP) with sensor based feedback loop and flexible component in the effector

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Abstract:

New applications for robots include tasks that were performed by specialized machines such as polish, milling, placement of fibers, among others. The implementation using robots in these new applications has the inaccuracies problems due to the flexibilities within the robot arm or the tooling when external forces are applied. The industrial robot controller does not take into account the flexibilities and the external forces. This paper is an introduction to the work done to improve the precision in the robotic fiber placement, taking into account the deformation in the compaction roller.

Keywords: automatic fiber placement, model elastic-static, artificial neural network, hybrid force control, hybrid pressure control

1. INTRODUCTION

The industrial robots are designed for simplifying repetitive process, they give flexibility to the industry. The serial robots used in industrial applications like: fiber placement, milling, polish, turning, drilling… do not have the required precision compared with a tool machine Gallot et al., 2012)

The principal goal of our work is to improve the robot's precision without stopping the productive processes in our special case for the automatic fiber placement (AFP).

The AFP is the automatic placement of pre-impregnated fiber or individual dried fibers (Contreras, 2014). The AFP task needs to compact the fibers for removing air in each ply to insure the homogeneity and a good contact between them (Parneix and Lucas, 2000). The fiber compaction must be the same during the laying-up to guarantee the homogeneity on the fiber part. However, if the contact varies in shape or size, the compaction changes according to variations when compaction force is maintained constant. So the fibers compaction is a force based task (compaction forces). For that, we need to add an external loop to control in force/position (Baeten et al., 2003, Albu-Schäffer et al., 2007, De Schutter and Van Brussel, 1988). Several works implement the hybrid force/position control to improve the robot accuracy, for example in haptic systems (chirurgical methods) (Tovar-Arriaga et al., 2012, Zemiti, 2005, Morel and Gangloff, 2005) humanoids robots (Prats et al., 2007) and industrial application (Degoulange et al., 1993, Ferguene and Toumi, 2009, De Schutter and Van Brussel, 1988). But this type of control is rarely used in AFP as in (Uhart et al., 2014). Our research is based on (Uhart, 2014) works. This loop is a sensor-based control one. It consists in controlling to the desired value the contact forces applied by a robot on its environment.

In order to improve the robot's precision, we must know the flexibility (or stiffness) on robot and external elements, to implement a correction (Makarov, 2013). The compaction roller is made of highly deformable material. So to take into account this deformation, our approach performs Finite Elements Analysis (FEA) modeling of the roller under load to get the roller behavior. The interaction pressure is linked to the interaction force and the surface contact patch. But the contact patch is also linked to the interaction force. The applied force and the contact patch are used to compute the pressure using in the FEA software.

We propose a new definition of the AFP task based on a compaction pressure instead of force. We want to control the pressure in the fiber to achieve the ply cohesion. An external hybrid control in position and force sends information to the industrial robot controller to improve the process accuracy. This new definition consists in computing a state space variable, the force to be applied, from the desired compaction pressure and the roller interaction. The control scheme measures the applied force with a force sensor in real-time then calculates and sends to the robot the tool correction.

2. MATERIALS, MODEL AND METHODS

2.1. Materials

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The robotic cell at CompositAdour has eight DOF. It is composed of a serial robot KUKA KR 240 (six DOF) mounted on a linear rail (one DOF) and a vacuum table or a steel mold for draping (one DOF). The robot integrates a special end effector for the fiber placement. This is composed of a heating system (laser or infrared light), a compaction roller, a cutting system and the wicks guide system. In this research, we use the robotic cell at ESTIA. This cell consists of a robot KUKA KR6 (Figure 1**Erreur ! Source du renvoi introuvable.**), a compaction roller, a mold and the RSI module. The KR6 and KR240 robots have the same kinematic and use the same controller (KRC2). The results can be applied to the industrial cell.

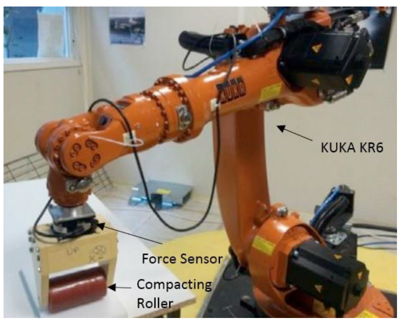


Figure 1 Robot Kuka KR6

2.2. Industrial problem

The placement fibers task could use an important compaction force. The compaction force range is between 0 and 1200 N, according to the fiber's tape. This force must be normal to the surface and must be constant during the tool's path. This compaction force is distributed in all compaction roller. When the roller is in full contact with a flat surface and surface has the simple contours such as the rectangle or square shapes and the AFP machine delivers a full number of fibers covering the roller. When the pieces have the complexes contours such as the triangle or circular shapes, the interaction surface changes and the AFP delivers a decreased number of fibers. Then the fibers do not have the correct compaction and the compaction excess generates fiber deviation and it is not possible to guarantee to stick on between the fiber layers. Then we propose to use the pressure control to guarantee the ply cohesion when the surface increases or decreases.

2.3. Robot flexibility modeling

The dynamic model (Makarov, 2013, Khalil and Dombre, 1999) allows taking into account the robot's flexibility and external forces. This model considers the robot's links as rigid body and the joints flexible. The fiber placement task is a force based task because it interacts with the environment (external forces). However, this model cannot be carried out in an industrial controller due to the warranty issue. For AFP, we consider the flexibility at the tool: compaction roller.

2.4. Compaction roller modeling in FEA

The compaction roller is a very flexible element. This characteristic generates errors during the AFP task because it is not considered in the robot trajectory. The roller material is P-type Sylomer. The behavior laws to model this material are hyper-elastic ones to model nonlinear materials with large shape changes (Bower, 2009, Jakel, 2010).

We use ANSYS Workbench 15.0 software to create and simulate the roller. The hyper elastic materials can be simulated with the several models: Neo-Hookean, Mooney Rivlin, Gent, Odgen and Yeoh. The roller material is not included in the ANSYS material library. Then to estimate the model parameters, we use a compression machine to compact real roller, with a compaction force between 0 N to 800 N. We use a range sensor to measure the roller deformation in the Z-axis. This experimentation allows us to know the behavior, stress –strain in Z-axis of the material. We decided to use the Ogden model because it gives the best simulation results for the real roller. To adapt the ANSYS parameters, we compare the simulation results with the results got in the testing machine. Table 1 shows the parameters uses in the simulation which gives the results closer to reality. The FEA modeling allows us to compute the information like the pressure, the contact area, the deformation, the strains, the stress and the energy in the roller. Also, the FEA modeling allows us to perform simulations when the roller is partial contact with the mold. In Figure 2 shows the FEA modeling results for the pressure.

Table 1 Simulation parameters uses in ANSYS

Simulation parameters	
Material constant MU1	0,83 Mpa
Material constant A1	0,68
Incompressibility parameter D1	0 Mpa^-1

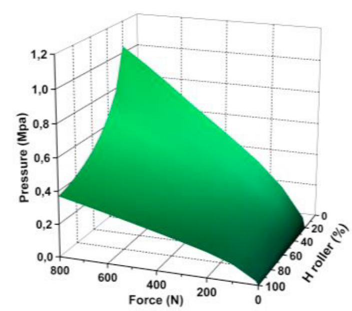


Figure 2 Compaction roller information obtained in ANSYS

The problem with FEA simulation is the computation time which is not compatible with robot control. So we propose a strategy to transfer this information based on Artificial Neural Network (ANN).

2.5. Neural Network

ANN is a mathematical or a computational model based on the biological neural network. (Akintunde et al., 2015). The ANN has inherent benefits such as learning incomplete data, working with imprecise, noisy and complex nonlinear data and its capacity for parallel processing (Perpetuo et al., 2012). In the last years, the ANN is one of the most used methods to model, approximate and optimize non-linear problems. Based on the fact that it provides good adaptive solutions and can re-estimate the parameters model with a facility.

An approximation model retakes the basic properties of the original model. However, this model must have enough information to guarantee that the model is close to reality and it has the required precision. The equation (1) represents the compaction roller model.

$$P = f(F, H) \quad (1)$$

where:

P= Pressure
F= Force
H= Contact surface between the compaction roller height and the surface

Our first approach is based on ANN to approximate our model to reality. The ANN learning has been carried on using software Matlab neural fitting tool. The information used in ANN is the model information obtained in simulation FEA, the Figure 3 shows the modelling results. This model has a relative error learning of 7x10-6 based on Mean Square Error (MSE).

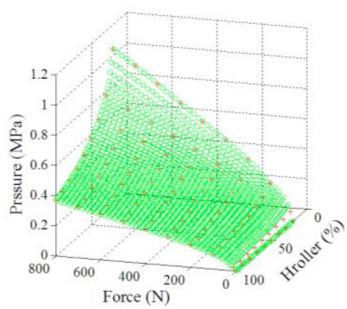


Figure 3 Model obtained with neural network in Matlab (red learning data, green interpolate data)

After exporting the ANN parameters from Matlab, the ANN simulation program is translated in c# to cope with our experimental setup.

For the control scheme, we need the reverse model which allows us to compute the force to apply in order to get the correct pressure for a roller height. The equation (2) shows the reverse model

$$F = f(P, H) \quad (2)$$

3. PROPOSAL

3.1. Modeling task

Nowadays, the AFP task needs a dual command: between force and position and between torque and orientation (Uhart, 2014). The force control proposes to use a dual command because it selects for each tool direction the control position or the control force (Figure 4). The X-axis direction has to control in position (tool-path) and torque (force distribution). The Y-axis direction must control in position (tool-path) and orientation (head normal to the surface). The Z-axis direction must control in force (compaction strength) and orientation (tool-path). However, this approach does not take into account the surface changes which involves a change in the fibers number on the roller.

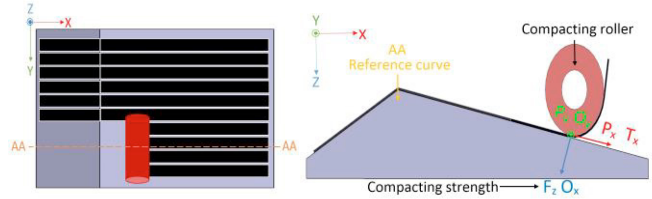


Figure 4 Force control

For example, in Figure 5, the mold has three elements. The first one is a square area (element 1) which has the same dimensions that the height compaction roller, where eight fibers will be in use. The next element is a trapeze shape which changes its dimension (element 2), where the fiber numbers will vary from eight to four. The third element is a square which is smaller dimensions than height compaction roller, where four fibers will be involved.

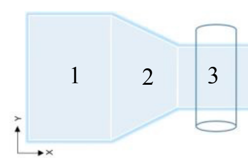


Figure 5 Mold with the three surface shape changes

The force control supposes that the interaction surface is constant. So the pressure applied to the fiber during the laying-up on elements two and three (Figure 5) will be over the specification. This extra pressure load can lead to fiber displacement within the ply or unwanted force/torque applied to the robot which leads to an error during the robot path. We propose to take into account these elements to improve the robot precision with a pressure based control. As we cannot to use a pressure sensor. The pressure control will base on a force control. Let (P) be the pressure set-point. The force sensor measures the compaction force and the ANN calculates the compaction pressure (Pc) (equation (1)). Once the ANN calculates the compaction pressure (Pc), we calculate the error pressure (ΔP) based on

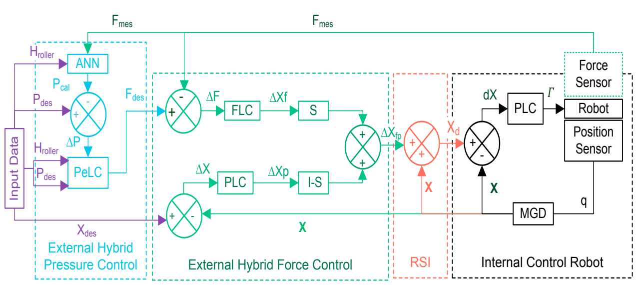
$$\Delta P = P - P_c \quad (3)$$

Using the reverse model, we compute the new force target (Fz). The force control calculates the increment position (ΔXZ). The robot controller receives the increment position and modifies the robot position.

3.2. External hybrid pressure control

The reverse model calculates the force target with the pressure target. But the compacting roller height in contact cannot be measured in real-time. Then we have chosen to estimate it using a robot position on the path (given by the forward kinematic model of the robot) and the off-line programming (based on CAD of the mold). To respect the task description (section 3.1), we use an ATI 6 DOF force/torque sensor. This sensor placed between the robot flange and the end effector (Figure 1). The external hybrid control (position/force-pressure) moves the robot in the Cartesian space. In this way, we can follow the theoretical tool path (Degoulange et al.,

1993) while applying a controlled compaction pressure P_z. The diagonal selection matrix S allows choosing the robot elements controlled in position (si=1) and the elements controlled in force (si=0) as S= Diag (s1… s6). In Figure 6 shows the external hybrid position/force-pressure control. The sensor force measures the forces and torques dues to interaction the tool and surface. The ANN calculates the pressure (P_{cal}) from the measured force (F_{mes}) and path contact (Hroller). The system compares the calculated pressure (P_{cal}) and the desired pressure (P_{des}) to get a pressure differential ($\Delta P=P_{des}-P_{cal}$). This differential allows calculating the desired force (F_{des}) in the pressure law control (PeLC) from a desired pressure (P_{des}) and a contact patch (H_{roller}). The force law control (FLC) receives the desired force (F_{des}) to convert in a position differential (ΔX_f). Simultaneously, the system compares the desired position-orientation (X_{des}) and the measured position-orientation (X) to get a position differential ($\Delta X_p=X_{des}-X$). The selection matrix (S) chooses the differential position for each direction. The position differential (ΔX_{fp}) is a chain composed of each differential position. This differential (ΔX_{fp}) adds the current position (X) to get the desired position (X_{des}). The robot controller gets the desired position and moves the robot to the position. The force control law implements a PI correction concerning the compaction forces and the torques.



PeLC: pressure law control FLC: force law control, PLC: Position law control, RSI: Robot Sensor Interface. $X_d=X+\Delta X$: Position-orientation desired in Cartesian space for the control position loop. $\Delta X=X_d-X$, Γ: Vector of the torques of actuators; q: Vector of joints.

Figure 6 External Hybrid Position/Force-Pressure Control

4. EXPERIMENTAL

4.1. Test environment

4.1.1. RSI module

The RSI module allows connecting an external system to the robot controller. In section 3.2, we have explained the external hybrid loop use in our research. The RSI module has to receive data every 12 ms otherwise the data is lost. The robot controller receives a differential tool position (ΔX), this differential adds to the current position, then the robot controller defines the target position tool.

4.2. Procedure test

In this research, we compare three control modes to see them pros and cons. The first control mode, the position control mode is the control by default in the robot. The second control mode the hybrid position/force control mode applied in (Uhart, 2014). The last control mode is the hybrid position/force-pressure control mode. In Figure 7, the robot path describes in XZ plan. Between the points B and C, the robot is in contact with the mold and it has some shape variation (Figure 8).

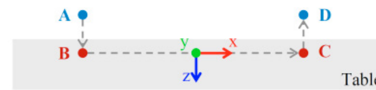


Figure 7 Procedure test

4.2.1. Position control mode

The robot goes to the position A with a joint space based trajectory and all the other movements are Cartesian space based trajectories. For (B→C) movement in order to get a compacting force, we have defined the positions B and C under the mold surface. The locations B and C learned with force sensor monitoring to have a compacting force of 20N.

4.2.2. Hybrid position/force control mode

The procedure for the movements (→A), (A→B) and (C→D) are identical to the ones in position control mode. However, for the movement (B→C), the robot controlled in position along the X-axis and the robot tool controlled by force on Z-axis to have a compacting force of 20 N.

4.2.3. Hybrid position/force-pressure control mode

The procedure for the movements (→A), (A→B) and (C→D) are identical to the ones in previous modes. The movement (B→C), is similar to the hybrid position/force control, but now the robot tool controlled by pressure on the Z-axis to have a compacting pressure of 0.078 MPa. This pressure value for a roller height of 100% gives a 19.97 N compacting force.

4.3. Study case

Figure 8 shows the mold used in the test, its dimensions are 440 mm long (X-axis), 150 mm width (Y-axis) and 5 mm thick (Z-axis). The compaction roller has an external diameter of 68 mm, an internal diameter (rotation axis) of 30 mm and a height of 118 mm. The mold divides into four equal areas along X-axis with 110 mm length for each one. In the first one (area1) and last one (area 4), the width is 150 mm so that the compaction roller is in full contact (100% Contact A, Figure 8). In the second one (area2), a variation in its shape is present, that is between 118 mm to 47 mm wide (Y-axis). So the contact with the compaction roller varies from 100% to 40% according to the robot displacement along X-axis. In third one (area 3), the width of the area mold is 47 mm thus the contact with the compaction roller is 40% (contact B Figure 8), during the robot displacement along X-axis.

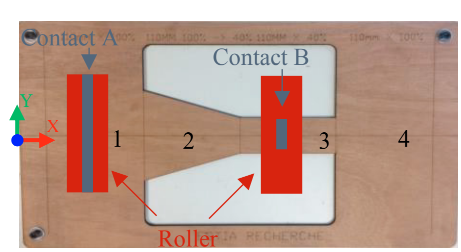


Figure 8 Mold

4.4. Results

Analysis of the results allows studying the relevance to have a pressure control and verify the homogeneous compaction force on the fibers with complex shapes as mold in Figure 8. The aim is to study the connection between the controls mode and the fiber placement accuracy. This relation takes importance in the movement (B→C) (Figure 7)

The position control mode does not take account the force neither the surface, then in this control mode, the robot moves according to the teach movements. The measured compaction force (Figure 9a)) and the calculated pressure (Figure 9b)) are variables along X-axis. The compaction force (Fz) takes values between 5 N to 37 N and calculated pressure its values are between 0.05 MPa and 0.150 MPa. A parasite force Y is around zero (Figure 9d)), but the parasite force in X is around 0.8 N (Figure 9c)). That meaning the robot has a small slide in X-axis. A parasites torques in Z is equal a zero (Figure 9g)), however, the parasites torques in Y is around 0.24 N-m (Figure 9f)) and parasites torques in X is variable but it increases in area fourth around 2.4 N-m (Figure 9e)). That represent the rotation in X and Y axis.

The force control is a work carried in (Uhart, 2014). This work considered a flat mold like our work, however, in this work, the mold does not have a change in the contact shape. So the force control does not consider the surface, only the force. The force control has shown the goods performances in the area one and area four. Because it keeps the compaction force (Fz =20 N) and calculated pressure constants (around 0.078 MPa), but in the areas with a change in the shape (areas two and three), the compaction force keeps constant (Figure 9a)), then it does not decrease according to the shape. The contact patch modification disturbs also the PI control so noise appears in area 2 and 3. The calculated pressure depends on the surface, so it increases due to the reduction in the shape, the calculated pressure is between 0.078 MPa to 0.14MPa (Figure 9b)). A parasite force in X is around zero (Figure 9c)), but a parasite force in Y increases its value according to robot movement (Figure 9d)). Its start value is around 2 N, it increases to around 5 N. That meaning the robot has a slide in Y-axis. The parasites torques in Y (Figure 9f)) and Z (Figure 9g)), are around a zero. However, a parasites torques in X is variable but it increases in area two and its value is between 1.2 N-m to 1.5 N-m (Figure 9e)). That represent a rotation in X-axis.

The pressure control consists in using a constant pressure on all the path regardless the surface. The compaction force is an internal state variable based on desired pressure and the surface shape. Then this control takes into account the pressure and the surface at the same time. The pressure control has shown the good performances in all areas. In area one and area four the compaction force is constant as the calculated pressure. The compaction force (Fz) is around 20 N and the calculated pressure is around 0.078 MPa. In area two and area three the compaction force has been reducing according to shape, but the calculated pressure keeps constant (0.078 MPa). In area two, the compaction force (Fz) is between 20N to 9N and in area three the compaction force is around 9N. Once the robot moves from area three to four, the compaction force increases around 20N. However, the calculated pressure keeps its desired value and the homogeneity in the piece is guaranteed. A parasite force in X is variable, but its values are between 0 N to 0.8 N (Figure 9c)). A parasite force in Y increases and decreases according to shape (Figure 9d)), in areas one and four its value is around 4.2 N and the area two and three its value is between 2.1 N to 4.2 N. That meaning the robot has a small slide in X and Y axis. A parasite torque in Z (Figure 9g)) is around a zero. However, a parasite torque in Y is variable, but its values are between 0 N-m to 0.24 N-m (Figure 9f)), a parasites torques in X is variable but it increases in area four and its value is between 0.5 N-m to 1.2 N-m (Figure 9e)). That represent the rotation in X and Y axis.

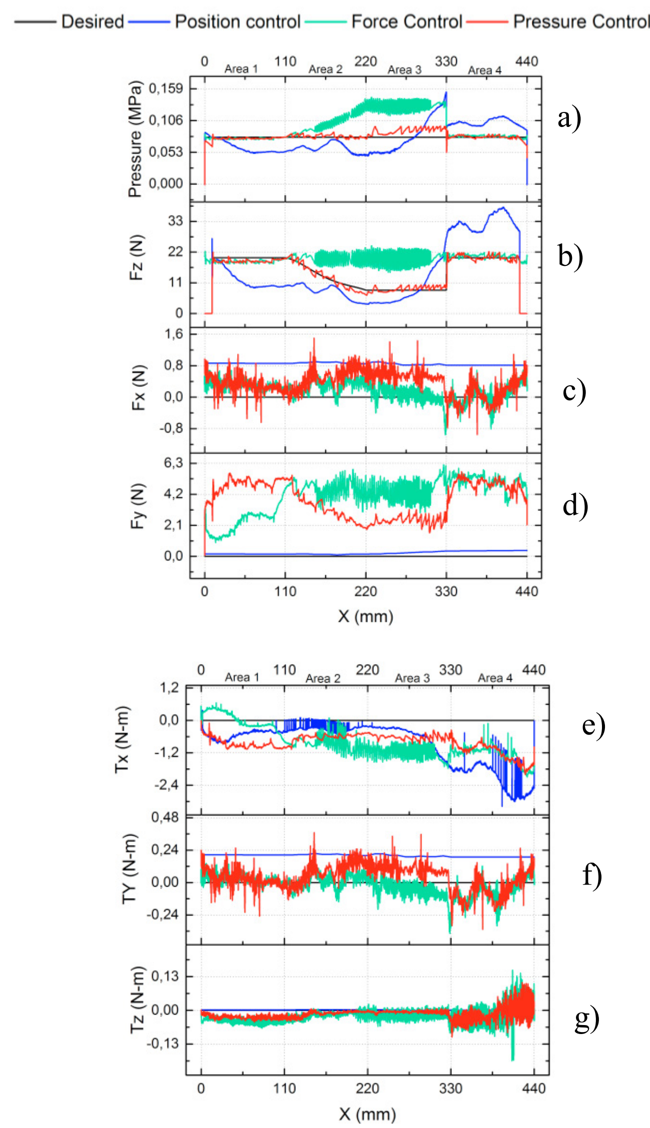


Figure 9 Result for the position control, force control and pressure control

5. CONCLUSIONS AND FUTURE WORK

The position control and the work carried in (Uhart, 2014) considers the mold is flat without changes in the contact shape. We are test this control, in the case the piece has the changes in its contact shape. In the first one, the homogeneous compaction in the piece is not guaranteed, because the compaction along X-axis changes. The second one, the force control keeps the compaction force sets as a constant one and the pressure increases due to the surface reduction, so the compaction is not homogeneous how we have demonstrated in Figure 9a) and Figure 9b). Our proposition improvement the compaction fibers, because we taking into account the changes in the contact shapes and the high flexibility of the compaction roller which modifies the robot-environment relation. The compaction force is linked to the contact area, as we have demonstrated in Figure 9b). The control pressure keeps the pressure constant and the force increase or decrease according to the contact area. Thus, the homogeneity in the piece is guaranteed. We have proposed the use of ANN techniques to create real-time models based on FEA models to cope with flexibilities.

In future work, we need to choose the good values for the controller gains or look for an adaptive controller linked to the contact patch because it creates the disturbing forces and torques variations. On another hand, the roller deformation creates a difference between the Tool Center Point (TCP) and the contact location. This difference has no effect on the flat surfaces because the tool orientation is constant. But the pieces with corners or complex curves, the TCP orientation changes. So, we need to consider a dynamic TCP in real-time.

6. ACKNOWLEDGMENT

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