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A PERPENDICULARITY MEASUREMENT SYSTEM FOR INDUSTRIAL ROBOTS

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Abstract. *Industrials robotic systems are able to work with a great part of the tasks of an automatic situation. The automotive industries impelled the evolution of the industrial robots with an increase of both technology and quantity of installed robots since the 1960's.*

These applications on the automotive industries needs a good accuracy, like 0,2~0,5mm. But normally, industrial robots are not applied on the aeronautical process, because the robots do not have a high accuracy (0,05mm or better).

Generally the aeronautical industries use bespoke solutions. Because of that, that is important to find a way to increase the accuracy of the ordinary industrials robots.

There is a possibility to correct the position and the orientation of an industrial robot with a large volume metrological system. This is the most used way to measure each position and orientation of the full envelope of the robot.

When the work area is smaller than the full envelope of the robot is common to use a vision system to correct the position of the robot. But that is hard to measure the orientation with a high accuracy when this method is applied.

This work is about the development of a system to measure small deviations of orientation of the robot in an edge to certify that the perpendicularity is correct to be used in an End-Effector that will be able to drill, apply sealants and fix fasteners on a surface.

The integration between all of the modules on this End-Effector are the focus of the project. The result is an optimized robotic measurement system.

Keywords: *Perpendicularity, robots, measurement system, End-Effector.*

1. INTRODUCTION

This paper approaches one of the problems related to the use of robots in aeronautic industry.

Historically, the evolution of robotic manipulators followed the evolution of industrial production systems. The number of robots in automotive industry grows exponentially since the 1970's. Today, it is impossible to imagine an automotive production line anywhere in the world without robots. Industrial robots are also commonly used in other manufacturing areas, such as electronics and microelectronics, pharmaceutics, food, etc. (Holland and Nof, 1999). However, the same is not true for the aeronautical sector.

Generally, most of the assembly activities of an aircraft are performed manually. Some features of aircraft production systems help to understand why robots are not used in aeronautical segment. The first one is the quantity of aircrafts manufactured per year. While automotive industries produce thousands of cars per year, the aeronautical industries produce about tens aircrafts per year. Furthermore, the use of the same robot to make a large range of operations is still a challenge. From a financial point of view, one reason that justifies the purchase of an industrial robot is the quantity of operations made per year. Generally, robots must produce more than a workman and keep the total quality of the product. Another important factor that keeps robots away from the aeronautical sector is the accuracy. Aeronautic applications usually demand absolute accuracies and work with external forces that are greater than the ones found in traditional robotic applications such as automotive (Summers, 2005).

Recently, the competition among aircraft industries made the process automation one of the main targets to be pursued in order to reduce production cost. This scenario motivated the development of researches in order to overcome the limitations related to the use of robots in aeronautic process. The low investment required for robotic systems when compared with the development of dedicated automation solutions is one of the reasons.

A recent study presented by Cibiel and Pratt (2006) elected the drilling operation as the best process to be automated using industrial robots, among the different task performed manually in aircraft industry. The reason is the large number of drilling operations to be performed in a single aircraft: there are more than thousands holes and fasteners on a aeronautical structure. Even with the low quantity of aircraft manufactured per year, the quantity of holes on a single aircraft can justify the investment in automation.

The motivation for using robots in drilling and fastening operations and the need to achieve the required tolerance are the start point of this work. This paper presents the development of a mechatronics system to measure and correct small perpendicularity errors in a robotic end-effector that performs the operations of drilling, applying sealant and fixing fasteners on an aircraft structure.

In an industrial robot, the positioning and orientation error can be characterized by two numbers: the absolute accuracy and the repeatability. Repeatability is related to random error. It is defined as the maximum distance between two real final positions of the robot´s end-effector that are achieved for the same desired (commanded) final position, considering different start points. Absolute accuracy is the distance between the desired (commanded) and the actual final position of the end-effector. The accuracy value provided by the manufactures generally refers to repeatability, even though users are mostly interested in absolute accuracy. The absolute accuracy is influenced by several factors: mechanical influences (backlash of the gears, flexure of the links), electronic influences (sensitivity of the internal sensor of the links, resolution of the motors) and mathematical influences (geometric deviation, cinematic approximation).

It is common knowledge that the absolute accuracy of an industrial manipulator is poor (Merlet, 2006) and can easily reaches values of about 2 mm for heavy loads. On the other hand, the repeatability is significantly lower. Some examples are illustrated in table 1, which presents the repeatability of some common industrial robots.

Table 1. Repeatability and load of industrial robots (Merlet, 2006).

Robot	Load	Repeatability
ABB IRB 140T	5 kg	± 0,03 mm
ABB IRB 2400L	7 kg	± 0,06 mm
ABB IRB 4400/45	45 kg	± 0,1 mm
ABB IRB 6400R/3.0-100	100 kg	± 0,15 mm
Fanuc Arc Mate 100i	6 kg	± 0,08 mm
Fanuc Arc Mate 120i	16 kg	± 0,1 mm
Fanuc M420iA	40 kg	± 0,5 mm
Fanuc R-2000iA 165F	165 kg	± 0,3 mm
Fanuc S-900iB/200	200 kg	± 0,5 mm
Kuka KR6	6 kg	± 0,1 mm
Kuka KR60-3	60 kg	± 0,2 mm
Kuka KR100	100 kg	± 0,15 mm
Kuka KR210L100	100 kg	± 0,2 mm

This paper is organized as follows. Section 2 presents AME Project and the EFIP, a robotic end-effector under development for aircraft assembly. Section 3 details the EFIP requirements. Section 4 presents the approach adopted for the design of the perpendicularity module and details the design steps. Finally, Section 5 discusses the main conclusions and details future work. The analysis of drilling forces and the deformation of the surface will be not studied in this paper.

2. THE AME PROJECT AND THE EFIP

The AME Project is an initiative of the Brazilian aeronautic industry in partnership with ITA (Instituto Tecnológico de Aeronáutica - Aeronautic Institute of Technology). AME stands for Automação da Montagem Estrutural, which means automation of the structure assembly. It is supported by FINEP (a Brazilian governmental agency) and by the Brazilian aeronautic industry.

The AME Project aims to develop national technology for the automation of aircraft structure assembly processes using industrial robots. One of the products under development for the AME Project is the EFIP (Efetuador de Furação e Inserção de Prendedores – end-effector for drilling and inserting fasteners).

Once that the absolute accuracy of industrial robots does not achieve the numbers required by the assembly operation, the EFIP must be able to verify and correct the position and orientation of the robot in order to drill, apply sealant and insert the fastener.

The EFIP is conceptually organized into a set of modules:

a. The drilling module, which performs the drilling operation;
b. The fastening module, which inserts the fasteners;
c. The vision module, which detects and requires the correction of the end-effector position;
d. The sealant module, which applies the sealant after the drilling operation and before the insertion of the fastener;
e. The clamp module, which pressures the EFIP against the fuselage structure;
f. The perpendicularity module, which detects and requires the correction of the end-effector orientation;
g. The mechanical platform, which integrates in a single structure all the modules.

The Figure 1 illustrates the layout of the modules on the mechanical platform. The robot that will hold the EFIP is represented by the block on the bottom of the Figure 1.

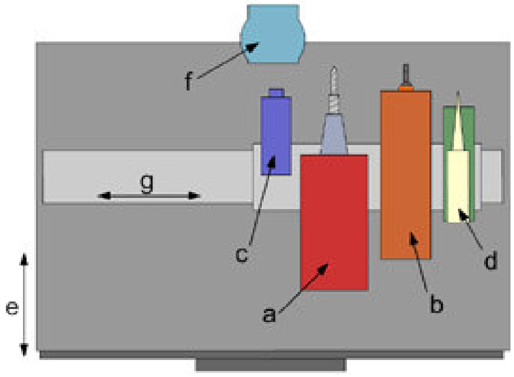

Figure 1. Layout of the EFIP's modules.

3. THE EFIP REQUIREMENTS

Each module of EFIP has its own requirements, which are related to the functionalities implemented in the module. Furthermore, each module has also to consider the global requirements of EFIP.

The global requirements are those that must be satisfied by the EFIP as a whole and are related to the EFIP dimensions, weight and process time (time for performing a complete cycle of drilling, applying sealant and inserting a fastener).

The EFIP weight is limited by the robot payload, which is a KUKA Robot (KR210-L100-2K). The maximum allowed weight is related to the distance between the EFIP CG (centre of gravity) and the robot flange and is illustrated in Figure 2.

The EFIP dimensions influence the CG position and limit the robot accessibility to the fuselage. The robot should be able to insert fasteners in a semi-circumference of fuselage.

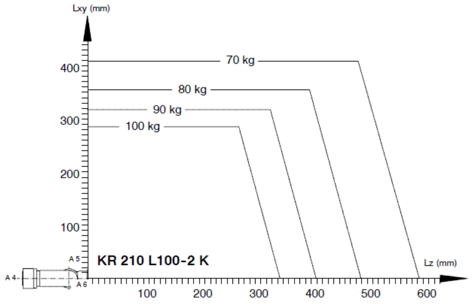

Figure 2. Diagram of payload of the KR210 L100 2K (KUKA, 2004).

The drilling process requirements result in a number of requirements that affect not only the drilling module but also the other EFIP modules. The position accuracy requirement of a hole performed by the EFIP in a fuselage structure is of 0,05mm. The perpendicularity accuracy requirement is of 0.5°. Both requirements are not achieved by ordinary industrial manipulator.

In order to guarantee that the hole will be within the perpendicularity tolerance, it’s necessary to correct the orientation of the drill.

Figure 3(a) illustrates the orientation of the drill within (θ1) and without (θ2) the allowed tolerance.

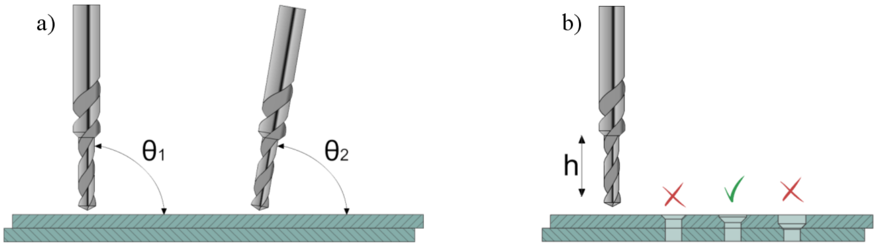

Figure 3. Driller perpendicularity error.

While the EFIP vision module corrects the linear position of the robot, the perpendicularity is corrected by a measurement system developed to detect small deviations of orientation. These angular deviations are then transmitted to the robot that will correct the EFIP orientation. The measurement is repeated until the perpendicularity enters on the allowed tolerances.

Another important feature of the drilling process is the formation of chips. In order to fix the fastener it's important to not have chips between the two fuselage surfaces. Generally the axial efforts of the drilling process separate the two fuselage plates and allow the formation of chips between them. In order to avoid this problem, the EFIP must be pressured against the fuselage surface.

The depth of the countersink must also be considered. This problem is illustrated in Figure 3(b). The EFIP must be fixed in relation to the fuselage and must control the driller axial motion, which is performed by the drilling module, as the robot does not have the necessary accuracy.

The pressuring of the EFIP against the fuselage is performed by the clamp module, but is applied through the perpendicularity module.

The perpendicularity module also affects the other modules, which, by there sides, also interferes on the perpendicularity module design. The width of the perpendicularity module must be surpassed by components of the following module: sealant, drilling and fastening module. The external diameter of the driller must pass inside the hole provided by the perpendicularity module. During the drilling process the perpendicularity module must provide refrigeration of the drill by applying a mixture of compressed air and oil fluid. After the drilling process, while the drill returns, the hole on the fuselage must to be cleaned. To this purpose, the perpendicularity module must be connected to an aspiration system that removes all the chips or dust of the drilling process. The seal applier and the fastener fixer must also pass inside the hole provided by the perpendicularity module.

Furthermore, the camera of the vision module must also capture the image through the perpendicularity module. As a consequence, the hole provided by the perpendicularity model must be large enough to view the references that are placed on the fuselage for the positioning of the EFIP.

4. THE PROPOSED DESIGN APPROACH

The strong relationship among the modules and the sharing of global requirements imply in an integrated design approach. The EFIP design has been organized as illustrated in Figure 4.

The first activity (Activity 1) is the definition of the process requirements. Based on the robot features and process requirements, a list of requirements for each module is defined (Activity 2). The next activity (Activity 3-) is the preliminary study of design solutions for each module. This preliminary study aims to detect how each module should interfere on the other modules. The preliminary study is concluded with a first baseline for the global requirement and a list of dependencies among modules (Activity 4). Each dependency can be characterized as a common variable that has a potential master (which will define the value of the variable) and potential slaves (which will be design according to the value defined by the master). An example is the width of the perpendicularity module, which is the master of the variable. The potential slaves are the drilling module, the sealant module and the fastening module.

Following the conception of each module is detailed (Activity 5). With appropriate time intervals, a joint meeting is organized to discuss the design of the modules and review the global requirement baseline and the list of dependencies, until all the modules are completely designed and integrated (Activity 6).

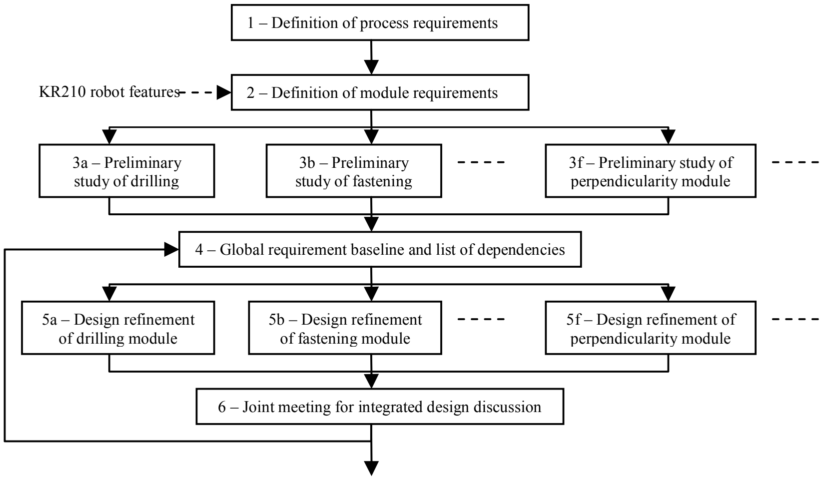

Figure 4. EFIP integrated design approach.

The purpose of this paper is limited to the design of the perpendicularity module. Its design integrates a number of techniques. These techniques aim to document and explain the module in order to provide integration with the designers of the other EFIP modules, according to Figure 4. It is organized as follows:

A) Elaboration of the objective tree (Activity 2)
B) Elaboration of the functional diagram (Activity 2)
C) Elaboration of the morphologic chart (Activity 3)
D) Detailed design (Activity 5)

The objective tree and the functional diagram are elaborated as part of the Activity 2 and are the input to Activity 3f, along with the process requirements related to the module. The morphologic chart is defined in Activity 3, when a number of module conceptions are studied and analyzed. After the revision provided by Activity 4, the morphologic chart is the input for the Activity 5f.

4.1. Objective Tree

The objective tree is a project technique that aims to simplify the representation of a problem by organizing in a single chart the many project objectives. It helps the project team to find solutions by mapping the 'anatomy' of the problem. In the EFIP integrated design approach, it is also used to illustrate the main dependencies among the modules. It is elaborated as part of Activity 2 of Figure 4 and is revised in Activity 4.

Figure 5 presents the objective tree of the perpendicularity module. The objective tree is divided in two branches. The right branch shows the measurement objectives. The left part of the tree has the requirements imposed by the integration with the other EFIP modules.

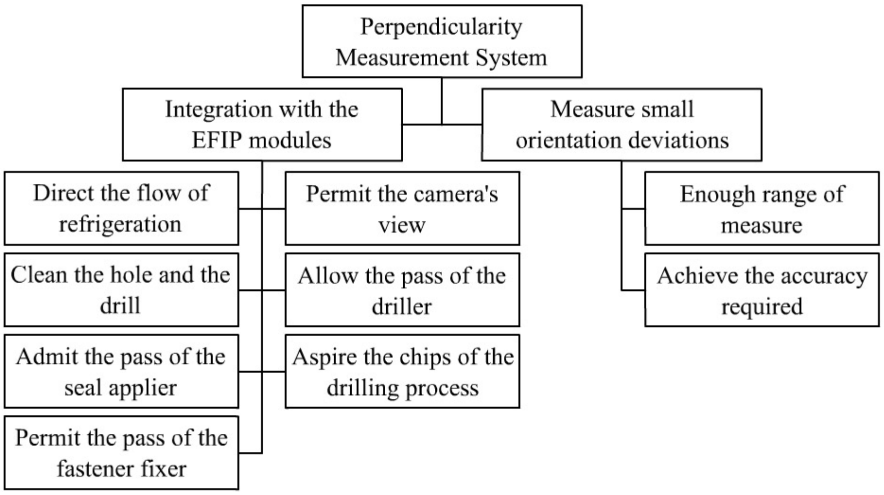

Figure 5. Objective tree of EFIP perpendicularity module.

4.2. Functional Diagram

Other important step of the initial activities of EFIP integrated design is the creation of a functional diagram for each module. The main functionality of the perpendicularity module is to measure the angular deviation between the EFIP and any aeronautical surface and to calculate the perpendicularity error. After that, when necessary, the robot must compute this information and increment the actual position. When the robot reaches the new position, another measure should be performed to validate the EFIP orientation and check if the orientation error is within the allowed limits (otherwise another correction cycle should be performed).

The EFIP tasks of drilling, sealing and fastening starts after the orientation of the EFIP is validated. All the EFIP modules must perform its own task without the interference of the perpendicularity measurement system. Because of that, the perpendicularity module functionality is not limited to the perpendicularity measurement. When the EFIP`s tasks begin, the perpendicularity module must allow the camera to capture the image of the reference on the fuselage surface. After that the driller module must execute its function and the refrigeration, cleaning and aspiration must to be activated. Finally, the seal application and the fasteners fixation must be done.

Figure 6 shows the function diagram of the perpendicularity module integrated in the EFIP.

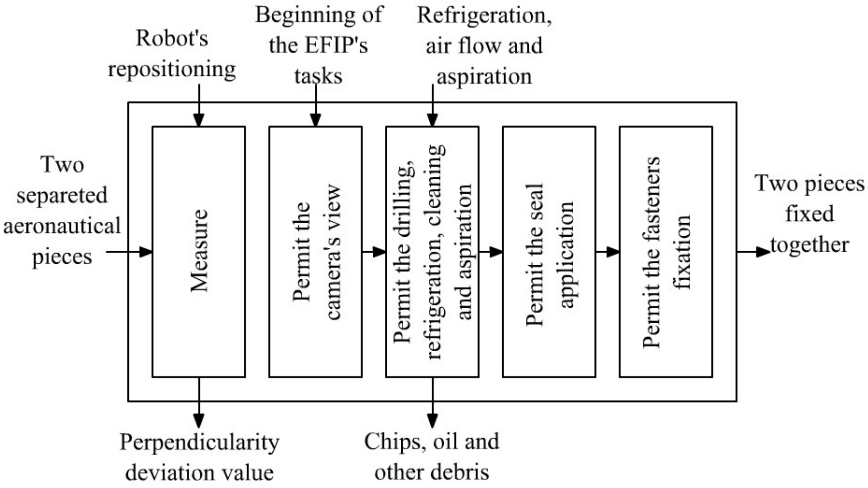

Figure 6. Function diagram of the project.

4.3. Morphologic Chart

The morphologic chart is a table with the functions of the project on the left column and the solutions in the others columns. This kind of chart is very important, because it shows the main possibilities to the product's development. The selections of which solution will be used generally use some criteria, like integration facility, cost and robustness. For this project, the most important criterion of selection is the impact of the choice in the EFIP weight and dimensions.

Table 2 shows the morphologic chart for the functions of the perpendicularity module. The painted cells on the table show the selected solution.

Table 2. Morphologic chart of the perpendicularity measurement system.

Functions	Solutions			
Measure	LVDT	Inductive sensor with analogue output	Optic distance sensor	Potentiometer
Permit the camera's view	To create a measurement system with the minimum diameter to permit the camera's view	To build the project with transparent materials	To do the perpendicularity measure out of the work area of the vision system	To develop the measurement system on a retractile structure
Permit the drilling process	To create a measurement system with the minimum diameter to permit the passage of the driller	To do the perpendicularity measure out of the work area of the drilling process	To develop the measurement system on a retractile structure	
Permit refrigeration	Guide the refrigeration's hoses on the outside of the measurement system	To create an inner cavity in the measurement system to guide the refrigeration flow	Ensure that the internal diameter allowing the passage of refrigeration's hoses attached to the drilling's system	
Permit cleaning	Guide the cleaning's hoses on the outside of the measurement system	To create an inner cavity in the measurement system to guide the cleaning flow	Ensure that the internal diameter allowing the passage of cleaning's hoses attached to the drilling's system	Add a new module on EFIP to do the cleaning after the drilling process
Permit aspiration	To do the aspiration from the back part of the measurement system with a high negative air pressure	Ensure that the internal diameter allowing the passage of aspiration's hoses attached to the drilling's system	To do the aspiration from the front part of the measurement system with a moderate air pressure	
Permit the seal application	To create a measurement system with the minimum diameter to permit the passage of the seal applier	To do the perpendicularity measure out of the work area of the seal application	To develop the measurement system on a retractile structure	
Permit the passage of the fasteners fixer	To create a measurement system with the minimum diameter to permit the passage of the fasteners fixer	To do the perpendicularity measure out of the work area of the fasteners fixation	To develop the measurement system on a retractile structure	

4.4. Detailed Design

Based on the morphologic chart presented on the Table 2, an engineering solution is proposed using a mechanical patella that will accommodate on the aeronautical surface. After that, the linear sensors measure this accommodation and calculate the angular deviation. This mechanical device touches the fuselage surface at reference point and the countersink depth is found. The patella must be pressured against the surface to avoid the creation of chips between the plates.

The measure of the angular deviation with linear sensor is complex, because the patella is a spherical joint and allows 3 degrees of freedom (dof). Just the rotation on the X and de Y axis are important to the perpendicularity measurement because the rotation on the Z axis makes no difference on the quality of the hole performed by the drilller. Figure 7 presents a spherical joint and the rotation around each axis.

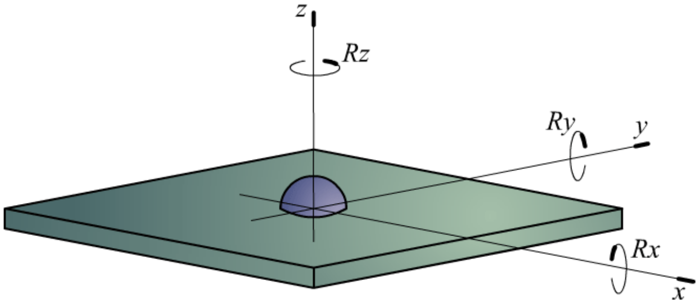

Figure 7. The spherical joint and dof.

It is necessary to force the contact with the fuselage in order to move the spherical joint. This pressure is provided by the clamp module. Figure 8 shows the lateral view of the spherical joint with a contact face. The basic principle used to calculate the patella's orientation is illustrated in Figure 8. The linear displacement measured by the sensor is called *b*, while the angular deviation is *Θ*. The value of *a* is constant and corresponds to the distance between the center of the patella and the center of the linear measure.

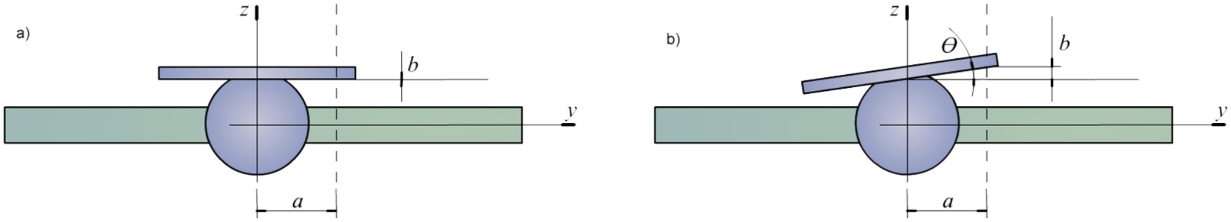

Figure 8. Lateral view of the spherical joint.

Figure 8(a) shows the patella in the initial position without any angular deviations and the value of the distance *b* is zero. When any deviation is applied (Figure 8(b)), the distance b is increased or decreased, and the angle *Θ* is calculated according to Eq. (1).

$$\theta = arctg\left(\frac{b}{a}\right) \tag{1}$$

Determiniation of the minimum accuracy

In the design of metrological system, it is a common practice to adopt an accuracy value for the system ten times better then the tolerance that should be measured. Following this criterion, the measurement system must have the accuracy of ±0,05°, which is the necessary accuracy to assure a perpendicularity tolerance of the holes of ±0,5°.

Eq. (2) shows the calculation of the minimum necessary accuracy of the linear measurement system using the variables of the Figure 8(b).

$$b = \pm a.tg\theta = \pm a.tg(0{,}05°) = \pm 8{,}73.10^{-4}.a \tag{2}$$

The accuracy of this measurement system is proportional to the distance between center of the patella and the center of the linear measure. The range requirement of this project is to be able to measure ±5°. The calculation is indicate by the Eq. (3).

$$b = \pm a.tg\theta = \pm a.tg(5°) = \pm 8{,}75.10^{-2}.a \tag{3}$$

Integration implication

According to Table 2, the perpendicularity module should have the minimum diameter that does not conflict with its functionalities. The higher required diameter is defined by the driller, which uses an HSK-32 system to fix the drill. That means a diameter of 32mm, so the internal diameter necessary for this application is about 40mm considering a good clearance.

Using the inner radius of 20mm, an estimated distance between the center of the patella and the center of the linear measurement system is about 35mm. With this value is possible to calculate the accuracy and the range of the linear sensor using the Eq. (2) and the Eq. (3). Table 3 shows the results of this calculation.

Table 3. Minimim accuracy and range of the linear sensor.

Accuracy	±30,5μm
Range	±3,06mm

Looking to the Table 2, it is possible to see that the refrigeration and the cleaning flow use an inner cavity on the patella. This is the better solution because there are no hoses in the contact face of the spherical joint, so the leaks problem caused by little chocks may be reduced. Both the refrigeration system and the cleaning system will use the same cavity, the control of the EFIP will chose which kind of mixture will pass according to the stage of the drilling process.

The aspiration process uses hoses, because the flow is too large for small cavities inner the patella.

Selection of the linear sensor

The main problem of the EFIP design is to reduce the weight and the dimensions. Because of that, the smallest sensor should be used, which are based on the inductive technology. There is a class of inductive sensors that uses an rectangular encapsulation and has the thickness of about 8mm. Table 4 shows the accuracy and the range of 3 inductive sensors with analog output from different manufacturer.

Table 4. Comparative of inductive sensors.

Model	Manufacturer	Accuracy	Range	Thickness
Bi7-Q08-LiU	Turck	40μm	3mm	8mm
BAW R03KC-UAE40B-BP03	Balluff	35μm	3mm	6mm
DW-AD-509-C8-309	Contrinex	10μm	4mm	8mm

All of the features of these sensors are in agreement with the EFIP project, but the range. The sensors from Turks and Balluff have the range of 3mm. Using the Eq. 1 and putting the range value of the sensor on the value of b it is possible to calculate the maximum angular range of each sensor, in this case ±2,4°. In order to solve this problem, two sensors will be installed to measure the linear deviation. One of them will measure the negative angle and the other, with 3mm of off-set, will measure the positive angle, resulting in a range of ±4,9°.

Mechanical Design

The sensors are installed on the back part of the patella to protect the metrological operations from the impact of the surface. Figure 9 illustrates the four sensor installed orthogonally (detail a) and the input device for these sensors (detail b). The internal diameter permits the passage of all modules of EFIP (detail c).

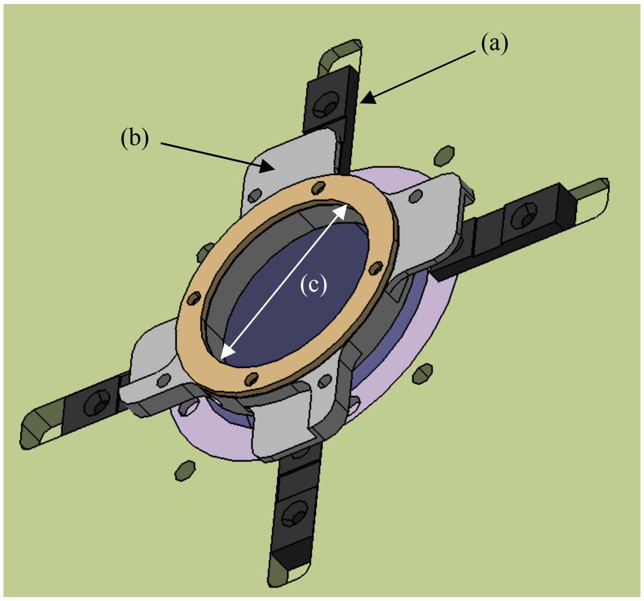

Figure 9. The back part of the perpendicularity measurement system.

Figure 10 shows the front part of the perpendicularity measurement system. It is possible to see the little hole from the cavity to refrigeration and cleaning (detail a) and the connection to the aspiration hoses (detail b).

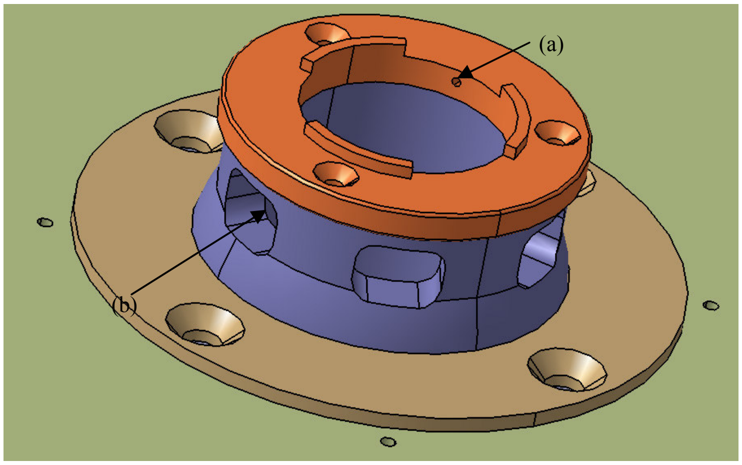

Figure 10. The front part of the perpendicularity measurement system.

Figure 11 is used to show the assembly of the perpendicularity measurement system. The front nose is easy to change, because the life of this part can be reduced by the contact with the aeronautical surface.

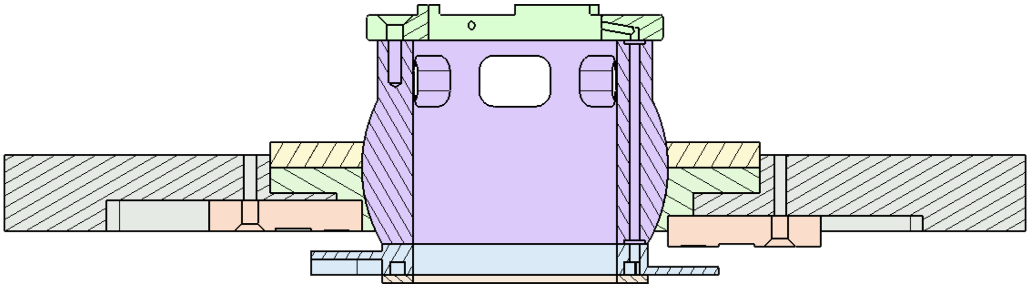

Figure 11. Assembly of the perpendicularity measurement system.

5. CONCLUSIONS

This paper presents the design approach used to develop a perpendicularity measurement system for an end-effector that should be used in the robotic automation of aeronautic fuselage assembly. The most challenge feature of the perpendicularity measurement design is the integration with the design of other end-effector modules, which imply in global requirements shared among the modules and on a number of dependencies.

The integration requirements are satisfied in the CAD model. The resulting product allows the passage of all requested modules and gives refrigeration, cleaning and aspiration to the drilling process. It also avoids the creation of chips between the plates by touching the surface with some axial force and reference the zero position to the countersink depth.

The metrological requirements are partially satisfied by the proposed system. The accuracy of the proposed solution is within the range specified by the requirements. However, the necessary range to the angular measure is 5° per sensor, but two of tree sensors has the range of 4,9°. Once that the difference between the required range and the real range is small, this is not considered critical for the EFIP. In the future, an algorithm should be implemented to broad the range based on the repositioning of the robot when the angular deviation is great than the sensor range.

A prototype is under construction, but is important to know how to calibrate this measurement system. In order to validate the measurement features a specific calibration device has been design. The calibration device will be installed in the front part of the perpendicularity module. A known deviation of perpendicularity must to be applied on this device and measured by a Coordinate Measuring Machine (CMM). It is then possible to measure the angular deviation and compare with the value calculated by the linear sensors.

5. ACKNOWLEDGEMENTS

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