Force Feedback for Assembly of Aircraft Structures

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Force Feedback for Assembly of Aircraft Structures

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ABSTRACT

Variability in composite manufacture and the limitations in positional accuracy of common industrial robots have hampered automation of assembly tasks within aircraft manufacturing. One way to handle geometry variations and robot compliancy is to use force control. Force control technology utilizes a sensor mounted on the robot to feedback force data to the controller system so instead of being position driven. i.e. programmed to achieve a certain position with the tool, the robot can be programmed to achieve a certain force. This paper presents an experimental case where a compliant rib is aligned to multiple surfaces using force feedback and an industrial robot system from ABB. Two types of ribs where used, one full size carbon fiber rib, and one smaller metal replica for evaluation purposes. The alignment sequence consisted of several iterative steps and a search procedure was implemented within the robot control system. The technology has the potential to lessen the need for dedicated tooling, reduce the need for traditional workspace calibration and can be used in several other applications, such as pin and socket type assemblies found in pylons or landing gear or "part to part" assemblies such as leading edge ribs to spar.

INTRODUCTION

Current automation in aerospace industry is based around large dedicated fixture systems. They take a long time to design and manufacture, inhibit a concurrent engineering process and often result in a lot of tied up capital. Industrial robots have the potential to be used to position parts during the manufacturing process but are often not accurate enough to meet the tight tolerance demands of aircraft manufacture. A standard robot such as, for instance, the ABB IRB4400 with 60 kg payload has a repetitive accuracy of ±0.05 mm but the worst case absolute accuracy within the whole workspace may generally be around ± 3 mm without extra calibration. Also, since the robot is a compliant structure, the accuracy is only guaranteed if no external force is applied.

There is also the problem of manufacturing variability especially in materials such as carbon fiber, and these challenges are likely to remain for the foreseeable future. Current assembly techniques do not address manufacture variability effectively and manual procedures such as shimming are often required to fit components together to the tolerances required in aerospace. In order to find a suitable automated assembly solution one requirement is that it must be able to account for the variations in manufacture which will inevitably occur.

Automation of aircraft assembly has been mostly focused around drilling and riveting but there has been both research and commercial developments to automate assembly. One example is presented in [1] which describes the AWBA-project where a robot was used to place compliant ribs in a wingbox using a metrology system and pre-drilled holes common to aircraft assembly to align the parts. Another approach using vision and laser based systems to improve positional accuracy of industrial robots and to handle part variations is described in [2]. In this case two off -the-shelf metrology systems were used to scan the part prior to grasping to calculate pick-up position and afterwards when the part has been picked up to calculate misalignment and deformation. This approach also handles variability in part geometry. Another way to handle geometry variations but also external forces acting on the robot is to use force control. Force control technology utilizes a sensor mounted on the robot to feedback force data to the controller system so instead of being position driven. i.e. programmed to achieve a certain position with the tool, the robot can be programmed to achieve a certain force. Common applications for force control are assembly, deburring, milling and polishing. In aircraft manufacturing force control has been used for drilling, see e.g. [3]. Force control opens up the possibility of using common industrial robots to best fit parts in an assembly operation by creating search patterns, for example to program the robot to do a circular motion with a tool until a pre-set condition is true.

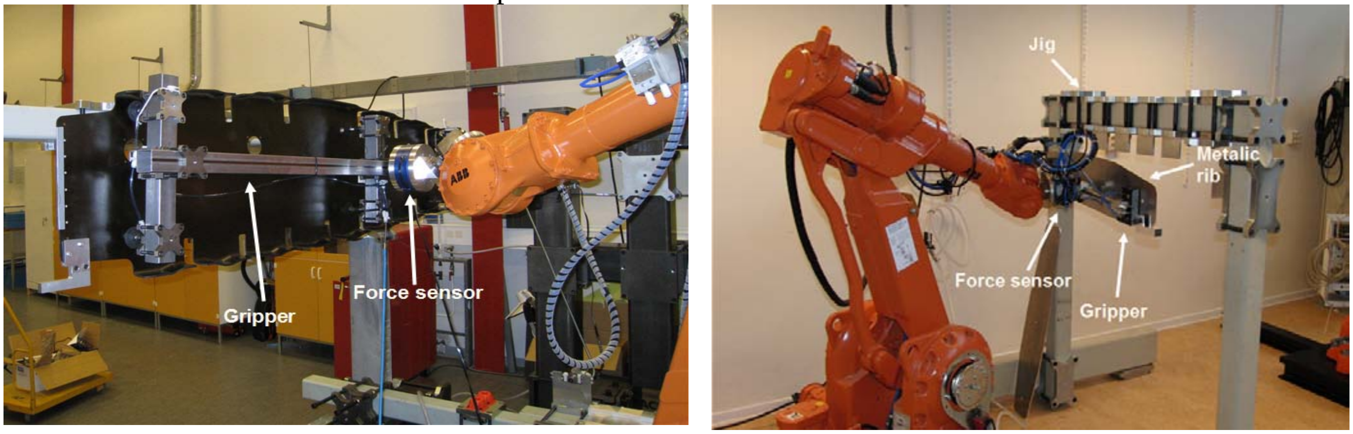

Figure 1 - Left; The IRB 4400 with the gripper and carbon fiber rib. Right; The IRB2400 duplicate setup with metallic rib.

THE ASSEMBLY SEQUENCE

The assembly case described in this paper is to "best fit" a semi-compliant aircraft component, in this case a rib, to multiple surfaces using an industrial robot equipped with force feedback. While holding the rib the robot must detect the points of contact and align the component to these surfaces to achieve the "best fit", i.e. to reduce the gaps and subsequently lessen the need for shimming. After the alignment procedure is completed there are a number of alternative solutions to close the remaining gaps, and these are left to be discussed later in the paper. The experimental setup was duplicated on two different sites, at Linköping University and at Lund University respectively. This was done to facilitate parallel development and testing. The experimental cell at Linkoping consists of an ABB IRB4400 robot handling a full sized carbon fiber rib, while the one in Lund utilizes a smaller IRB 2400 robot and, due to payload restrictions the carbon fiber rib was replaced by a smaller thin metal rib replica (see figure 1). The experimental jig consists of brackets in a metal frame (se figure 2). The brackets can be positioned to replicate variability in part surfaces.

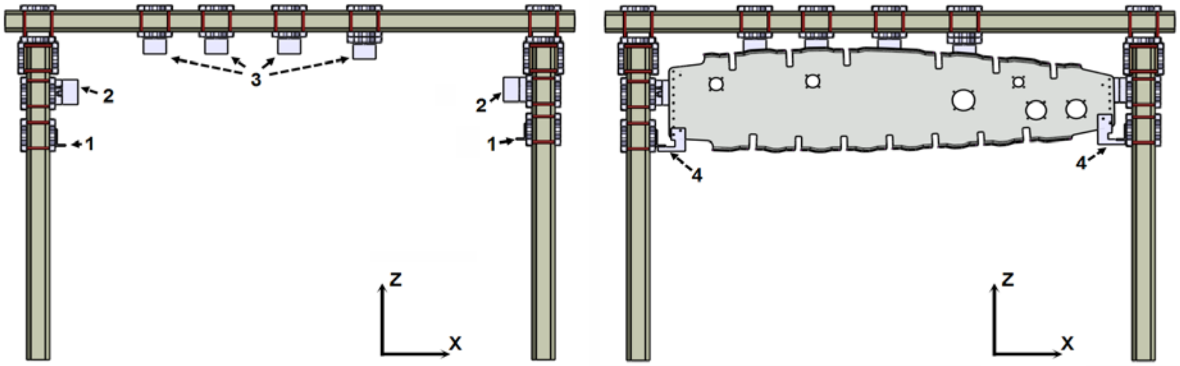

Figure 2 - Left: Overview of the test jig and the brackets. Right: The jig with the rib in final position.

The brackets in position 1, figure 2, can be adjusted in the Z-direction, and the brackets in position 3, figure 2, can be rotated around Z and moved in the Y-direction. The actual bracket is showed in figure 3. This means that the brackets in pos 3-6 in figure 2 can be skewed in relation to each other and to the other brackets, making it possible to evaluate how well the force control handles variability. The brackets are used to set the location of the rib in 6 degrees of freedom. The brackets in position 1 in figure 2 together with two stops (position 4 in figure 2) mounted on the rib are used to set the height (Z) and the brackets in position 2 (figure 2) are used to set the vertical location (X) but also sets the Y-location along with the four brackets in position 3.

Figure 3 - The top brackets can be moved in two degrees of freedom.

The assembly sequence can be compared to a search pattern where the final assembly location is reached by the following steps;

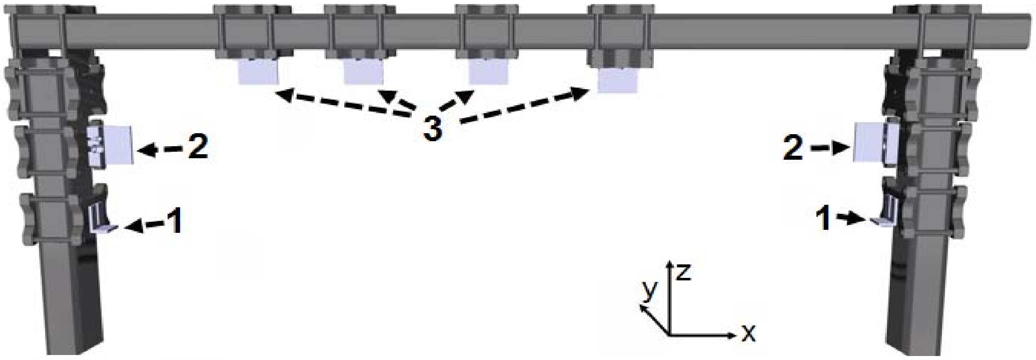

Figure 4 - The test jig in 3D

1. From initial position drive the robot so that the rib makes contact with the left bracket at position 2, figure 4
2. Rotate around left rib edge until rib hits the opposite bracket (right position 2 in figure 4)
3. Tilt the rib forward until it hits the brackets in position 3 in figure 4 (se also figure 5).
4. Store position and back out.
5. Raise the rib until it hits one (or both) of the brackets in position 1, figure 4.
6. If only one of the brackets is in contact, rotate around that edge until the other bracket is found.
7. Store position and move the rib down until the contact is released.
8. Move the rib vertically until it touches the inner edge of the left bracket in position 2, figure 4. Store position.
9. Move in the opposite vertical direction until the rib touches right inner edge of right bracket in position 2, figure 4.
10. Middle position is calculated and data from step 4 and 7 is used to achieve final position.

The transition from one step to another is triggered by the force sensor readings and the sequence is modeled in a Matlab add-on called Stateflow, which will be further described later in the paper. The use of Stateflow has the benefit of enabling the assembly sequence and the force control model to be developed independently.

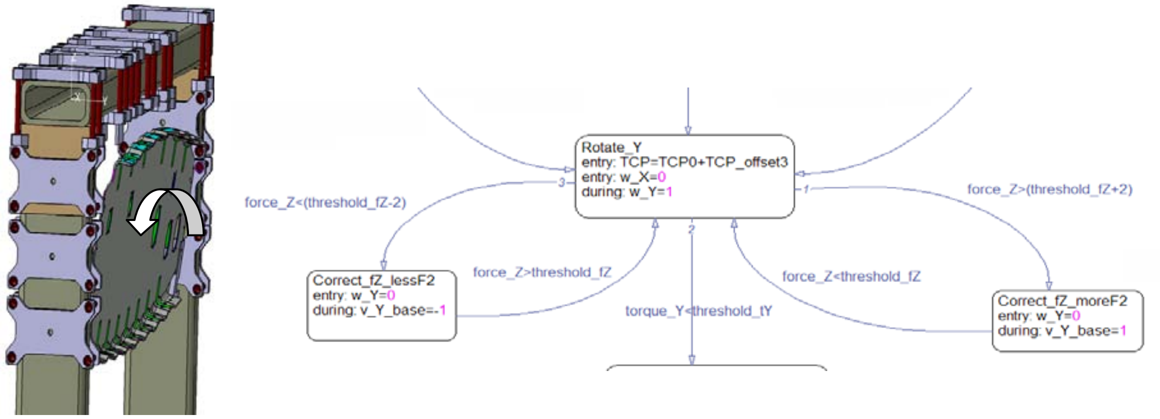

Figure 5 - Assembly step 7 pictured to the left, where the rib is tilted forward until in contact with the top brackets. To the right are the suggested corresponding Stateflow blocks.

THE SYSTEM

The systems consist of an industrial manipulator (an IRB4400 and IRB 2400 respectively) with an industrial robot controller, a master computer and a force/torque sensor attached to a vacuum gripper. The robot, gripper and force sensor can be seen in figure 6. The sensor is a 6 degree of freedom JR3 force sensor which can measure forces in X, Y and Z and corresponding torques. The robot controller is the S4CPlus system, the fourth generation of ABB robot controllers. However, the industrial controller has been extended with an open robot control system developed for research and rapid prototyping, see e.g., [3]. For a recent overview of open robot system architectures for industrial manipulators, see [4]. Although force control functionality has appeared among the major robot manufacturers during the last couple of years, still a more flexible solution regarding both control algorithm implementations and task description has been required in the described case. The inner positioning loop has been opened up by ABB Robotics in order to enable interaction with the robot. There is also additional hardware for handling force sensor data and the force control algorithms. One of the hardware features added is a Motorola G4 processor which communicates with the S4CPlus system through a common bus enabling a sampling time of 4 ms. This makes it possible for the robot to react to forces in both magnitude and direction with suitable performance for a large variety of machining and assembly operations.

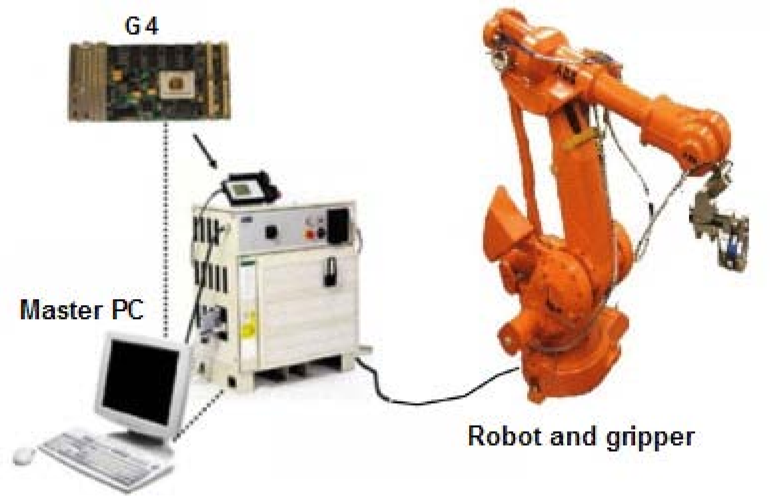

Figure 6 - The system

The master PC handles data and acts as the cell controller, and it is through this computer that the force controller code is downloaded to the G4 processor. The executable controller code is generated through Matlab/Simulink and the Real-Time Workshop toolbox with the actual sequencing modeled in Stateflow within the Simulink model. In the Simulink blocks different position/force algorithms have been implemented and the task specifications are using the constraint-based methodology from [5].An example of the Matlab/Simulink controller is shown in figure 7. The advantage with modeling the sequence in Stateflow is that the different steps of the assembly sequence (or states) can be visualized, one example is showed in figure 5. The squares denotes the steps (states) and the text inside is a description of what will happen during the state (for example making the robot search in a certain direction with a specified velocity).

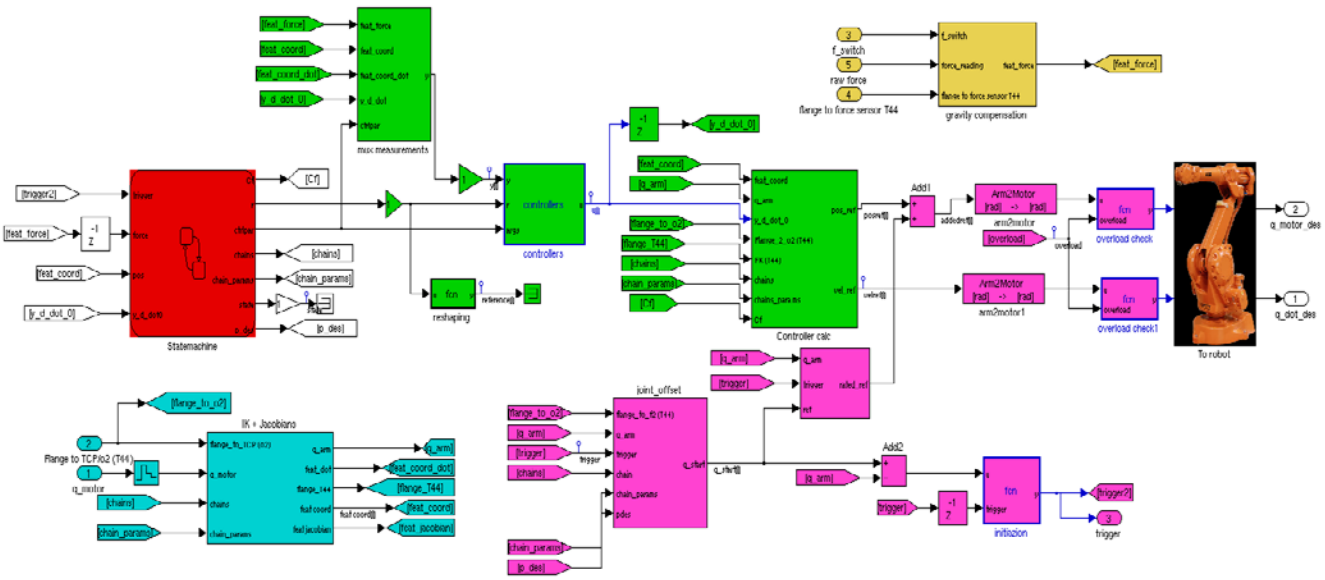

Figure 7 - Example of Matlab/Simulink block for the robot controller. The red subsystem encapsulates the assembly sequence modeled in Stateflow and the dedicated position/force control algorithms are marked with the green subsystems.

The arrows denote the transition between states along with a text describing the condition for change. The robot is programmed manually and the assembly program starts by the robot positioning itself in the start position.

RESULTS

A simplified assembly sequence using the IRB4400 and the full size carbon fiber rib has been successfully tested where the robot searches linearly to achieve a desired force. The Stateflow model for this can be viewed in figure 8. When the force control is switched on the run starts with the robot searching in the vertical direction (Z in figure 2) for one of the stops in position 1 (figure 2 or 4). This corresponds to the "SearchZ" state in figure 8. If no contact force is sensed within a specified period of time, or if the specified contact force is achieved the next state is initialized; the "WaitingA" state. After a 4 second waiting period the robot then seeks the brackets in position 2-7 (figure 4) and upon contact (or time limit reached) transitions to another waiting period ("WaitingA1") before it starts to back out. The test has been run a multiple of time successfully.

With the smaller metallic rib replica (using the IRB2400-robot) the different unit operations of the assembly sequence have been verified (both linear and rotational search/contact sequences). Experimental results of the two first steps of the sequence are shown in figure 9. As a complement to the fully automated sequence, human-robot cooperation using “lead-through techniques” i.e. manually guiding the robot using force control, has also been experimentally validated. This can be used for either programming the assembly sequences or for actually performing a subset of the sequences on-line (e.g., the operator leads the robot, which is carrying the heavy rib, to a contact, from which another subsequence is initiated).

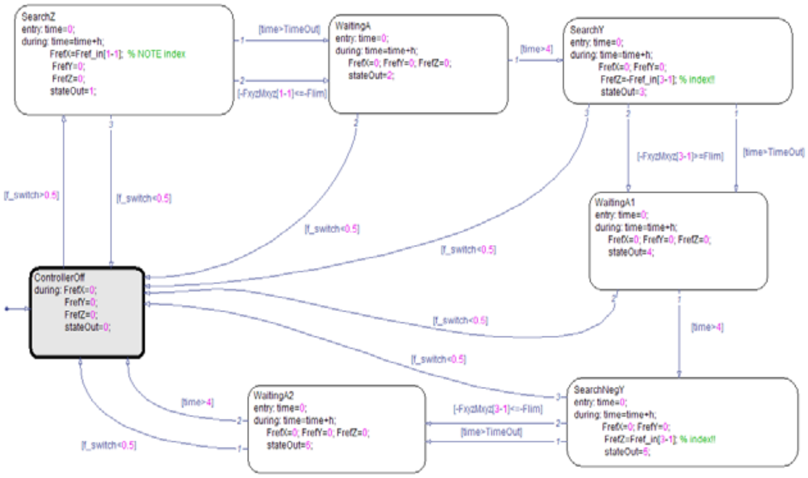

Figure 8 - Stateflow model of search for contact in Y and Z.

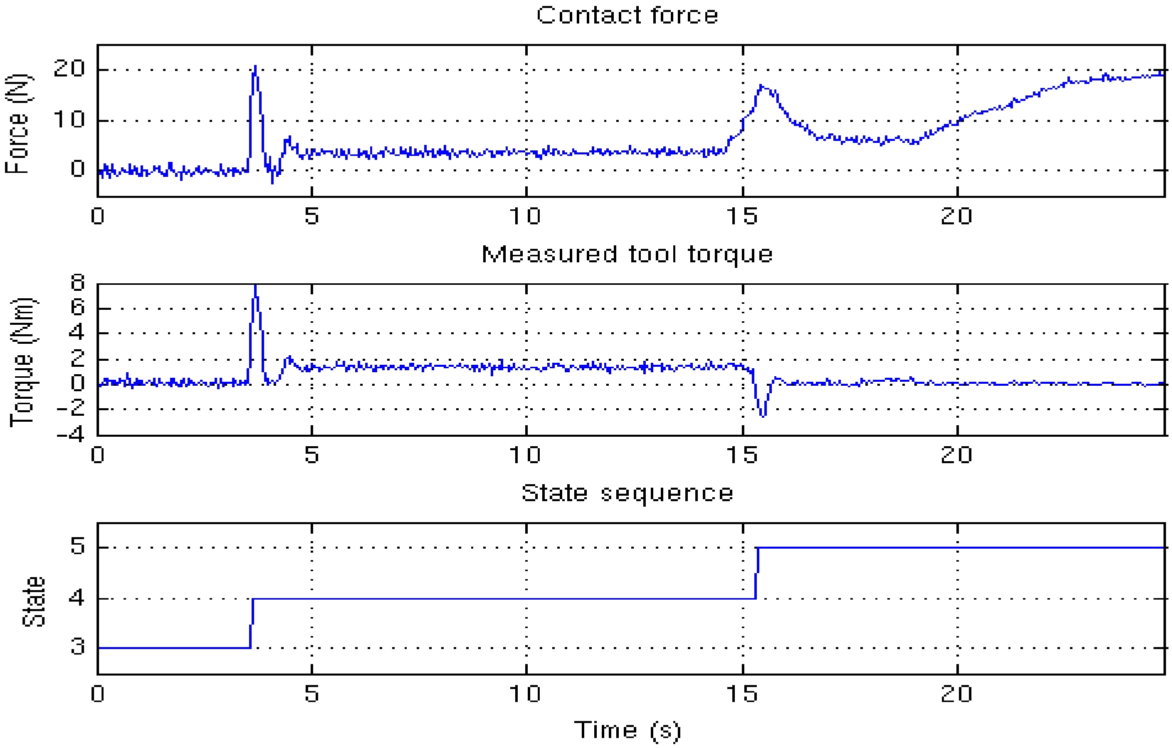

Figure 9 - Results of two first steps in the assembly sequence: The upper plot shows the measured contact force, the middle plot the measured torque around the tool center and the lower plot the corresponding mode/transition in the Stateflow diagram (“search until contact”, “rotation while keeping contact with the left rib edge”, “steady contact with both rib edges”). The transition conditions are clearly visible in the measured variables.

SUMMARY/CONCLUSIONS

In aircraft manufacturing it is common to correct the contact points so that the products that are to be assembled will fit almost perfectly. The products can then be clamped prior to drilling. Although this option presents the most advantages in terms of speed of assembly there will be non value added time in the correction of components either through machining or shimming. Another feasible situation occurs when the contact points have not been corrected and the products must be assembled in a "best fit" location as the focus has been in this paper. This is a more complex operation as the robot must detect the contact points and then position the rib to minimize the shim/gap requirements. After the "best fit" procedure is complete there are a number of alternative solutions to close the remaining gaps.

a) Firstly the robot/rib gripper mechanism could be capable of closing gaps by applying a suitable force at certain locations if the products' contact points were designed to flex. This is not a straight forward exercise to establish how much stress and strain is allowed to be applied to a rib and contact points without exceeding allowable stress. If feasible however this solution gives the most efficient performance and is most suited to a high rate production line. A clamping mechanism would still be required prior to drilling.

b) A similar solution would be if the rib was initially best fitted with gaps still present, suitable clamps could then provide the necessary force through which the gaps were closed. Again the forces applied to the rib/attachment points in addition to the values of the gaps closed would need to be monitored to ensure allowable force were not exceeded. Finally if the gaps were not closed with applied force or clamping and instead only a best fit solution resulted, another procedure would be required to determine shim requirements.

Instead of letting the robot run the whole assembly sequence it is possible to let a human operator guide the robot to desired positions. To use the force control to move a robot is done in for example in lead-through programming, where an operator programs the robot by moving the end-effector (the tool or gripper) using so-called "lead-through" and storing the desired positions. In the assembly case described an operator would move the robot by the gripper and perhaps execute only parts of the program automatically, as for example the tilting of the rib where it is important to achieve a certain force between the assembled products. A film showing how the robot can be moved in X, Y and Z using force control is available at http://www.iei.liu.se/mt/research/files where also other movies of the linear and rotational search sequences can be downloaded.

The flexibility of using a standard industrial robot and the high performance of the force feedback system highlighted a number of additional applications to be investigated within wingbox and aircraft manufacture and assembly. Machining of composite components after cure, assembly of leading or trailing edge ribs to a spar, pin and socket type assemblies such as those found in pylons or landing gear are such examples. The search pattern needed to achieve the best fit of the components is expected to increase the overall assembly time when compared to a laser or vision system for example. However the assembly time is still far superior to current techniques and more than sufficient for high volume aircraft manufacture. Due to its autonomous nature the technology is suitable for high volume, repeatable yet variable manufacturing and assembly. Its low purchase cost and the fact that a single sensor has can be used for multiple operations gives excellent productivity. In addition the technology supports future jigless assembly with small reconfigurable pick ups providing the means of handling components rather than conventionally large bespoke tooling.

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