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Snake-arm robots: a new approach to aircraft assembly

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ABSTRACT

This paper describes work being conducted by OC Robotics and Airbus to develop snake-arm robots to conduct assembly tasks within wing boxes – an area currently inaccessible for automation.

The composite, single skin construction of aircraft structures presents new assembly challenges. Currently during box close-out it is necessary for aircraft fitters to climb into the wing box through small access panels and use manual or power tools to perform a variety of tasks. In future wing designs it may be that certain parts of the wing do not provide adequate access for manual assembly methods. It is also known that these manual interventions introduce health and safety concerns with their associated costs.

Snake-arm robots provide a means to replace manual procedures by delivering the required tools to all areas of the wing box.

Such a development has broader implications for aircraft design and assembly. There is potential for considerable cost savings for the aerospace industry through reduced weight, improved aerodynamics, standardisation of assembly processes, increased rate and reduced health and safety costs.

This paper presents early results of the demonstration snake-arm robot and outlines expectations for future development. It also identifies critical design parameters for the snake-arm and considers the tools and processes delivered by the snake-arm.

BACKGROUND: ROBOTICS IN THE AEROSPACE INDUSTRY

The key drivers in aircraft manufacture are increasing production rate and reducing costs. These are compounded by the additional challenges involved in reducing emissions and operating in an increasingly competitive, global market.

Energy efficient flight is such a fundamental requirement that lightweight aerodynamic design is a higher priority than ease of assembly.

However the proposed thinner wing sections become increasingly difficult to assemble using standard manual techniques. In particular there may be sections of the wing where the wing is both too small for a person to climb inside and at the same too big for a person to reach in with their arm. In such situations an alternative solution is essential.

This issue is further exacerbated by increasing health and safety requirements of confined space working which may in time make in-wing working unacceptable or too costly. For instance, the local fire department may be required to cut open a wing if an operator is unable to climb out.

Furthermore there is an unquantified but recognised risk of manual damage to composite structures caused by operators using composite structures as ladders to climb around within the wing, or damage caused by dropping a tool. Currently any such events need to be marked and investigated using NDT techniques.

The confluence of these risks and opportunities make minimally invasive automated assembly of low access structures extremely appealing.

However the creation of a robot with long arms is not the global panacea. The easier solution is to minimise the amount of assembly and maintenance work that is required once the wing box is closed. Designing a wing to be at least partially equipped when it is an open structure makes it much more amenable to manual or automated methods.

However in all cases there comes a point when a wing has to become a box, and aerodynamic and weight saving conditions may dictate that the box is constructed earlier than is ideal for assembly.

Some of the tasks that are currently conducted manually within a wing are best described as ‘skilled’ tasks. For instance parts may be hand fettled in order to fit. Sealing is also a complex skilled task. Even when space is not limited, the level of skill required to assemble an aeroplane is a clear differentiator between automotive and aerospace assembly techniques.

The comparison between the automotive and aerospace industries is often made and used as a driver for change. The critical breakthrough for the automotive industry, which occurred about 100 years ago, is now commonly referred to as ‘interchangeability of parts’. This enables tasks to be deskilled and automation to be used.

Interchangeability of parts is of course a priority within the aerospace industry, although the crucial difference between the aerospace and automotive industries is the scale of the end-product. For reasons of aerodynamics, aircraft have to be made with about the same absolute precision as cars. But since aircraft are more than ten times the scale of cars this effectively means that components have to manufactured and positioned at least ten times more precisely. This level of precision over such a large range of movement creates a real challenge for automation engineers.

AEROSPACE DEMONSTRATOR

Airbus UK is working in close collaboration with KUKA and others to actively develop aerospace robots [1]. These large industrial robots will deliver end effector packages capable of drilling and sealing.

When considering low access automation, the approach being taken is to consider a snake-arm robot [2] as an additional tool that the larger industrial robot can deliver. The basic concept is shown in Figure 1.

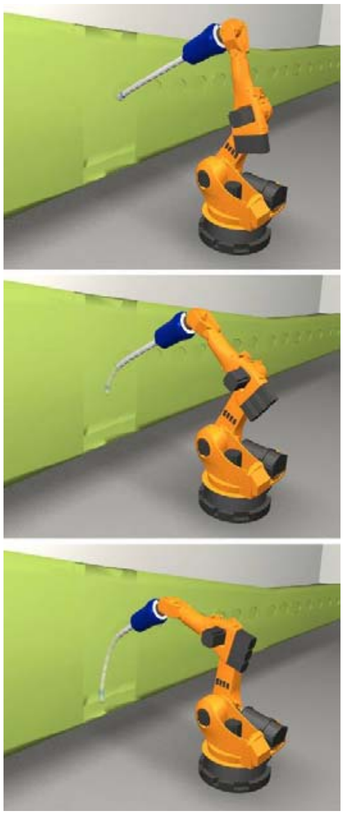

Figure 1 - Snake-arm robot reaching into the wing box

Figure 1 shows a simulation of the snake-arm advancing into the wing box in nose-following mode. This is the essential characteristic of OC Robotics’ proprietary control software. The robot is programmed offline to reach specific locations and the body of the snake-arm tracks the position taken by the tip of the arm. This allows the snake-arm to operate through the access hole whilst also avoiding the rib bay walls.

This nose-following motion is achieved by coordinating linear movement of the base of the snake-arm robot with the motion of the snake-arm robot axes. Figure 1 shows the industrial robot providing the linear movement required for path-following with the snake-arm robot attached as a forearm at the industrial robot’s wrist. It is the coordinated motion of the industrial robot and snake-arm which gives the system its flexibility.

A full size snake-arm robot demonstrator has been built that can snake into a rib bay to inspect, apply sealant and swage lockbolts (Figure 2).

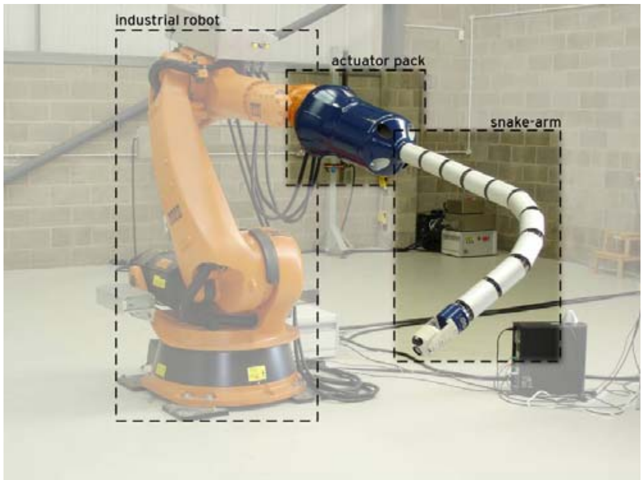

Figure 2 - Snake-arm robot mounted on a Kuka industrial robot

The snake-arm is the long slender ‘proboscis’, which is mounted on a standard Kuka industrial robot.

Figure 3 shows a snake-arm robot developed for Airbus by OC Robotics reaching into a mock-up of a rib bay in a wing and conducting swaging tasks.

Since the industrial robot and the snake-arm have separate control systems and different mathematical architectures, it is necessary for the industrial robot to act as the slave of the snake-arm control system. This allows for the overall system to be decoupled into two kinematic chains.

Figure 3 - Snake-arm robot reaching into a rib bay mock-up

The snake-arm is also equipped with a wrist and interface to attach different tools. The tasks considered as the focus of the work were swaging a standard aerospace fastener, applying sealant and conducting inspections.

The complete snake-arm robot demonstrator system (Figure 4) has a number of sub-systems. The design of the snake-arm required careful consideration of size, flexibility and payload. Establishing these parameters determined the design of the links that make up the arm. The arm is driven by an actuator pack, which includes linear actuators that pull the wires and the necessary control circuits. The actuator pack is mounted on a mechanism to allow it to be introduced into the working environment in the required orientation. The arm has a single degree of freedom (“pitch”) wrist at its tip to allow a tool to be placed in the required orientation for a task. The entire snake-arm robot is rotated about its axis to enable orientation of the wrist in the “roll” axis.

The arm was designed using proprietary software tools that allow the kinematics of the arm to be optimised for a given environment. This software is also used to drive the actual hardware and can therefore be used for training.

The demonstrator snake-arm is 1.2m in length and 100mm in diameter, with a hollow bore that is 25mm in diameter. The complete system has a mass of 50kg and a centre of gravity 250mm from the attachment to the industrial robot wrist axis. The arm has 10 segments, with each segment having two degrees of freedom. This gives the arm the flexibility to nose-follow into the rib bay. The complete system has 27 degrees of freedom.

Figure 4 - Demonstrator and rib-bay mock-up

The snake-arm robot follows a path into the wing-box, either by joystick control or from a pre-determined ‘path library’. The arm then moves in ‘Cartesian mode’ either by joystick control or automatically, assisted by tool-mounted cameras and machine vision to ensure it is correctly aligned before beginning each task.

END EFFECTORS

Three process tasks were selected to demonstrate the capabilities of the snake-arm: inspection, lockbolt swaging and sealant application (Figure 5).

Figure 5 – (Left to right) inspection tool; sealant tool; swage tool

Inspection is the most straightforward of the three tasks and demonstrated how a small, relatively low payload, non-contact end effector might be used.

The swaging task involved precisely positioning the 5kg tool over the lockbolt and then reacting any forces from the swage process that were transmitted through the snake-arm. It is impossible to guarantee the position of a lockbolt from a priori data, for example from a CAD model, so the tool design had to include a vision system to guide the tool onto the bolt. 1/4”, 5/16” and 3/8” lockbolts have been successfully swaged.

One by-product of this contract is that OC Robotics has designed an all-electric swage tool. Swage tools are currently pneumatic and have trailing services. This new tool means that it would be possible to convert to using all electric, battery powered, swage tools on existing production lines.

Sealant application is the task that currently requires the highest level of manual skill. With composite structures the application of sealant or adhesive becomes even more critical.

OC Robotics designed and implemented an all-electric sealant tool that extrudes a bead of sealant. The arm can drive the tool along complex paths, such as following around a rib foot profile.

In production, many tasks in the wing box involve very restricted geometry, requiring long tool noses with ‘shark bites’ for clearance or offset heads. The demonstrator shows the feasibility of using representative tools on a snake-arm robot rather than using precise worksite geometries. Future work will include adapting the tools for specific work sites with restricted geometry, and developing the tools to achieve the tasks to acceptable production quality.

MODES OF OPERATION

Various modes of operation of automation equipment have been identified by Airbus UK, and have been identified as requirements for the system. These are outlined below.

FULLY AUTOMATIC OPERATION

The system has been designed to allow automatic operation without an operator being present. The operator is only required if the system encounters a problem or when a manual operation is necessary, such as a non-routine task or quality control check.

SEMI-AUTOMATIC OPERATION

The system has been designed to allow semi-automatic operation. The operator initiates a program, which the robot executes. The robot then waits for the next manually selected start signal. The semi-automatic selection also allows the operator to drive the robot to a position before selecting a program, which then runs automatically, and the operator then drives the robot out of the area manually.

MANUAL OPERATION (TELE-OPERATION)

This is where the operator controls the motion of the tip of the snake-arm using a robot control pendant and visual feedback from the various cameras. Manual control also allows functions such as jogging, zeroing, homing and maintenance checks etc to be made. Control of a snake-arm is never fully manual. It is not practical for an operator to control all 27 degrees of freedom, hence the operator’s tip motion requirements are used as inputs to he robot control software that ensure that the remainder of the arm, and in this case the industrial robot, move in a way to avoid collision with the environment.

VISION-ASSISTED OPERATION

Industrial robots work on the principle of being adequately rigid so that the position of the tip is known to better than the process tolerances required. This ability can be affected by variable loading conditions and depends on the robot configuration. These disturbances, some of which are dynamic, can be compensated for by calibration and the use of external tracking and measurement devices such as laser scanners [1]. The same issues apply to snake-arm robots, although whilst line of sight is possible in a typical industrial robot environment, this is not the case when working within enclosed spaces.

The important relationship in the various production processes under consideration is the relative position of the tool with respect to the component and how the forces are transmitted during the process. Such considerations lead to the concept of tools that take their reference from local features of the aircraft structure. The kinematic challenge is to deliver these tools to the work place and provide the range and motion resolution necessary to adapt to the local environment.

The approach taken within this work for responding to geometrical variation is to employ machine vision – using cameras to identify features within the enclosed spaces in order to control motion. This is particularly challenging for real situations, such as sealant bead application where it is necessary to find the end of a bead and recommence the bead whilst ensuring there is no leak path.

The static/dynamic force challenge is to react process forces either through the delivery structure (the robot) or through the aircraft structure. The latter is the preferred option for snake-arm robots, since this type of robot will tend to be less rigid than an industrial robot. However, this approach has strong benefits for industrial robots too.

DISCUSSION

The prototype has been designed to complete only the specific processes that were identified by Airbus UK. These were chosen to be representative of the wider range of tasks that would be required to manufacture a future aircraft. A snake-arm robot is a method of delivering any tool or sensor package into restricted access sites. As such, it is expected that these robots will be used for in-service inspection and potentially repair as well as production. The work on field-capable snake-arms for security applications funded by the UK Ministry of Defence and US Department of Defense indicates that snake-arm robots are suitable for field use. In particular the actuators that drive the arm are all at the base of the arm and the arm itself is of constant diameter, which in turn leads to simple sealing. Snake-arms can be used as stand-alone systems or in cooperation with industrial robots. As a standalone system, a snake-arm robot is a steerable video probe. Independent research is continuing on diameter reduction, which would allow a snake-arm to be used for engine inspection and repair.

Other tasks that could be considered for aircraft manufacture include deburring, drilling, extraction of foreign bodies, installation of components, insertion of wire looms, laser welding, leak detection, non-destructive testing, nut-running, painting, removal of debris (foreign bodies, liquid, particulate, swarf), and thermal imaging.

The detailed design of specific snake-arm robots that have the required performance to achieve each of these tasks will vary. In general, the detailed design is affected by the size and mass of the payload, any dynamic loads transmitted through the arm and the desired response to such dynamic loads, as well as the repeatability/accuracy with which the package needs to be delivered.

There are also constraints on the size and mass of tools. As a rule of thumb, the tool should be of the same diameter as the arm itself and less than 1.5 times the diameter in length. This 1:1.5 rule tends to produce a tool of the correct payload mass for the size of arm and of a size that can be manipulated. A larger diameter tool tends to indicate that a larger diameter arm is also possible. A longer tool becomes increasingly cumbersome to manipulate and starts to negate the benefit of the flexible snake-arm.

The combined effects of the parameters that define the response to the variety of loading conditions result in a specification for the required arm stiffness. Unlike standard robots, however, the stiffest arm is not necessarily the ideal solution. A compliant arm has many benefits when collisions are unavoidable or where a robot arm is working unguarded alongside a person. Contact with the environment can be gentle rather than catastrophic. Compliance is also useful to attenuate the effects of large impulses.

Snake-arm robots enable different approaches to be considered. In the long term, such technology may provide aircraft designers with the option to consider structures that cannot be built with existing manual methods.

CONCLUSION

Snake-arm robots can become an essential component of automated aircraft assembly (Figure 6). This technology enables people to be removed from rib bays, weight savings to be made, and aircraft to be manufactured more quickly and more cheaply.

Figure 6 – Snake-arm robots on an assembly line

There are many additional benefits of using increasing levels of automation. These include replacing manual skilled assembly processes with more repeatable and higher rate automated processes. The application of sealant and adhesive in particular will become an even more critical process for assembly of composite parts.

These drivers make the development of new automation solutions for the aerospace sector critical for future aircraft production. In addition, if aircraft are produced using advanced automation it is likely that new tools will also be required for maintenance and repair operations.

More widely, the development of snake-arm robots could eventually enable major design and process changes, creating the opportunity for considerable cost savings in the aerospace industry. Future structures could be designed with fewer and smaller access panels, and maintenance times could be reduced. In this way, snake-arm robots may help in the reduction of greenhouse gases.

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