2006-01-3141

Snake-arm robots: a new approach to aircraft assembly

Rosalind Anscombe, Andrew Bryant, Rob Buckingham, Geoff Ferguson, Andrew Graham, Mariusz Lichon, Nick Parry,
OC Robotics, Unit 5, Abbey Wood Business Park, Emma-Chris Way, Filton, Bristol, BS34 7JU

Paul Brandrick, Mike Redman, Mark Summers
Airbus UK, New Filton House, Filton, Bristol, BS99 7AR

Brett Green
KUKA, Hereward Rise, Halesowen, West Midlands B62 8AN

ABSTRACT

This paper describes work being conducted by OC Robotics and Airbus to develop snake-arm robot technology suitable for conducting automated inspection and assembly tasks within wing boxes.

The composite, single skin construction of aircraft structures presents new challenges for robotic assembly. During box close-out it is necessary for aircraft fitters to climb into the wing box through a small access panel and use manual or power tools to perform a variety of tasks. These manual interventions give rise to a number of health and safety concerns. Snake-arm robots provide a means to replace manual procedures by delivering the required tools to all areas of the wing box. The advantages of automating in-wing processes will be discussed. This paper presents early stage results of the demonstration snake-arm robot and outlines expectations for future development.

BACKGROUND

ROBOTICS IN THE AEROSPACE INDUSTRY

The automotive industry was very quick to embrace automation as a means to achieve mass production, while the aerospace industry has been much slower. In recent years, however, there has been a general move towards automation as a means to increase throughput and standardise processes.

The reasons for the slow uptake of industrial robots into the aerospace can be largely attributed to the need for high accuracy over large structures. In particular, holes must be drilled within large structures with both high absolute and relative accuracy, relative to other holes and features of the aircraft assembly.

Airbus has been researching low cost, highly flexible robot automation for a number of years. A robot test programme determined that standard industrial robots cannot meet the high accuracy process requirements. Closed loop control systems have been developed to achieve adequate position accuracy with industrial robots [1], thus enabling high precision drilling tasks to be automated.

However, tasks within rib bays and other low access areas found throughout aircraft structures have remained inaccessible to automation. Manoeuvring an industrial robot (Figure 1) through a small opening becomes an ‘eye of the needle’ problem (Figure 2): it becomes practically impossible to use a conventional robot-arm to pass through an access panel, for example, and conduct work within a wing box.

Figure 1 - 350kg payload Kuka

Figure 2 - "Through the eye of a needle"

Operating within a rib bay requires some of the capabilities of industrial robots, e.g. the ability to place tools precisely, but other capabilities must be added in order to be able to operate within confined spaces. In particular it is necessary to have a robot structure that does not have prominent ‘elbow’ joints. A suitable structure is one with low profile elbows or continuous curvature that is able to snake into confined structures. This type of robot, called a snake-arm robot is the subject of research being conducted by OC Robotics [2] and Airbus.

SNAKE-ARM ROBOTS

Robots with many independently controlled degrees of freedom are referred to as ‘super-redundant’ mechanisms, where ‘redundant’ is a mathematical term that means ‘excess’. In particular, a super-redundant snake-arm robot has many joints, similarly to a natural snake. This belongs to a body of work related to continuum robots and this is being conducted around the world e.g. Walker [3] This paper is a useful reference for citations including work by Hirose, Chirikjian, Burdick and Kobayashi By introducing more joints into the robot structure it becomes physically possible to pass the arm through a small hole. However, standard mathematical techniques of motion control no longer apply since, for any given tip position, there is now an infinite number of joint solutions. One of the mathematical challenges solved by OC Robotics is the ability to choose a series of solutions in time so that the robot arm follows a path and avoids collisions.

The OC Robotics patented design uses a number of flexible ‘segments’ that can be independently controlled by applying a moment at the end of each segment. Consider a flexible rule: end loads cause the rule to bend along its length rather than bending at a joint. Whilst there are a number of ways to introduce moments at the end of each segment, the OC Robotics design uses three actuators that each pull an individual wire. These three wires are equally spaced at 120° intervals around the circumference of the segment and terminate at the end of each segment, Figure 3. By controlling the length of these wires, the segment can be made to bend to form an arc. This plane of bending can also be rotated by appropriate actuator wire length changes. Each segment therefore has two degrees of freedom – curvature and orientation of the plane of curvature.

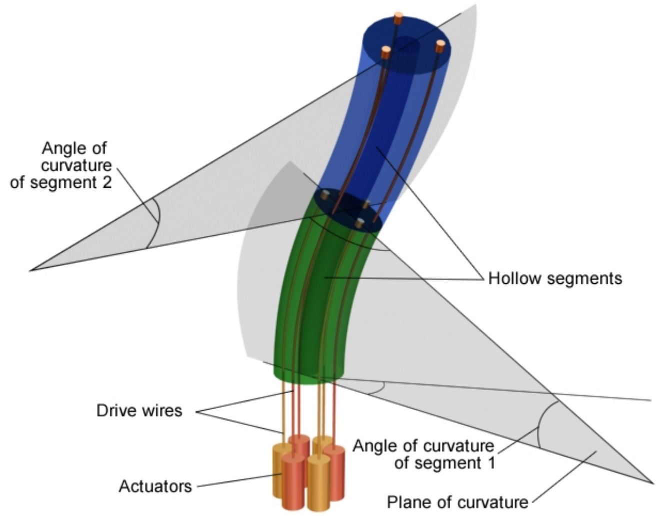

Figure 3 - Principles of wire drive

An OC Robotics snake-arm robot can have a large number of segments, whilst maintaining the same cross section along the length of the arm. An arm is therefore a series of serially connected flexible tubular segments. The stiffness (compliance) of the tubular segments can be chosen according to the task.

The design of the segments is critical to the performance of the arm. OC Robotics’ design is similar to a backbone, with alternating rigid sections (vertebrae) and thin elastomer layers (discs). These sub components of a segment are called links. The stiffness of the link must also be balanced by the ability of the actuators to apply loads in order to bend the segments. This bending moment is a function of the diameter of the arm and the tension in the actuator wire. The tension in each wire and the length of each wire are controlled by an individual motor. These motors are grouped together at the base of the arm, in the actuator pack.

Having the actuators at the base of the arm greatly simplifies wiring and sealing considerations, as well as offering a suitable location for a single quick-release interface. This enables very quick arm replacement, while retaining the high-cost actuators and controllers.

An important design feature of the patented arm design is the constant arm diameter. This leads to a simple arm design, reducing both complexity and cost. It also means that the curved external surface of the arm is reasonably smooth and can be easily sealed using a thin elastomer or bellows tube.

SNAKE-ARM ROBOTS IN INDUSTRY

In April 2003, OC Robotics signed a contract with the UK MoD to build a 2.5m long snake-arm robot able to carry a payload of 25kg (Figure 4).

Figure 4 - 2.5m snake-arm robot for UK MoD

In early 2005 OC Robotics successfully demonstrated the capability of the arm to reach into a car through an open window. The arm reached through the driver's window to the back seat of the car where an object was viewed through the tip-mounted camera. The contract also stated that the arm must be strong enough to tow a car. Snake-arm robots are axially strong because of the high loading ability of the wires running along their length so the 95mm diameter arm was able to tow a car with ease.

OC Robotics completed its first commercial nuclear contract in the summer of 2004. Two types of robot (five in total) were supplied to Ringhals AB to complete an urgent pipe replacement in an extremely awkward area below one of their reactors [4]. Before the operation could be performed on the real environment, there was extensive training on a custom-built mock-up. After thoroughly practising the whole procedure, the team, led by Uddcomb Engineering AB, conducted a trial installation and operation within reactor containment as part of the acceptance tests. Replacing the leaking section of pipe involved more than 30 distinct procedures with the majority being conducted by the robots working cooperatively. The more flexible snake-arm was used to get the ideal camera location to monitor the process (Figure 5) whilst the other snake-arm was used to deliver the processing tools and fixtures, remove the old pipe, introduce the new pipe and conduct tasks such as welding and inspection.

In August 2004 a single pipe repair was successfully completed and, a month later the generic solution based on the robots, which is able to repair any of the other 156 similar pipes, successfully completed the Factory Acceptance Tests.

Figure 5 - The Inspection Arm carried cameras to the work site

AEROSPACE APPLICATIONS

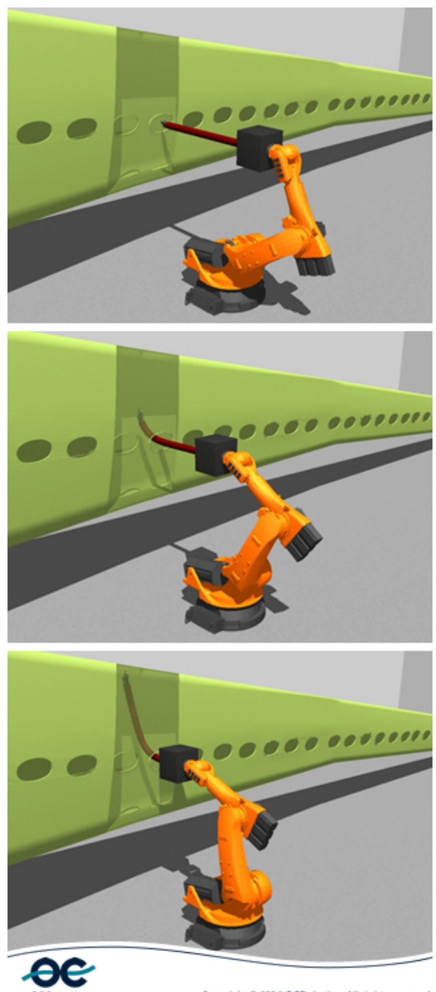

Figure 6 - Snake-arm robot reaching into the wing box

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

The approach being taken is to consider a snake-arm robot as an additional tool that the larger industrial robot can deliver. The basic concept is shown in Figure 6.

The 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 6 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.

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.

The snake-arm is also equipped with a wrist and interface to attach different tools. As a focus for the work, three tasks are being considered. The tasks are swaging a standard aerospace fastener, applying sealant and conducting inspections.

The swaging and sealing tasks are to be carried out at the front spar and at the rib feet. Inspection is to be carried out around the whole rib bay.

THE DEMONSTRATOR

A prototype has been designed which will be used to demonstrate all the required tasks inside a mock-up of a rib bay.

The complete snake-arm robot demonstrator system (Figure 7) is comprised of a number of sub-systems. The design of the snake-arm itself 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, plus 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. The hollow bore is 25mm. 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 be able to rotate in two dimensions. This gives the arm the flexibility to nose-follow into the rib bay. The complete system has 27 degrees of freedom.

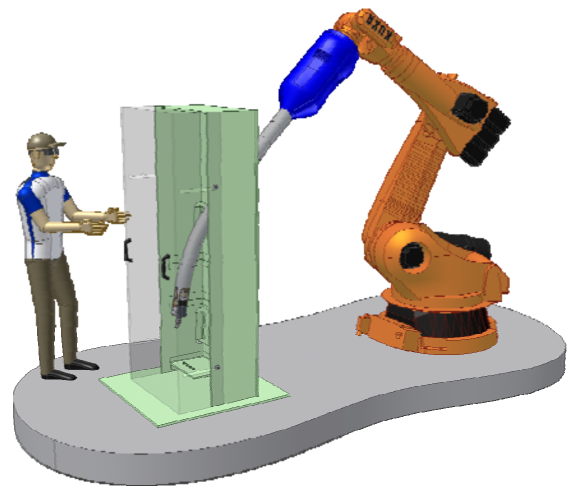

Figure 7 - Demonstrator and rib-bay mock-up

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 using visual servoing to ensure it is correctly aligned before beginning each task. When applying sealant, a camera on the toolpiece tracks the line of the seam to ensure accurate and even application.

END EFFECTORS

In order to maximise the benefit of a snake-arm's path-following capability, the diameter of the end effector's envelope must be equal to or less than the diameter of the snake-arm. The length of the end effector must be minimised, ideally to the diameter of the snake-arm or at least to less than 1.5 the diameter.

In addition to these considerations, further restrictions were placed on the design by the snake-arm robot specification and the rib bay geometry.

Three interchangeable end effectors have been designed by OC Robotics:

AN INSPECTION TOOL

This tool will contain several cameras with various functions to ensure adequate inspection of all areas of the wing box. Although it is probably the easiest of the three tasks, the inspection of the wing box is complicated by several factors: low lighting in the wing box and the uniform colour of the interior compounded the differentiation and identification of defects. The approach being taken is to use a range of wide-angle, spot and close-up lights around the cameras.

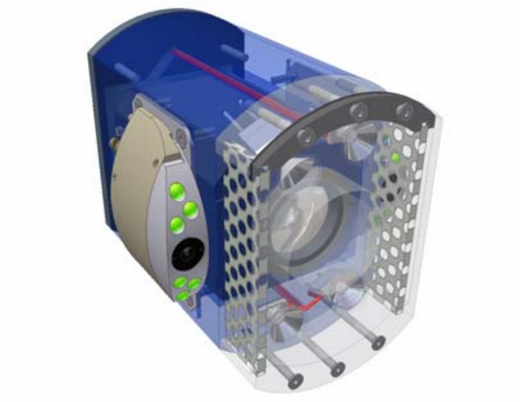

Figure 8 - Inspection tool

A SWAGE TOOL

Swaging involves high forces which can be reacted through the structure. Automated tools must be electrically actuated whilst remaining small enough not to restrict motion within the rib bay. This tool will swage a rivet and direct the removed section into a collection area. An additional challenge included within this part of the project is to use electric servo motors rather than pneumatics. This has advantages for use of tool exchange and minimises the size of the tool. This tool also includes cameras for visual servoing. In the model below it can be seen that there are four cameras on each tool, two on each side. The more distal cameras are mounted on the snake-arm wrist and are required both for tool exchange and provide an extra 'shorter' but lower resolution inspection tool. The more proximal cameras on the tool itself are required because the tool obscures the view of the wrist mounted cameras.

Figure 9 - Swage tool

A SEALANT TOOL

This tool will incorporate a standard sized sealant cartridge and nozzle, with cameras to allow automatic orientation of the toolpiece to the seam.

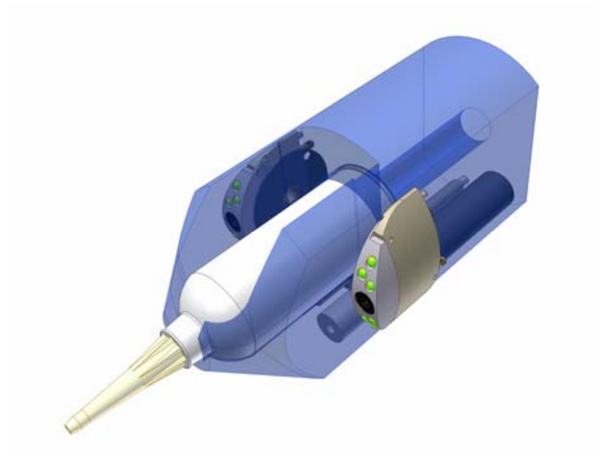

Figure 10 - Sealant tool

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 purpose of the demonstrator is to show the feasibility of using representative tools on a snake-arm robot rather than recreating precise worksite geometries. Future work may 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. The robot executes the program and 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, the program 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.

VISUAL SERVOING

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, the complex configuration dependent ability to react loads and time. 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 whereas 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. This line of thinking leads 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 use visual servoing – 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 as being relevant to the manufacture of future aircraft. However, 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 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 leads to simple sealing. Snake-arms can be used as stand-alone systems or in cooperation with industrial robot. As a standalone system a snake-arm robot is a steerable borescope. 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 liquids, gases or particulate matter; removal of 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; and 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 only 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 flexibility of the 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. But, unlike standard robots, the stiffest arm is not necessarily the 'best' 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 the option to consider structures that cannot be built with existing manual methods.

CONCLUSIONS

This paper has described research being conducted by OC Robotics and Airbus to develop robot technology suitable for the aerospace industry. The focus of this paper has been the development of snake-arm robots to conduct automated inspection and assembly tasks within rib bays.

The removal of the need for specialist fitters to conduct a range of tasks within rib bays has many advantages for the aerospace industry. In particular rib bays have severe access restrictions and are very confined spaces in which to work. There are also areas of the wing which are in practice extremely difficult to reach using manual methods. In addition, drilling of composites gives rise to fine dust which, along with use of solvents and noisy equipment in confined spaces, has the potential for significant health and safety issues.

These drivers, along with the unrelenting pressure to increase productivity by standardising aircraft production, 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 ultimately enable major design and process changes creating the opportunity for considerable cost savings for the aerospace industry. Future structures could be designed with fewer and smaller access panels and maintenance times could be reduced.

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

REFERENCES

1. “Robot capability test and development of industrial robot positioning system for the aerospace industry”, Summers M., 2005 Transactions Journal of Aerospace, p1108
2. "Snake-arm robots - a new tool for the aerospace industry", Buckingham R. & Graham A., Aerofast 2003, Palais des Congrès, Montreal, Quebec, Canada, September 2003
3. “Kinematics for Multi-Section Continuum Robots”, Jones B. & Walker I.D., IEEE Transactions on Robotics, Vol. 22, No. 1, February 2006, pp. 45-53.
4. "Snaking around in a nuclear jungle", Buckingham R. & Graham A., Int. J. Industrial Robot, Vol. 32, No. 2, p120-127, 2005, ISSN 0143-991X

CONTACT

Rob Buckingham: OCRobotics, Unit 5, Abbey Wood Business Park, Filton, Bristol BS34 7JU, UK; rob@ocrobotics.com; www.ocrobotics.com