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Snake-arm robots – a new tool for the aerospace industry

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ABSTRACT

This paper introduces a type of robot, called a snake-arm robot, which offers the potential to change aircraft assembly and maintenance processes in order to reduce costs and lead times.

A snake-arm robot has many segments and belongs to the family of hyper-redundant robots. The appeal of this type of device is that a snake-arm uses its many segments, controlled by a nose-following algorithm, to reach into restricted access spaces in a minimally obtrusive manner.

In addition to nose following, a second artifact of the **OC**Robotics design is the use of flexible rather than rigid segments. Whilst this improves the ability of the arm to reach into awkward spaces, it also means that the arm is compliant and has the potential to be used unguarded in human environments.

Historically industrial robots have been developed for the automotive industry and are not widely used for aircraft assembly. This is partly because the challenges of aircraft manufacture and maintenance are quite dissimilar to those of the car industry. Differences include production volumes, size and range of components, process tolerances and the level of control over the working environment. The assembly of aircraft stubbornly remains a ‘craft industry’.

If significant cost reductions are to be achieved through increased use of automation then process change needs to happen in parallel with the development of new tools and technologies. Whilst some of these technologies can be transferred from other sectors, other ideas need to be pulled through by the aircraft industry for the aircraft industry.

This paper explains how snake-arm robots operate and identifies strengths that may be relevant to various aircraft assembly and maintenance procedures including inspection, cleaning, application of sealant, painting, laser welding, leak detection, NDT and riveting.

The paper concludes with progress in the area of explosive ordnance disposal. This military application demonstrates key features of similar technology that could be applied to the aerospace industry.

AUTOMATED ASSEMBLY OF AIRCRAFT

In 1900 cars were hand built. Each part was crafted into shape and assembled by skilled operators. It could not be assumed that two parts made from the same drawing were the same. In 1908 Ford with the Model T achieved a significant breakthrough. Ford achieved complete, consistent and simple interchangeability of parts. This led to the moving production line, mass production and the automated assembly of cars. Industrial robotics has a close symbiotic relationship with automated car assembly.

In comparison the size and complexity of parts, access, and structural requirements imposed by fatigue, aerodynamic and engineering design criteria lead to aircraft assembly processes that are only achievable by people and therefore structured around the capabilities of people.

This generality is contradicted by the use of large, capital intensive, dedicated CNC riveting machines, [1], for production of detailed part panels and primary components. However, beyond the CNC riveting machines, assembly of sub structures, box assemblies, fuselage sections, wing final assemblies and final assembly all involve teams of operators working in parallel to maintain the required throughput. One significant barrier to the use of automation is that health and safety legislation separates automation from people. If automation results in a reduction in throughput, because parallel working is no longer possible, the commercial case for automation becomes even harder to make.

The interrelated challenges for automation include: size of components; required process tolerances; access and interaction with people.

Access and interaction with people are areas where snake-arm robots have appeal.

Access, in this context, is used to signify two different challenges. The first is related to scale. Accessing a large structure has tended to imply a substantial robot structure, especially considering the precision requirements that must be delivered throughout the work volume. Such robots have the consequential problem of potentially excluding people from large areas.

The second is related to the assembly sequence that requires a large percentage of internal operations.

Existing robots have not been designed to work through access holes and are generally difficult to mount inside structures even when space allows.

TECHNOLOGY

Super-redundant robots have been a research topic for many years but there have been notably few commercial successes [2-7]. With the advent of new materials, cheap computational power and an increased level of understanding, snake-arm robots are now a practical option.

The concept is to design a robot that is relatively long and thin, which can reach into restricted access spaces by following its nose. As such a snake-arm robot is suited to delivering tools and services to an internal cluttered task space.

In addition, the **OC**Robotics design uses compliant members. This compliance can be reduced in order to either give considerable payload capacity (e.g. 50kg) or increased to allow soft collision with an operator.

Figure 1 shows the **OC**Robotics demonstrator. It is a 5 segment arm, with each segment having 2 degrees of freedom. The curvature and plane of curvature of each flexible segment are independently controlled by a number of actuators connected to the relevant segment by wires. Each segment bends in an arc. The demonstrator allows more than 90 degrees of bend per segment. The arm is 1m in length with an external diameter of 35mm. The arm is also hollow with an internal 15mm diameter working channel that runs the entire length of the device.

Figure 1 – Demonstrator

The design of the bending element that forms the basis of each segment is critical both in terms of achieving mathematically tractable motion and a design that can be manufactured in volume for an acceptable cost. In addition, the adopted design enables various parameters including number of segments and diameter to be varied in order to achieve the required reach, payload, compliance and repeatability requirements.

The mathematical challenge comes in two parts. The first is to solve the wire length calculations to achieve the required static configuration. The second is to link a series of static configurations together in order to create motion. This is achieved using a combination of numerical techniques to resolve the redundancy issue.

The series of images in Figure 2 shows an 11 segment (22 degrees of freedom) arm following a path through the **OC**Robotics logo. This path has six 90º bends.

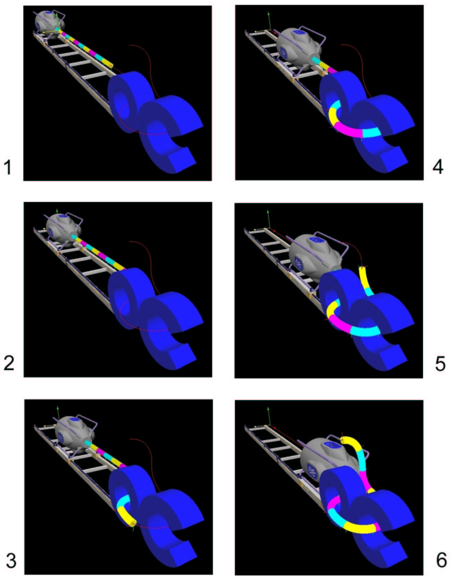

Figure 2 – Path following

Length	0.5m	2.5m	3.5m	10m
Diameter	6mm	85mm	120mm	120mm
Payload	10g	20kg	50kg	2kg
Total curvature	180 degrees	720 degrees	450 degrees	720 degrees
Working channel diameter	2mm	25mm	75mm	75mm
Number of segments	4	8	10	8

Table 1 – Indicative specifications

Both the hardware and software have been designed to be scalable and, as such, the demonstrator is one member of a large family of devices. Table 1 indicates some specific specifications within the continuum of options.

The concept of a family of devices is extended by making the arms interchangeable. This means that a range of arms can be connected to a common drive unit. The three main elements of the snake-arm robot: the drive unit, a quick release mechanism and a range of arms, Figure 3.

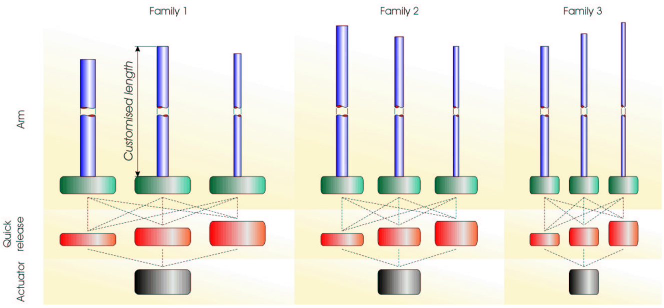

Figure 3 – A family of devices

DESIGN FEATURES

Hyper-redundant robots have, in general, been anything but simple mechanisms to build and control. Multiple degrees of freedom must mean more motors than a non-redundant robot and the complexity of the software is well documented.

The **OC**Robotics design counters these issues by implementing a highly modular design. The demonstrator has only 17 part drawings and by using a wire drive system there are no active elements in the flexible arm. By incorporating a quick release mechanism the arms are interchangeable and, as such, can be replaced to conduct difference tasks or for scheduled maintenance. For some activities the passive, replaceable arm could be single-use disposable or sacrificial.

The drive unit can be separated from the arm by a few meters so that only the arm is within the working environment. This means that the more expensive parts of the robot are less vulnerable to damage. This is particularly useful for operating in a vacuum, or wind tunnel, in an irradiated environment or under water.

The arm has a smooth external surface. This avoids potential snagging and trapping issues for the environment or fingers. The arms are easily skinned with an appropriate elastomeric material, making the arm washable. Smart skins are also possible with embedded heat, chemical, force and touch sensors. The arm also has a continuous constant cross section hollow bore. In effect the arm is a steerable hose, with all services (electrical, fibre-optic, pneumatic, power drive, liquids, gases) being routed internally providing protection and avoiding issues of snagging.

AEROSPACE APPLICATIONS

To date discussions with more than one commercial aircraft manufacturer indicate that there are two broad ranges of tasks that could be conducted with appropriate snake-arm robots.

The first involves limited contact with the environment. Examples of this might include inspection, laser welding, leak detection, painting, removal of swarf and NDT. These tasks would typically be achieved either with operator guidance or by following programmed paths. Considering inspection, operator guidance typically involves using a joystick to control the motion of the tip camera so that the operator can interactively explore the structure and check on particularly areas in more detail. This might also be a mode of operation for leak detection. Where an inspection procedure could be standardised a camera could be moved throughout internal volumes along a preset path with the operator viewing images in real time or offline. Laser welding might involve the operator identifying start and end points of a particular weld with the snake-arm interpolating a straight path between these points. Alternatively standard seam tracking technology could be transferred from existing welding processes.

The second range of tasks involves contact with the environment with the assumption that such contact must occur at specific positions and will involve certain levels of force being applied to the arm. Examples include deburring, drilling and riveting, installation of components, and insertion of wire looms.

It is perhaps counter-intuitive to use a compliant structure for drilling and riveting. A ‘compliant’ structure cannot be used in the same way as a ‘rigid’ robot although both terms are relative.

Figure 4, shows a single robot working on one side of an aircraft component. In this case the chain of transform matrices that describe the relative positions of each of the elements is:

$$T(t)_{tool}^{component} = T(t)_{compdatum}^{component} \bullet T_{earth1}^{compdatum} \bullet T_{earth2}^{earth1} \bullet T(t)_{robot}^{earth2} \bullet T_{tool}^{robot}$$

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 issues are resolved by calibration and the use of external tracking and measurement devices such as laser scanners.

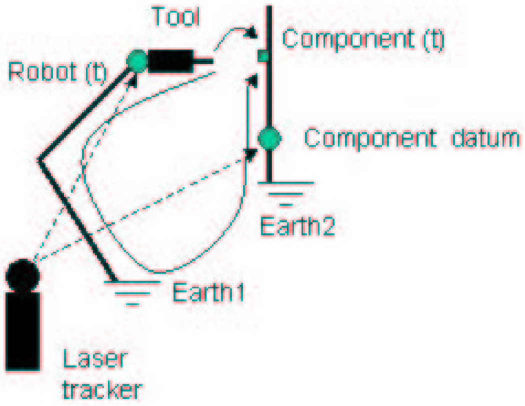

Figure 4 – Position and force loop closure

The light beam of the laser scanner is effectively a perfectly rigid link from the tool to earth and cuts out the kinematic errors related to the configuration. However, a line of sight laser scanner does nothing for the static and dynamic errors that relate to the transmission of the forces through the robot.

The important relationship is the relative position of the tool with respect to the component and the transmission of forces. 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 motion resolution necessary to adapt to the local environment. The static/dynamic force challenge is to react process forces either through the delivery structure (the robot) or through the aircraft structure.
Smart tools, for instance including PosEye [8] type capability, provide the opportunity to control $T(t)^{target}_{tool}$ in real time directly without reference to the delivery device. The delivery device or devices no longer need to be rigid, high speed, high accuracy and high payload. Issues of reach, both in open and restricted access areas and interaction with people become much more significant, Figure 5.

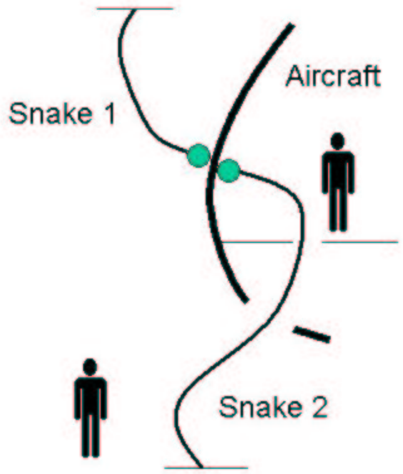

Figure 5 – Multiple robot interaction in a human environment

CURRENT STATUS – EXPLOSIVE ORDNANCE DISPOSAL

Over the last few decades the UK has acquired a significant level of knowledge of dealing with improvised explosive devices. Such devices have been placed in cars and other restricted access spaces.
Under contract from the UK MoD, **OC**Robotics is currently developing a snake-arm robot to be deployed on a mobile vehicle. The snake arm will have a length of 2.5m and payload of 20kg, Figure 6. The operator will use a joystick to 'fly-the-head' with computer algorithms ensuring that the rest of the device follows the head (also called 'nose-following'). This arm will have the ability to reach into a car, through the window and down to locate a device beneath a seat. Equally the snake-arm can be used to search the underside of a vehicle and reach into the engine compartment.

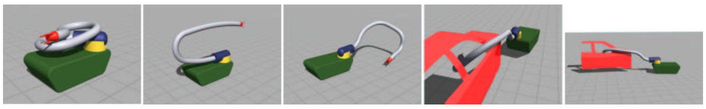

Figure 6 – Snake-arm concept on an EOD remote vehicle

CONCLUSIONS

This paper has briefly considered reasons for snake-arm robots being appropriate for use in low access environments and for operation in human environments. Hardware has been described which allows a hyper-redundant snake-arm to reach into and explore complex environments by following its nose.
Near term applications of snake-arm robotics within the aerospace industry include: visual inspection, painting, cleaning, leak detection, NDT and laser welding.
The concept of using snake-arm technology for more complex tasks such as drilling and riveting has been proposed.
The inherent compliance of these devices means that operation in human environments becomes feasible. Soft collision as an expected operating mode is achievable.
As an emerging technology, snake-arm robots offer the capability to consider applications that have been beyond the reach of existing robots. Snake-arm robots create the potential to change aircraft assembly and maintenance processes in order to reduce costs and lead times.

REFERENCES

1 Electroimpact – http://www.electroimpact.com/a380.asp

2 Various papers by Shigeo Hirose et al – Tokyo Institute of Technology – http://mozu.mes.titech.ac.jp/fastidx.html.

3 Various papers by Ian Walker et al – Clemson University – http://www.ces.clemson.edu/~ianw/

4 Various papers by Howie Chosat et al – Carnegie Mellon University – http://voronoi.sbp.ri.cmu.edu/projects.snake.english.html.

5 Various papers by Gregory Chirikjian et al – Johns Hopkins University – http://custer.me.jhu.edu/html/publication.html#hyper

6 Various papers by Joel Burdick et al – Caltech – http://robotics.caltech.edu/papers.html

7 "Robocrane and EMMA applied to waste storage tank remediation", R.V Bostelman, J.S. Albus, R.E. Graham, *American Nuclear Society Seventh Topical Meeting on Robotics and Remote Systems*, Augusta, Georgia, April 1997

8 PosEye, http://www.meeq.se/

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