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Reaching the unreachable – snake-arm robots

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Abstract

Various forms of flexible hyper-redundant robot have been built and tested since the 1960s, but none have been a significant commercial success. **OC**Robotics is developing a family of compliant flexible snake-arm robots with the intention of making snake-arm robots widely available for a range of applications.

Hyper-redundant robots are particularly appealing for applications in restricted access spaces. By following its nose a snake-arm can reach into such spaces in a minimally obtrusive manner.

In addition to hyper-redundancy, a second artefact of the designed presented in this paper is the use of flexible rather than rigid segments. 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.

This paper considers some of the design issues and the motivation behind the developments to date and identifies various significant markets, including bomb disposal, aircraft assembly and operations in human environments.

Technology

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.

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 1 – Demonstrator

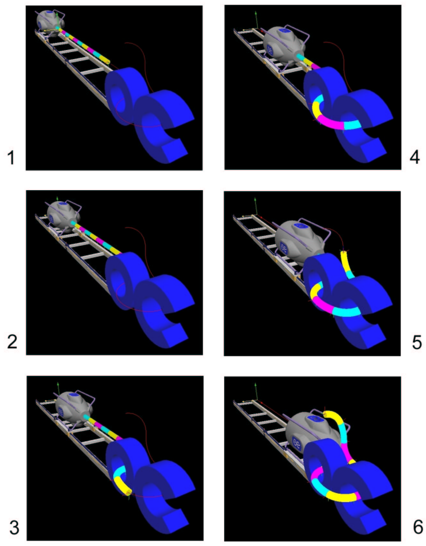

Figure 2 – Path following

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 a range of achievable specifications.

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 – Achievable specifications

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.

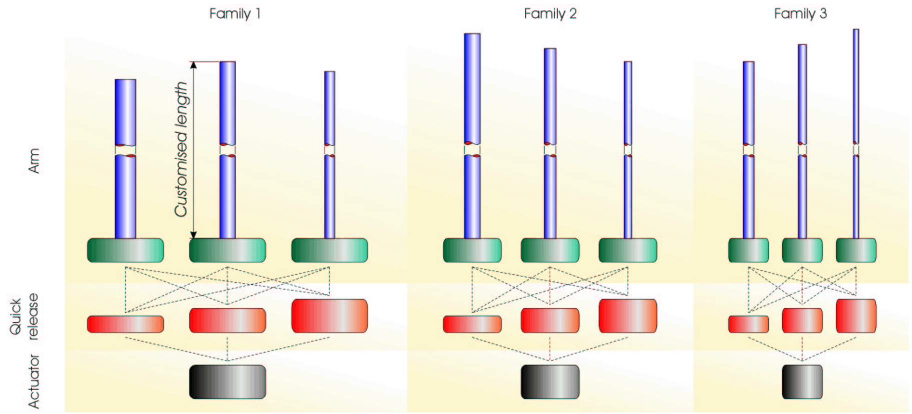

Figure 3 – A family of devices

Design issues

Safety, reliability and operational robustness cannot be divorced from cost. The single ingredient that binds all four of these issues together is simplicity. A simple design will be safer, in that it is easier to understand in terms of failure modes and potential corrective measures. Simple systems tend to be more reliable and are easier to understand, operate and maintain. Simplicity also affects the cost of manufacture.

Hyper-redundant robots have, in general, been anything but simple. 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 in the following ways:

- The demonstrator has only 17 part drawings and is highly modular.
- 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 in accordance with a scheduled maintenance plan. For some activities the passive, replaceable arm could be single-use disposable or sacrificial.
- Each wire is pulled by an individual wire-pulling unit. There are a large number of these units, but they are identical. The fact that each wire-pulling unit is identical also means that the control electronics and low level software are identical for all axes of motion. Once a component is produced in volume it is much easier to identify and resolve reliability issues.
- The wire-pulling units are interchangeable and hot-swappable, i.e. if a unit becomes damaged the arm can be locked in position and the unit changed.
- The shape of the arm is controlled by many individual wires. The loads that the wires experience are calculable and hence an appropriate factor of safety can be applied. In the event of a wire-pulling unit failure or damage to a wire, loosening the other wires in that segment causes the damaged segment to be absorbed into the adjacent distal segment. Such graceful failure modes are essential for extreme applications.

- The drive unit can be separated from the arm by a few meters so that only the arm is within the working environment. This can make the expensive parts of the robot such as the actuators less vulnerable to damage.
- The arms have 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 arms have a continuous constant cross section hollow bore. This allows all services to be routed internally providing protection and avoiding issues of snagging.

Applications in restricted access environments

In the context of this paper 'restricted' is used to indicate that the task space is cluttered to the extent that the path to reach a particular goal is either narrow or non-straight and often both.

Bomb 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.

Snake-arm robots with a length of 2.5m and payload of 20kg have the ability to reach into a car, through the window and down to locate a device beneath a seat. Equally a snake-arm can be used to search the underside of a vehicle and even reach into the engine compartment.

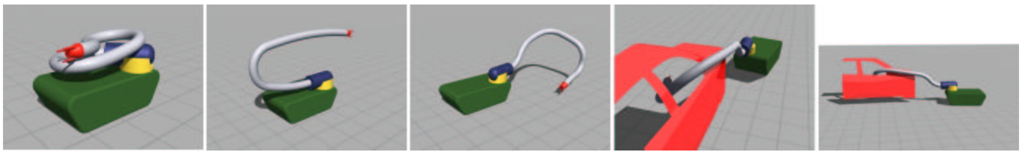

Figure 4 – Snake-arm concept on a bomb squad remote vehicle

Aerospace

Focusing on assembly of aircraft, it is widely recognised by the aerospace industry that existing industrial robots are of limited use. The reason that very few such robots are used is because of the tolerances required during assembly, the scale of the components and the requirement for access to the internals of wings and fuselage.

Snake-arm robots are ideally suited to working on the inside of aircraft: to apply sealant, to clean, for laser welding, for riveting and for inspection. Arms as long as 5m are required for certain applications. Snake-arm robots may be a tool that enable change in the aerospace industry in the way that current industrial robots have transformed the automotive industry.

Search and rescue

When a building collapses the search and rescue challenge is to explore a complex cluttered 3D environment. Ideally an arm would need to be 10m long with less than an 80mm diameter. At this length to diameter ratio the device needs to use environmental support. The shape of the device must be controlled so that the device follows its nose and can also return along the path used. In this way a device can explore a tree of paths within the environment.

A useful image is that of an elephant's trunk or a steerable robotic hose, attached at one end with the other end free to explore a complex cluttered volume. Snake-arm robots offer the potential to reach into a pile of rubble carrying video and audio equipment and taking warm air, oxygen, food and liquids to a survivor. Often it is also necessary to take vital signs sensors to identify the living from the dead. A snake-arm can also seek out heat sources, check for dangerous gases and take samples before people enter hazardous areas.

Nuclear facilities management

The size and scale and complexity of nuclear facilities, coupled with the exclusion of people, make inspection of nuclear facilities in many ways similar to that of search and rescue. We have had enquiries for a 15m arm capable of carrying a 15kg payload to conduct in situ non-destructive testing.

Potential applications in human environments

Flexible mechanisms are ideally suited to working in human environments because they can be designed to be more compliant than people whilst still carrying a relevant payload. In the event of collision between a person and the mechanism the result must be that the mechanism loses gracefully. However, in the process of losing, the mechanism should not be damaged and must not lose track of where it is.

Pick and place tasks whilst interacting with people

A redundant robot is useful when the environment is likely to be unconstrained and will contain obstacles. This is typical of human environments. Being able to reach a desired position in the presence of static or moving obstacles that cannot be avoided is a key requirement. One approach to dealing with obstacles is to skin the arm with proximity, touch and force sensors. Sensory feedback can then be used to generate reflexive behaviour (e.g. move away from the stimulus) or could be integrated within a virtual environment model.

Keyhole surgery

Using a controlled path flexible scope it becomes possible to reach further and more safely into various body lumens, the abdomen and the brain. In addition devices could be used to assist in various types of surgery, for instance on the spine or knees, for instance where the view of the drill exiting a bone would be helpful. The two big issues are user interaction and dependability.

Conclusions

This paper has considered reasons for snake-arm robots being appropriate for use in low access environments and for operation in human environments.

Software has been described which allows a hyper-redundant snake-arm to reach into complex environments by following its nose. Applications in bomb disposal, aircraft assembly and search and rescue have been described.

The inherent compliance of these devices means that operation in human environments becomes feasible. Soft collision as an expected operating mode is easily achieved. In turn, soft collision allows contact and force sensors to be integrated into the skin of the device to avoid the need for proximity or vision sensors and the associated software to calculate avoidance strategies.

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 opportunity to reach the unreachable.

Useful links to active researchers

Hirose – Toyko Institute of Technology – http://mozu.mes.titech.ac.jp/fastidx.html.

Walker – Clemson University – http://www.ces.clemson.edu/~ianw/

Chosat – CMU – http://voronoi.sbp.ri.cmu.edu/projects.snake.english.html.