LaserSnake2: An Innovative Approach to Nuclear Decommissioning – 17080

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ABSTRACT

Nuclear decommissioning challenges exist the world over and require innovative approaches to ensure safe and cost effective dismantling of high hazard nuclear facilities. LaserSnake technology makes use of the flexibility and dexterity of snake-arm robots to deploy high-powered laser cutting, lifting and manipulation tools. This paper describes the development and use of the system to achieve the successful size reduction and removal of a substantial stainless steel vessel within the First Generation Reprocessing Plant (FGRP) at Sellafield in the UK.

Due to the environment, nuclear decommissioning is an extremely challenging activity. High ambient radiation levels often preclude entry to the areas involved, and as industry tries to minimise dose uptake, even moderate radiation levels now require remote solutions. 'In-situ' size reduction of process plant, including vessels and pipework, will allow the removal of the nuclear inventory from a building prior to further decontamination and demolition. The term 'in situ' is in this case used to mean work done on plant items within their existing cells as opposed to moving items from their original location to a dedicated size reduction facility.

Traditional size reduction cutting methods, such as reciprocating saws or grinders, pose a significant challenge for remote deployment platforms. This includes the loss of haptic feedback and the length of time taken to perform the task, and difficulty dealing with the reaction forces. Although remote engineered solutions for these tools are possible, they are are typically complicated, unreliable and expensive. Robot deployed laser cutting is widely used in non-nuclear industrial sectors, and offers a simpler method for size reduction.

LaserSnake2 is a UK collaborative project, co-funded by the Nuclear Decommissioning Authority, Innovate UK and the Department of Energy and Climate Change. The project combined the skills of robotic experts and laser and optic specialists, to develop a remote handling technology suited for deployment within active nuclear environments. As well as meeting strict safety case requirements, the system provides a safe and cost effective method for decommissioning of complex nuclear spaces. An overview of the system development and deployment is presented in this paper.

In July 2016, a successful decommissioning campaign was conducted in the FGRP at Sellafield. The LaserSnake2 system was used to size reduce a double-skinned dissolver vessel within a radiologically active nuclear cell. Planning of the size-reduction method and processes, as well as results of the campaign itself are described in this paper. The containment procedures and radiological considerations for the system are presented along with the effects of operations on the cell and

ventilation systems.
LaserSnake, developed as a modular arm system with up to 4.5m of articulation, carries an integrated tool comprising a high power, decommissioning specific, laser cutting head, high definition cameras and high powered illumination LEDs. It is designed for precise dismantling work within confined and hazardous environments. The tool can be interchanged, allowing the snake-arm robot also to carry grippers, environmental mapping sensors and other tools which may prove advantageous during a decommissioning campaign.

INTRODUCTION

Nuclear decommissioning is an extremely challenging activity. Nuclear cells are typically highly congested, hazardous environments, with limited access. In many of the cells on the Sellafield Site, access is either very limited or impossible without significant work to reduce hazards. High ambient radiation levels preclude entry to the areas involved and as industry tries to minimize dose uptake, even moderate radiation levels require remote solutions. Where manual dismantling is still possible, traditional cutting techniques (reciprocating saws, grinders etc.) take significant lengths of time, in part due to the care taken to reduce spread of contamination, but also due to the difficult of working in restrictive personal protective equipment.

Historically, remote decommissioning and size-reduction using traditional size reduction cutting methods has involved bespoke systems, which have increased cost and added significant uncertainty. Traditional methods pose a significant challenge for remote deployment technologies, where the haptic feedback or 'feel' associated with manual operation of such tools is lost. Although remote engineered solutions for these tools are possible, they are typically complicated, unreliable and expensive. This highlights the need for the development of reliable and transferable technology to enable remote dismantling of cell furniture. Robot deployed laser cutting is widely employed throughout non-nuclear industry and offers a much simpler method for cell dismantling, as a flexible, non-contact process, effective across a range of materials.

LaserSnake2, a UK collaborative project, has successfully developed and delivered remotely operated laser cutting techniques for the nuclear decommissioning sector. The project focused on combining highly dexterous snake-arm robots with high-powered laser cutting tools, to selectively dismantle structures in challenging nuclear environments. The project required innovations in snake-arm robot design, as well as in the development of new laser cutting techniques and hardware. The resulting system is known as Lasersnake.

In July 2016, supported by Sellafield Ltd, the Lasersnake system successfully conducted a 'first of its kind' deployment during a decommissioning campaign in the FGRP at Sellafield. Sellafield is the largest nuclear site in the UK, and the FGRP was built in the 1950s to reprocess the uranium metal fuel rods from early reactors.

A feasibility study was conducted by OC Robotics and TWI in 2011, assessing the integration a high-power fiber laser with a snake-arm robot. The LaserSnake2 project builds upon this work, developing the technology and conducting an active deployment. It also complements work undertaken by TWI in collaboration with Magnox, size-reducing pond skips using industrial robots integrated with laser cutting process heads, in a purpose built 'ex-situ' decommissioning facility [1]. In contrast, by using a flexible snake-arm robot, the LaserSnake system enables decommissioning in-situ within active environments.

DESCRIPTION

LaserSnake

The LaserSnake system combines versatile snake-arm robot technology with innovations in laser cutting technology to deliver an integrated solution, enabling powerful, fast and clean cutting, whilst negotiating obstacles. The snake-arm has up to 4.5m of flexible length and an additional 2m rigid length at the base to traverse through concrete penetrations. It also has an integrated containment system and is ideally suited to small and medium sized process cells within nuclear sites.

Figure 1: The LaserSnake system

The robot is driven by wire ropes and controlled by OC Robotics' proprietary software. Snake-arm robots are highly dexterous robots ideal for working in confined and hazardous spaces. The arm has two degrees of freedom at each joint, allowing it to 'snake' through an environment. Snake-arm robots, which have been developed for the aerospace, construction and petrochemical industries, are particularly suited to nuclear applications, as the sensitive electronics are situated outside of the environment – away from potential contamination or radiation, with only the arm deployed into the work space. In the nuclear industry, access into cells is often through a thick shield wall, so to compensate for this, rigid base links are integrated with the flexible arm – improving reach and maintaining the articulated section for work inside the environment.

The LaserSnake2 project enabled significant advances in snake-arm technology, with material and design development resulting in an increase in length of over 100% on previous snake-arm robot designs, increases in the total curvature of the arm to over 180 degrees, and an increase in payload capacity from 5kg to 20kg. Snake-arm robot developments are covered in more depth in the Discussion section of this paper.

Two cutting heads were designed for the snake-arm robot by ULO Optics, one water-cooled, one air-cooled – both with innovations in diffractive optical elements to extend the depth of focus of the cutting beam and allow thicker materials to be cut with a greater stand-off tolerance.

Water is typically used to cool the optics and optic fiber couplings in high-power laser materials processing heads. As water is a moderator and also poses a contamination risk when crossing the boundary of a radioactive environment, an air-cooled process head was also developed. This head used a secondary supply of compressed air to cool the optical components.

The optics have been used with both 5 and 10kW laser sources, using 200 micron core diameter optic fibers to transmit the beams. The optic fiber in the LaserSnake system has an armored sheath, this fiber was inserted through the central service bore of the snake-arm, and then coupled to the laser cutting head using a standard industrial connector. Laser Cutting developments are covered further in the Discussion section of this paper.

Figure 2: Dissolver vessel before diamond wire cutting

Active Decommissioning Campaign: Dissolver Vessel for Size Reduction

During the active decommissioning campaign at Sellafield in July 2016, LaserSnake size-reduced a stainless steel dissolver vessel. (Figure 2)

The unit weighed approximately 5.5 tonnes and was 1.3m in diameter. The majority of the vessel was dual walled, with an outer shell 12mm thick and an inner shell 32mm thick. An air gap of 40mm separated the two shells. In earlier work, the dissolver vessel had been cut into three sections using a diamond wire saw, at the approximate positions indicated by the arrows in Figure 2. Each of these sections was placed on a wheeled steel bogey, such that the central axis of the dissolver was now horizontal.

The task was to size reduce the three sections of the dissolver such that the maximum weight of a cut part was ~20kg or less. All three sections of dissolver were located in a concrete walled cell of internal dimensions ~3m x 4m and wall thickness 1.5m. Personnel access into the cell was via a door and a concrete labyrinth type wall. The snake-arm robot was deployed from its sealed housing through a 300mm diameter access hole through the main wall. The dissolver vessel was considered one of the most difficult cutting challenges on site due to the wall thickness and vessel geometry. It is one of many challenging items that will be encountered during decommissioning of the Sellafield Site.

DISCUSSION

Snake-arm Robot Developments

In order to develop a reliable, safe robot for long term deployment at Sellafield, OC Robotics spent 3 years improving many aspects of the mechanical, electronics and software design. Improvements to arm materials to facilitate greater reach and payload, along with extensive testing regimes for actuator pack drive components are detailed in reference [2].

A navigation camera, HD inspection camera, lighting and sighting lasers were incorporated into the tool, along with the laser process head, which can be seen in Figure 1. By providing multiple views of the laser nozzle tip and using a visible laser co-axial to the high powered beam, the operator is able to judge standoff distance (the distance between the material being cut and the tip of the cutting nozzle) precisely.

Working closely with Sellafield Ltd, a modular and scalable containment system, to prevent release of contamination when the snake-arm is withdrawn from the cell, has been developed, which can be seen in Figure 3. As the cells are held at negative pressure an inlet vent was provided at the rear of the containment, to ensure a positive flow of air through the containment and through the access hole past the snake-arm, during insertion. The front of the containment was fitted to a wall plate, with an integrated liner, which extended through the cell access hole.

Where possible, components housed inside the containment were also sealed and if required, positive pressure could be applied to these components, to reduce the likelihood of contamination spread in the event of a leak. The rail drive mechanism used to push the snake-arm into the cell was sealed and the rack and pinion was dry (no lubrication) to reduce contamination capture. Each rail module included polycarbonate windows, which could be fitted with glove ports for inspecting, cleaning and changing the tool if required.

Navigation of the robot and positional control of the laser process head was conducted using OC Robotics proprietary software. The principal mode of deployment is using 'nose-following', which allows the snake-arm to reach into an environment whilst avoiding obstacles. The operator maintains man-in-the-loop control at all times. For cutting motion, the operator switches to Cartesian control of the laser process head. Using this mode, the tip of the laser process head was accurately positioned over the work piece at an appropriate standoff and then waypoints were saved to define the cutting path. A 'teach and repeat' process was used to drive through these waypoints and confirm the path prior to undertaking a cut.

Figure 3: LaserSnake containment housing, on site at Sellafield

Laser Cutting Process Developments

Laser cutting is a thermal process, where a focused laser beam is used to melt the material being cut. A gas stream, coaxial with the laser beam, is used to blow away the molten material, thus producing the cut kerf and allowing separation of the material. This is known as 'assist gas'. In commercial laser cutting, this gas stream is either oxygen, which adds exothermic energy to the process and is usually used for cutting carbon-manganese steels, or an inert gas, usually employed for cutting stainless steel. For nuclear decommissioning applications, TWI have shown that it is feasible to use compressed air as the assist gas, as it is inexpensive to produce compared to the alternatives.

The laser used in this work was a commercially available unit, capable of producing 5kW of output power down a 200 micron core diameter optic fibre. The cutting tool was a decommissioning-specific design, configured to require minimum adjustment on site, and weighed less than 2kg. The optics cassette in this tool took the laser beam diverging from the optic fibre and focused it to a spot approximately 0.4mm in diameter, at a distance 15mm beyond the tip of the cutting nozzle. The laser beam exited the nozzle tip coaxial with a stream of cutting assist gas, at a pressure of 8 bar. Compressed air was used as assist gas throughout the work.

During experimental cutting trials, prior to active deployment, it had been found that a distance of 15mm from the beam focus to the cutting nozzle tip would produce acceptable cutting speeds, over the range of material thicknesses expected in cutting the dissolver vessel. In addition, it was found that this configuration also provided a good tolerance to the stand-off distance employed, i.e. the distance from the nozzle tip to the surface of the material being cut. When cutting the dissolver, this distance was set remotely by using the tool cameras to view the position of a spot produced by a visible laser passing through the same delivery fibre and focusing optics as the main cutting beam. The high tolerance to stand-off distance was particularly important to give flexibility to the path programming process and reduce the time taken.

The majority of the dissolver consisted of a dual wall construction. The outer shell, 12mm thick, was separated from a thicker (32mm) inner shell, by an air gap of 40mm. During inactive cutting trials, simulating this geometry on flat plates and using a 10kW laser, it was possible to cut both plates simultaneously from one side. Indeed, the complete section could be cut with either the 12mm material or the 32mm material uppermost. However, using the 5kW laser available for the on-site active trials, at this power it was only possible to cut both plates simultaneously when the thicker material was uppermost and then only at a very slow cutting speed.

For cutting in the active cell, the three parts of the dissolver were presented on their sides, with the central axis of the dissolver horizontal, each part resting on a wheeled, painted steel support bogey. For the active work, it was decided that the approach taken would be to first remove the 12mm thick skin from the upper sections, thus revealing the 32mm thick inner shell. Removing the upper sections of the 32mm thick inner would then reveal the 32mm thick inner lower section. When the lower 32mm section was removed, the remaining lower 12mm outer shell section became available.

Typically, laser cutting is performed with the cutting head perpendicular to the surface being cut. One benefit of cutting through each layer in turn was that the beam could be contained. By adjusting the orientation of the head away from perpendicular, it was possible to ensure that the (expanding) beam passing through the material being cut would be absorbed by another wall of the dissolver. In this way no additional beam absorbing materials were used, until the very last cuts on the underside of the dissolver were made, revealing the support bogeys. For these final cuts, sheets of graphite (a very good absorber of the laser light used) were positioned on the floor of the cell.

During in-active trials, for cutting a 40mm wall thickness steel tube, using the equipment described above, two approaches were examined. The first was to remove a scallop shape at one open end of the pipe. Following this, more linked scallops could be cut, moving circumferentially round the tube. After one layer was removed a second layer could be removed, and so on. The second approach, involved first the removal of a rectangular or square section of the pipe, again starting on the outside edge. This was followed by long circumferential cuts round the top sections of the pipe. These were followed by series of cuts along the axis of the pipe, thus releasing square or rectangular shaped pieces. For both approaches described, cutting the first piece, so that it fell cleanly, required careful angling of the beam, to produce a part which was significantly smaller on its uppermost side than its underside. Only in this way, when it fell, did it not trap itself. Angles used in this 'keystone' process, effectively increased the depth of cut by 25%. The latter technique of cutting square or rectangular parts, was chosen for cutting both the inner and outer shells of the dissolver vessel. It was thought this technique would lead to reduced parts of a more uniform size.

Active Decommissioning Campaign: Deployment in the FGRP

The deployment was managed by Sellafield's Active Demonstration team and funded through the Sellafield Remediation's Future Decommissioning Project. Prior to installation of the robot, the Active Demonstration team completed a programme of work, much of it with input from OC Robotics and TWI, which included:

- Modification of plant to create a laser light safe cell.
- Installation of infrastructure (mobile filtration unit, compressed air supply, electrical distribution, CCTV, lighting).
- Arrangements (Plant Modification Proposal, HAZOP, Quality Plan, Risk Assessment, Operator Instruction, Lifting Plan, COSHH assessment)
- Logistics (transport, training, passes, site access)
-

OC Robotics' and TWI's experienced team of engineers, with Sellafield's support, then installed, deployed and operated the LaserSnake system, successfully size reducing the vessel, during July and August 2016.

During deployment on site, the vessel, which weighed approximately 5.5 tonnes, was cut into ~175 pieces, each weighing up to 20kg. OC Robotics software allowed the system to be 'taught' a cutting path which could then be repeated – enabling the rehearsal of cuts before the laser was used.

During 45 hours of cutting, 66m of cuts were made. Due to the geometry of the dissolver, many of the cuts were made at angles not perpendicular to the surface, increasing the thicknesses of material cut with cutting depths of up to 60mm typical. At one location, an annular flange had been used to join, by welding, the outer and inner shells and at this point the thickness of material to be cut reached 75mm. Images from the deployment can be seen in Figure 4.

Figure 4: Deployment within the FGRP, including the size reduced vessel (right)

A highly time compressed video showing the complete size reduction of the middle section of the dissolver can be seen by following the link in reference [3]. In this video, the implementation of the cutting techniques described above for cutting the dual walled section can be clearly seen, as can the attenuation of the residual laser beam by the opposite internal wall of the dissolver. The cutting path eventually exposed the thick ring joining the two skins together. The video shows how this was cut, revealing the dexterity of the snake-arm robot and cutting tool.

Days on site	48
Programming time	120hrs
Cutting time	45hrs
Total cutting length	66m
Average cutting speed	80mm/min
Thicknesses cut	12, 32 and 75mm stainless steel

Table 1: Deployment Statistics

During the project, the main challenge the team overcame was ensuring the regulations and logistics associated with deploying technology in a radiologically active nuclear environment were met:

- Several meetings between key Sellafield stakeholders and technical staff from OC Robotics and TWI including two HAZOP studies.
- Collaboration between technical staff at Sellafield and OC Robotics on design of the containment of the system and interfacing with existing structures, including developing a modular glovebox to house the snake-arm.
- OC Robotics and TWI personnel undertook nuclear safety courses to ensure procedures and processes on site were followed.
- Installing the system on site involved the challenge of coordinating different teams - careful and considered planning was required to achieve this.

With global nuclear decommissioning costs running in to the $trillions, tools that enhance safety and cost efficiency such as LaserSnake are essential as part of the decommissioning toolbox. With significant time and financial savings to be made from the deployment of such a system and reduced dose uptake to personnel, the project has sparked significant interest across the nuclear industry internationally, with many use cases already identified for challenging tasks in confined and hazardous spaces.

The Future of LaserSnake

After the successful demonstration of remote, confined space laser cutting, the project partners intend to further exploit the technology within the nuclear decommissioning industry. The very successful trials at Sellafield were widely publicized and other locations where the system can facilitate safer, faster and more cost effective decommissioning have been identified.

Outside of Sellafield, other nuclear site license companies have expressed a strong interest in the tool for other decommissioning challenges, not only for laser cutting, but also deployment of inspection, cleaning and manipulation tools.

Two significant applications of laser cutting have now been conducted on UK nuclear sites over the past two years (at Magnox [1], and at the FGRP). The safety case work, and underlying research into the effects of laser cutting, contamination and fume, have built confidence in this technology for use in nuclear environments. It is expected that both the laser technology and snake-arm robots will play a big role in UK nuclear decommissioning.

Many characteristics and decommissioning challenges of UK nuclear power plants are repeated the world over. With the versatility of the system there are a large range of opportunities where this technology can contribute to safer and cheaper decommissioning.

CONCLUSIONS

The work reported in this paper has shown there are significant benefits to using advanced systems of this type for size reduction in an active cell, over the use of standard cutting techniques, including reduced dose uptake and cost savings through reduced duration of work.

Designed for remote deployment through existing cell penetrations and controlled by intuitive software, the system can be deployed on site quicker and more practically than alternative techniques which require significant plant modifications (e.g. for 6 DoF robots), human intervention (e.g. using cold-cutting tools) and regular replacement of parts (e.g. diamond wire processes). Cutting using laser light delivered by optic fibre has been shown to have lower fume than other hot cutting techniques, and a much greater tolerance to stand off, particularly beneficial for remote delivery in unstructured/unknown environments in nuclear decommissioning. Additionally, the active trials at Sellafield showed that the system could be deployed using a third of the labour resource, with less consumables, and complete dismantling tasks in less time than with the current industry standard hot technique – plasma cutting.

The cost of decommissioning cells at Sellafield is in the £billions. A typical nuclear cell is estimated to cost ~£15million to decommission. A conservative 25% reduction in cost through improved efficiency and a reduction in the 300%

estimating uncertainty, could realistically save in excess of £2billion over the lifetime of the site. The LaserSnake system has the potential to contribute to a significant proportion of that saving.

REFERENCES

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