Remote Characterization Technology for Decomissioning – 14131

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ABSTRACT
The University of Manchester is one of the leading academic nuclear research centres in the UK. An import part of the engineering research at Manchester is being conducted to support the decommissioning plan for the Sellafield nuclear site in Cumbria. The primary focus of this research is the remote characterization of legacy waste using semi-autonomous systems. The main challenges at Sellafield are unique for a number of reasons and relate to the legacy fuel storage facilities (both dry and wet) which were built between 1950 and 1980. The University of Manchester is developing a number of semi-autonomous systems for this characterization challenge.

INTRODUCTION
The Sellafield site in Cumbria, UK (Fig. 1), is the world's most compact and complex nuclear facility. The site is nearly 70 years old and has over 2600 buildings and 290 active facilities in a $6km^2$ area. With the cessation of fuel reprocessing operations, all activity on the site post-2020 will be focused on decommissioning activities and waste management. This on-going work is part of the Site Decommissioning program which is scheduled to run until 2120.

Fig. 1. The Sellafield Site in Cumbria, UK

The University of Manchester is one of the leading academic nuclear research centres in the UK and is supporting the decommissioning of the Sellafield site through the Dalton Nuclear Institute. To facilitate closer collaboration between academics, industrial partners and Sellafield Ltd, a National Nuclear User Facility has been established at the University of Manchester's Dalton Cumbrian Facility, 10 miles north of the Sellafield site.

The Dalton Cumbrian Facility (DCF, Fig. 2) is a joint venture between the University of Manchester and the UK Nuclear Decommissioning Authority (UK NDA) and supports nuclear science and engineering research, both at the fundamental level and the applied level. Whilst its primary focus is on assisting the decommissioning of the Sellafield site, it is also involved in research for new build technology.

Fig. 2. The Dalton Cumbrian Facility, Westlakes, UK

Nuclear Engineering Decommissioning

The primary focus of the nuclear engineering decommissioning (NED) work being conducted at the University of Manchester is the remote characterization of legacy waste using semi-autonomous systems. Sellafield have identified a number of target areas for future R&D activities such as Site Restoration, Waste Management and Spent Fuels. All of the areas identified require some form of characterization.

Within the Sellafield decommissioning plan are the High Hazard Programs, the top 5 of which represent 35% of the total site costs in the first 4 years of the decommissioning plan and 77% of the major project costs. These 5 programs relate to legacy facilities which are difficult to characterize using traditional technology and could potentially result in high dose uptake for operators using manually deployed techniques.

The remote characterization research which is being conducted is split into two areas; semi-autonomous vehicle and platform development and autonomous characterization methods. The remainder of this paper covers both of these topics.

SEMI-AUTONOMOUS VEHICLE RESEARCH

The University of Manchester is developing a number of semi-autonomous vehicles which are able to deploy sensors in storage ponds, areas of contaminated land and caves. This section describes the various vehicles which have been developed for these purposes.

The Aqua Vehicle Explorer of In-Situ Sensing (AVEXIS)

The AVEXIS vehicle, shown in Fig. 3, was developed as part of an Engineering and Physical Science Research Council (EPSRC) funded project (Actuated Acoustic Sensor Networks for Industrial Processes, AASN4IP) which was concerned with the development of generic technology for the monitoring and characterization of liquid-based processes [1]. The project was conducted in collaboration with the UK National Nuclear Laboratory (UK NNL) and the demonstrator for the technology was for use in the monitoring of legacy storage ponds on the Sellafield site.

Fig. 3. The AVEXIS Prototype

The long-term vision is that multiple AVEXIS vehicles will form a swarm of untethered mobile underwater sensor nodes capable of sensing, communicating, localizing and exploring in confined and cluttered spaces (Fig. 4). Localization is achieved using a small set of base-stations, located on the *shore*, which also provide a route for the communication of sensor data and control information. Whilst the vehicles would be able to perform basic surveys of areas independently, the intention and need is for faster and more complex surveys to be completed by using multiple vehicles. In this mode the vehicles would form an underwater wireless sensor network (WSN) where each vehicle is equipped with a range of different sensors to measure and map conditions. For example, the vehicles could be used to generate a map of temperature, gamma radiation level or the location of radioactive isotopes within a storage facility.

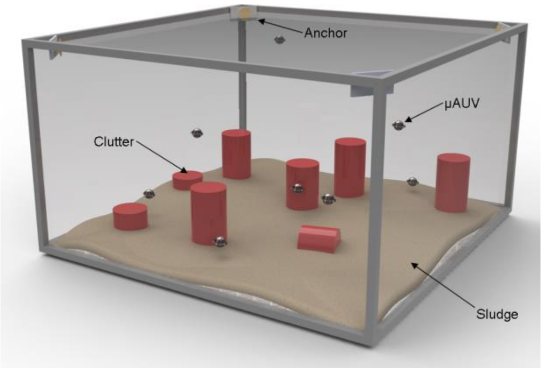

Fig. 4. Plan for AVEXIS Vehicles Monitoring a Storage Facility

To date, a single sensor node has been constructed and tested at a UK NNL facility and in a local swimming pool. The current prototype vehicle is characterized by the following features:

- 4 degree of freedom maneuverability, allowing it to access space inaccessible to other vehicles
- An embedded computer system, which allows for independent control of all 6 thrusters and real-time collection of measurements
- Automated regulation of depth and rotational movement
- Manual or pre-programmed specification of horizontal movement
- Sensing capabilities: Depth (pressure), Angular Position and Velocity (Digital Compass and Gyroscope) and Temperature
- Position estimates with an accuracy of ~25cm (within a 25m pool)

The main novelty of this system is its size and cost. There are currently no commercially available AUVs of this size which can be deployed into a cluttered environment. The vehicles themselves have been constructed using low-cost off-the-shelf components so that they can be viewed as disposable. The unit cost per vehicle is approximately $1000 - $1500 which is significantly cheaper than specialist vehicles which can cost in excess of $150k. The vehicles are also highly maneuverable and their use in a swarm means that the functionality and scalability can be increased to reduce the exploration and measurement time.

There are currently two projects on-going which are concerned with the further development of the AVEXIS vehicle. The first project involves the development of core technology for the vehicle. Specifically this project is focused on the design of an acoustic communications and positioning system, the embedded system and the obstacle detection system. The mechanical robustness of the hull and propulsion system is also being considered. At the end of the project (end of 2014), there will be a demonstrator system comprising of 2 AVEXIS vehicles communicating with each other and with the shore and navigating around an uncluttered environment.

The second project is being conducted with Sellafield Ltd and is concerned with the modification of the vehicle such that it can be deployed through a small access port via a tether. This AVEXIS-ROV system will be able to be used in very confined areas (the access point is approximately 150mm in diameter) and provide real-time video images back to the operator.

Ground and Aerial Vehicles
A number of other vehicles are currently under development at the University of Manchester for use in the above-ground storage facilities and caves. A 6-legged robotics spider has been developed which will be used to explore cluttered environments. The spider will be able to climb over obstacles, which would be a barrier to traditional wheeled-vehicles, and deploy sensors where required.

There are two projects currently on-going investigating vehicles for the inspection of groundwater contamination sites. There are several areas on the Sellafield site where contaminated liquor has leaked out of a storage tank into the surrounding soil. The current method of investigating the radiation levels in the groundwater is to drill a bore-hole and manually place a gamma probe down it (Fig. 4). A wheeled vehicle is being developed which will automate this process. The vehicle will move to the pre-drilled bore hole and lower the gamma probe down on a winch taking readings as it goes. Work is also being conducted on the development of a burrowing ‘mole’ robot which will remove the need for bore holes. The molebot will travel through the contaminated ground localizing itself and sending back measurements to the surface.

The final set of vehicles being developed are UAVs. There are a number of projects investigating the use of small-scale off-the-shelf quadcopters in radioactive environments and using ground and aerial vehicles collaboratively to explore an area, identify points of interest and retrieve items. A demonstrator of cooperative control of an UAV and a wheeled ground vehicle working cooperatively to explore an area is planned for mid-2014.

Localization, Navigation and Multi-Agent Systems

A number of industries, including the nuclear sector, are taking the initiative to use semi-autonomous mobile robots instead of remote control robots to increase efficiency and to reduce failures caused by human. To achieve this level of autonomy, several challenges need to be addressed, such as localization, navigation, and multi-agent systems.

Localization is the ability of the robot to determine its location in the environment at all times. This challenge is an essential element for mobile robot navigation. A mobile robot is an object that can wholly move with respect to its environment and external factors can affect the robot's movement and position, such as wheel slippage and loss of traction. Measuring the position in this case introduces a great challenge. Localization can be achieved based on either proprioceptive sensors or exteroceptive sensors. The latter is the preferable approach because the uncertainty associated with the estimation is bounded by the sensors error.

Navigation is another challenge and it represents the ability of the robot to drive from the current position to a goal position or series of goal positions reliably and efficiently. The navigation problem can be classified into two major competences: reacting and planning. Reacting competence tends to use a range of the exteroceptive sensors to build a local map where the robot moves towards the goal position with the main objective of avoiding obstacles in the environment. Planning competence, on the other hand, lies on the other extreme of the navigation spectrum. Given a complete and exact map of the environment, the robot plans the entire path from current position to goal position before it starts the execution. This approach provides global solution where some cost function, usually in terms of travelled distance, is minimized.

When mobile robots are used in any industry, it is unlikely to use a single robot with absolute capabilities. Instead, a group of robots with different skills work as a team to accomplish some high-level goals. This problem can be seen as a multi-agent system where communication and the hierarchy of decision-making are vital elements to insure best performance of the team.

These features of autonomy do not exclude the human factor entirely. In fact, for applications such as the decommissioning of nuclear power plants, it is required to have human supervising the entire process, and intervening, in certain cases, to control the robot remotely. This is also another field of research that the University of Manchester is targeting.

The localization, navigation and multi-agent control capabilities of mobile robots are being investigated using the platforms which were described in the previous section. Each type of vehicle has its own unique challenge with respect to these research areas, such as severe multipath propagation in the underwater acoustic localization system for the AVEXIS system, or the collaborative control of UAVs with limited computation power, however the overarching principles are the same.

Radiation Testing of Electronic Circuits

The most common question asked about all of the vehicles being developed at the University of Manchester is will they survive in a radioactive environment. Anecdotal evidence suggests that off-the-shelf vehicles can survive for extended periods in storage ponds and facilities. The Dalton Cumbrian Facility offers unique facilities to be able to conduct experiments to investigate the effects of radiation on electronic devices.

DCF has two primary pieces of equipment: a 5MV tandem Van de Graff ion accelerator and a self-shielded Co-60 gamma irradiator. These are supported by fully equipped analytical and post-irradiation examination laboratories. These facilities are unique to the academic sector in the UK and work is underway to explore the effects of both gamma radiation and neutrons on electronic circuitry.

AUTONOMOUS REMOTE CHARACTERISATION METHODS

Decommissioning is an essential step in any nuclear power plant. This process needs thorough knowledge of the plants in terms of blueprints or as-built drawings. This knowledge however is not always available and the blueprints for some facilities are either inaccurate or even lost. Therefore it is necessary to understand and characterize the nature of such hazardous environments such as shown in Fig. 5. Mobile robots fitted with proper sensors as described in the previous section have been identified as the best approach due to the high-level of radiation.

Fig. 5. Pipework Which Needs to be Mapped Before it can be Dismantled

In the University of Manchester, the characterization process is approached using laser scanners and stereo vision, where basic shapes, such as cylinders and prisms are identified as CAD models. These shapes are selected due to their predominance in industrial landscapes. This type of characterization is very important to determine the cutting paths and the handling procedures during decommissioning. To accomplish this, four major stages are applied:

1. **Data Acquisition:** use technologies such as LiDAR and Kinect.
2. **Filtering:** remove noise and outliers.
3. **Clustering:** classify each point in the cloud to different objects. Also, use algorithms for interest point detection in order to determine signatures on the scenes for registration and further detection of objects.
4. **Modeling:** determine a mathematical model for each object in the scene.

During the *Data Acquisition* stage, a Microsoft Kinect sensor is used for perceiving a point cloud that corresponds to the scene with different objects. Filtering is then applied to remove any outliers or noisy measurements.

In the *Clustering* stage, the University of Manchester is developing methods to determine interest points on the cloud using two-dimensional image algorithms adapted to a three-dimensional space. Robust descriptors of features are computed, and they serve as reference points for registration of scenes and matching with CAD models.

Finally, in the *Modelling* stage, the clustered point cloud is transformed into mathematical models using Principle Component Analysis (PCA) and RANdom SAmple Consensus (RANSAC). Fig. 6 shows examples of the shape recognition in both images and point clouds. Once the shapes have been identified, optimal cut-paths can then be identified so that the objects can be dismantled by a laser-cutter, removed and packaged for long-term storage.

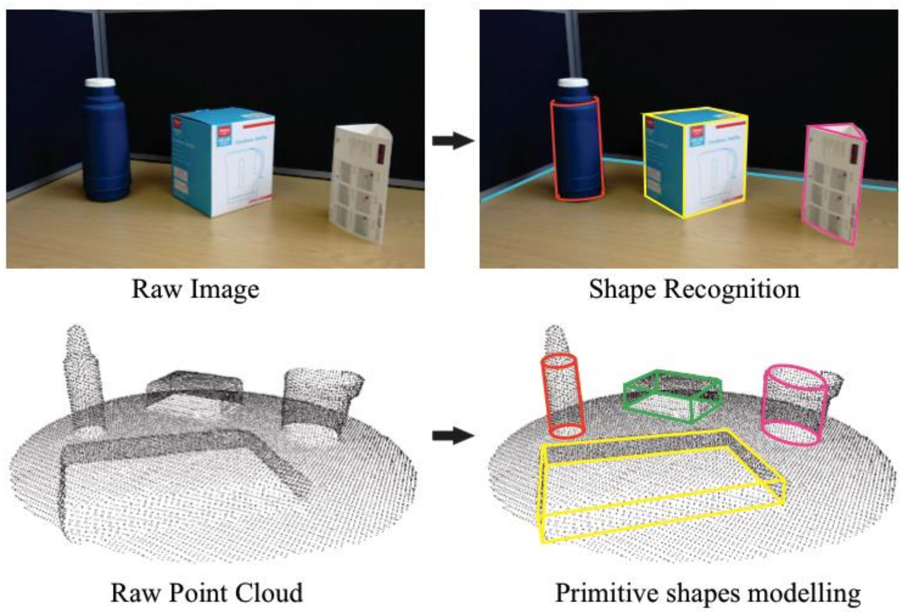

Fig. 6. Shape Recognition and Primitive Shape Modelling

CONCLUSIONS

The University of Manchester is working closely with Sellafield Ltd to supporting the decommissioning process at the Sellafield site through the development of semi-autonomous mobile robots which will be used to remotely characterize hazardous storage facilities. Vehicles have been developed to explore both underwater and above-ground facilities and remote characterization techniques for mapping and optimal cutting of objects are also being investigated.

The aim is to develop the technology such that it is able to be deployed in active facilities within the next 2 – 5 years. Whilst the primary focus is the deployment in nuclear facilities, the technology also has applications in other industries such as the oil & gas sector and the water industry. Opportunities in these other sectors are currently being explored.

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