HUMAN ARM-LIKE MECHANICAL MANIPULATOR

The Design and Development of a Multi -Arm Mobile Robot for Nuclear Decommissioning

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Abstract: This paper reviews the design and development of a human arm-like mechanical manipulator, which is the basis of research currently being undertaken at Lancaster University, in order to address the complex tasks found in the rapidly expanding field of nuclear decommissioning. The requirements of multi-arm robot architecture for use in decommissioning tasks are discussed. The manipulators are integrated to work cooperatively and perform similar functions to humans in both scale and dexterity. The role that automation and robotics can play in enabling quicker demolition and at the same time reducing the exposure of workers to harmful radiation is examined. The key issues surrounding radioactive materials and safe dose levels are explained. The different stages of a particular system engineering process are outlined together with the essential physical steps. The paper will conclude by identifying the compliance of the system engineering used here with the requirements of designing a multi-arm robot.

1 INTRODUCTION

Hundreds of nuclear facilities will come to the end of their working lives over the next decades and will require decommissioning. Much of the decommissioning process utilises well established demolition techniques, however the overwhelming complication in the case of the decommissioning of nuclear facilities is the exposure of workers to radiation. The primary use of robotics in decommissioning applications is to reduce the radioactivity dose levels to which workers are exposed. Nearly all Deactivation & Decommissioning (D&D) activities that are too hazardous for direct human contact are presently executed using robotic systems; however many of these systems are custom-designed for specific projects and hence expensive, often unreliable and limited (IAEA, 2001). The purpose of the research being undertaken at Lancaster University is to develop a generic tool that can be used for a wide range of decommissioning tasks. The importance of multi-arm robots has been noted by many researchers (Cox,1995; Miyabe, 2004; Alford, 1984) in the past two decades who have pointed out the advantages of such robots as compared to the “handicapped” single-arm robots. There is indeed a real desire for such systems in decommissioning robotics, undersea robotics and space robotics. For example, manipulating flexible objects or fixtureless assembly (Cox, 1995). A multi-arm robot has the ability to perform two distinct operations simultaneously or separately, they also have the ability to perform the same processing operation in a coordinated manner or share the task such as holding and cutting an object (Miyabe, 2004). Cecil Alford (1984) presents a case study of material handling by two robot arms.

2 MULTI-ARM MANIPULATOR SYSTEM

There has not been much research to date that has reported on the simultaneous utilization of a multi-arm robot configured on the basis of the size and

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relationship between two human arms, deployed from a remote vehicle with a manipulator. Previous studies concerning multi-arm robot systems have been deployed by either a rigid boom overhead transporter or by a crane rather than a remote vehicle. I have given below two examples of these forms of multi-arm robot systems: DAWM (Noakes, 1999) is a multi-arm robot platform equipped with two schilling Titan II or Titan T hydraulic manipulators and mounted to a 5-DOF base. DAWM as shown in Figure 1, was developed at Oak Ridge National Laboratory (ORNL) by the Robotics Development Program (RTDP) as a development test bed to study issues related to dual arm manipulation, including platform configuration, control, automation, operations, and tooling. These activities were conducted under the Deactivation and Decommissioning (D&D) Focus Area robotics product line.

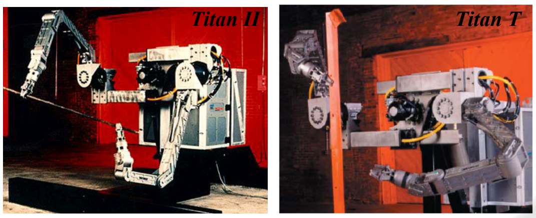

Figure 1: DAWM with Titan II and Titan T manipulators.

RODDIN multi-arm robot system is a crane-deployed work platform and is equipped with two hydraulic manipulators (SAMM or MAESTRO). RODDIN as shown in Figure 2, was developed by CYBERNETIX and it is used for pipe and metal cutting in decommissioning.

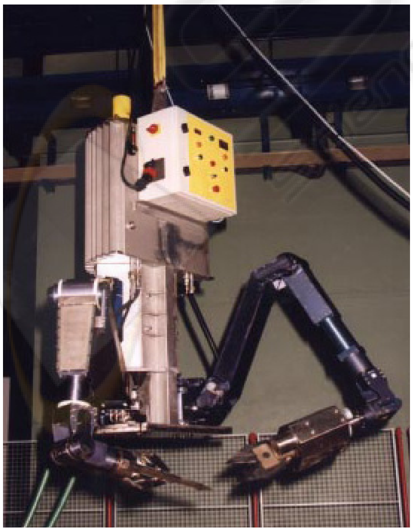

Figure 2: RODDIN with Maestro manipulators.

Neither of the multi-arm robot system manipulators described above is based on human-scale size or dexterity, they are also not light weight.

In the research being undertaken at Lancaster University we are focusing on the development of a multi-arm robot system based on human-scale size manipulators which can be deployed by a remote vehicle. The focus on the development of human-scale size manipulators is to undertake pipe-cutting decommissioning tasks; reconfigure the system for other necessary decommissioning tasks, such as dismantling; and to use the system in small restricted spaces that are too dangerous for humans, or in which a bigger manipulator could not be deployed.

Because of radiation hazards there are specific requirement for a robot to fulfil in order to undertake decommissioning tasks. A reconfigurable, multi-arm robot system needs to have the following operational features (Cox, 1999).

Operational features:

- Human scale reach and dexterity
- Force control
- Obstacle and collision avoidance
- Remote teleoperated control (both manipulators)
- Cooperative manipulator ability
- High reliability

It is widely believed that *human scale and dexterity* can satisfy many situations occurring in decommissioning tasks. Operators have the confidence to know that if a human can accomplish the task, then the robot can also achieve it. It is also necessary, however, to consider collision avoidance and planning strategies which are in themselves complex processes.

Forces and torques experienced at the end effectors of robot manipulators should be reflected back to the human operator at the manual control station, thus the operator can feel the work in process. The dynamic behaviour of the end-effector is one of the most significant characteristics in evaluating the performance of robot manipulator systems. Adding force information to robot control therefore improves robot interaction with the environment in the presence of uncertainty (Oussama, 1987).

The goal of *collision avoidance* is to permit a robot to work in an obstacle-strewn environment without damaging itself or any of the obstacles it encounters. Obstacle avoidance in an obstacle-strewn environment is needed to assist the operator of a remote system and help avoid damaging expensive equipment or, even worse, causing further contamination of the environment from the hazardous materials in the decommissioning sites.

Furthermore, the robot must prohibit self-collision in the case of a multi-arm robot.

Teleoperation has been successfully applied to unstructured tasks such as nuclear facility maintenance, cleanup, underwater operation and microsurgery (Parker, 1999). A telerobotic system consists of a human operator, a remote robotic system, and a human-machine interface. No matter how good the remote robot is, unless the human-machine interface is properly designed, the system will not perform well. A poorly designed human-machine interface can also introduce mental stress to the operator that will further deteriorate the system performance.

Cooperative manipulation is an important enhancement to robotic capabilities which enables a multi–arm robot to perform more complex tasks, manipulate greater payloads, and span a greater workspace (Dauchez, 1988). The task performed by cooperating manipulators can be achieved in either teleoperated, semi-autonomous and, or autonomous fashion.

An important deciding factor for use of robotics and automation lies in the *reliability* of the overall system. It is given that the robot makes it safer for the human. Reliability is a serious concern in hazardous environments. Task plans can be developed to optimise the safety of the system by avoiding situations that place components near the edge of their performance envelopes. Integration of operational software with fault-tolerance and condition based maintenance can further enhance the system reliability.

3 THE ROLE OF AUTOMATION AND ROBOTICS

The primary use of robotics in decommissioning applications is to reduce the radioactive dose levels to which workers are exposed. There are many situations where, owing to the degree of radiation and the very long half-lives of the radioactive materials involved, robotics is the **only** feasible option.

Remote cutting for equipment dismantlement is a common need in the deactivation and decommissioning community. Where possible, suited humans are used to complete the cutting, but there is significant safety, health, and cost issues involved. Robotic systems have also been used where radiation levels eliminate the possibility of using humans; however cost and task completion time are major issues. A time-efficient, cost-effective approach to safely complete D&D operations without the use of humans in the hazardous environment is a direct need.

The Nuclear Regulatory Commission's regulation 10 CFR 20 states that an occupational worker cannot receive more than 50 mSv per year for the full body dose (NRC), once this dose has been reached the worker has to stop working immediately. This necessitates an increased number of workers to be employed in order to accomplish the necessary task. By using robots the number of workers is minimised, this in turn creates many additional savings including a reduction in the quantity of protective clothing needed, and a decreased administration.

4 RADIOACTIVE MATERIALS AND SAFE DOSE LEVELS

The effect of radiation on the human body is measured in Sieverts (Sv). The International Commission on Radiological Protection (ICRP) has set public dose limits for exposure to radiation; this is linked to the requirement to keep radiation exposure as low as possible.

The radiation limits are usually set at 1mSv per year above background (Burk, 2001). In most countries the current maximum permissible dose to radiation workers is 20 mSv a year averaged over 5 years, with a maximum of 50 mSv in any one year. The following table indicates the physical effects on human of excessive exposure to radiation:

Table 1: Health Effects of Nuclear Radiations Doses.

Dose	Health Effects
0.5 Sv	Possible minor blood changes, no obvious effect
0.5-1 Sv	Radiation sickness, vomiting and nausea. No death anticipated
4-5 Sv	Radiation sickness more severe. 50% deaths in 3-8 weeks from infection or anaemia. Survivors convalesce for about 6 months
≈ 10 Sv	Vomiting and nausea within 1-2 hrs. Probably no survivors. Death within 3-5 days following damage to lining of small intestine
≈ 50 Sv	Tremors, convulsions almost immediately. All deaths in less than 2 days due to brain damage

Decontamination and decommissioning (D&D) of all nuclear facilities produces radioactively contaminated materials. Some of these materials continue to have economic value because they are in forms that can be recycled or reused. Others will have little or no economic value and thus constitute waste that has to be disposed of or stored if no acceptable method of disposal exists.

The radioactive waste classification and disposal routes (IAEA, 1994) are as follows:

1. Very low-level waste (VLLW). This waste can be disposed of in normal landfill sites.
2. Low-level waste (LLW). This waste contains 1% of the radioactivity but accounts for over 80% of the volume and is stored in containers at a dedicated site.
3. Intermediate-level waste (ILW). This waste contains higher amounts of radioactivity than LLW and requires shielding. There are no dedicated facilities in the UK at present, so it is currently stored on the site of the decommissioning facility in a specially constructed facility.
4. Higher-level waste (HLW). This waste contains at least 95% of the radioactivity in radiation waste but no more than 3% of the volume and requires special storage with cooling facilities.

In order to illustrate the above proportions of radioactive waste, 1 tonne of spent fuel from fuel processing gives rise to 0.1m^3 HLW, 1m^3 ILW and 4m^3 LLW.

5 SYSTEMS ENGINEERING PROCESS

The systems engineering process, as shown in Figure 3, derives from the consideration of a specific concept, and the consequent selection of appropriate technology. Defining the *user requirements* is the first step in the development process using the system engineering principles and the finished products should satisfy these requirements (Zied, 2004). The user requirement in this research is the creation of a robot manipulator with the operational features of human scale and dexterity.

The *system requirements* are an intermediate step between the user requirements and the design stage, which aim to show what the system is going to do. In this research, the system requirements derive from the multi-arm robot configuration which needs to have the capacity for force control, collision avoidance, remote controlled, cooperativeness and high reliability.

The *architectural design* is the system design that defines the major components, their arrangements, decompositions and interrelationships. The human scale manipulator developed in the research is called Hydro-Lek which is a six degree of freedom robot manipulator and consists of six links with a gripper, four linear actuators and two rotary actuators.

The *component development* step is the detailed design of the individual Hydro-Lek manipulator links including functionalities, interfaces and layouts. The given information is enough to manufacture the robot components or to purchase off-the-shelf components. The manipulator links then have to be tested, assembled and finally accepted.

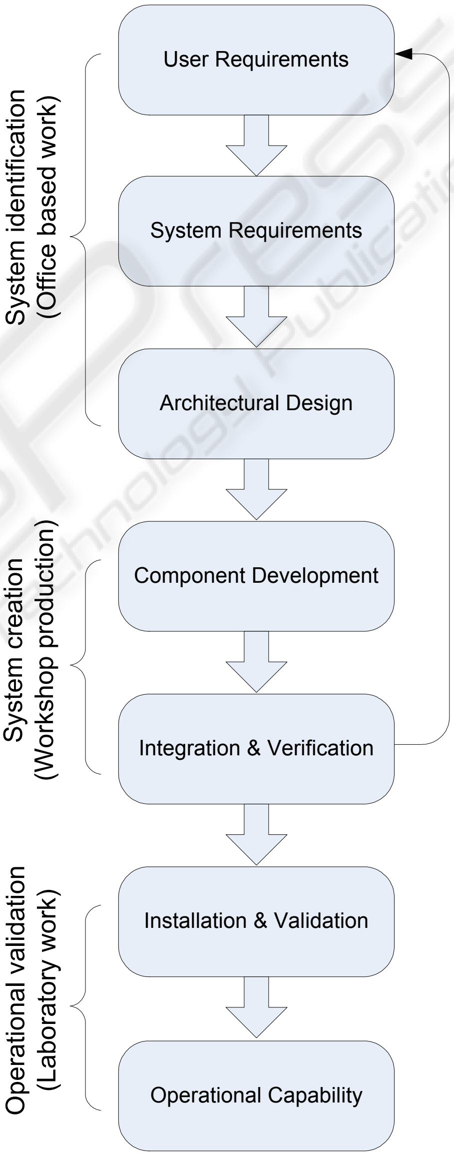

Figure 3: Sequential development model (Stevens, 1998).

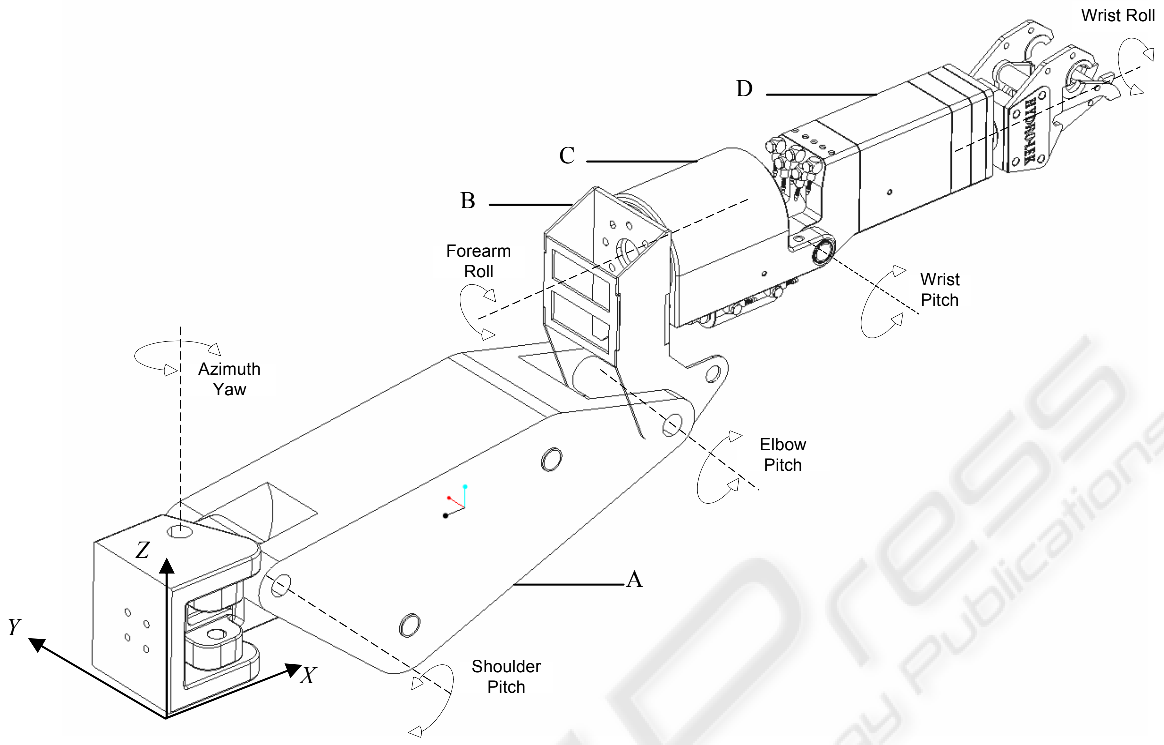

Figure 4: Hydro-Lek 6 DOF Arm.

Figure 4 above, shows the six joints Hydro-Lek manipulator layout. Joint one rotates with axis perpendicular to plane XY. Joint two rotates perpendicular to joint one. Joint three rotates parallel to joint two and is offset by the link indicated as A. Joint four is perpendicular to joint three and is offset by the link indicated as B. Joint five is perpendicular to joint four, parallel to joint three and is offset by the link indicated as C. Joint six is perpendicular to joint five and is offset by the link indicated as D.

Verification can be performed in two stages. The first stage is design verification in which the design is certified against the requirements and it assures that the product will work properly if it is manufactured. Computer simulation provides a means of viewing robot motion to aid in human perception and decision making for both design and operation. Interactive software packages that generate computer animations have found wide acceptance for programming and simulating industrial robots. Animated work-cell design involves graphically placing the robot in its environment, also called the work-cell.

Machines, tools, parts and any other objects that the robot manipulators will interact with are also placed in the workcell. Computer animation is then used to visually simulate these interactions as the robot manipulator performs its task. The verification step in this research was carried out using a CAD/CAM software package which included Pro/ENGINEER Wildfire 2.0, used for modelling, modification and animation of the Hydro-Lek arm components; and robot simulation software, Workspace 5.04, in order to assemble and integrate the imported arm components from the Pro/Engineer software, and carry out the necessary kinematics simulations by defining all of the arm joint translations and orientations.

Table 2 explains the Hydro-Lek manipulator arm functions.

Table 2: Hydro-Lek arm functions.

Joint	Actuator Function	Type	Nom. Range
1	Azimuth Yaw	Linear	90^o
2	Shoulder Pitch	Linear	120^o
3	Elbow Pitch	Linear	120^o
4	Forearm Pitch	Rotary	180^o
5	Wrist Pitch	Linear	180^o
6	Wrist Roll	Gerotor	360^o

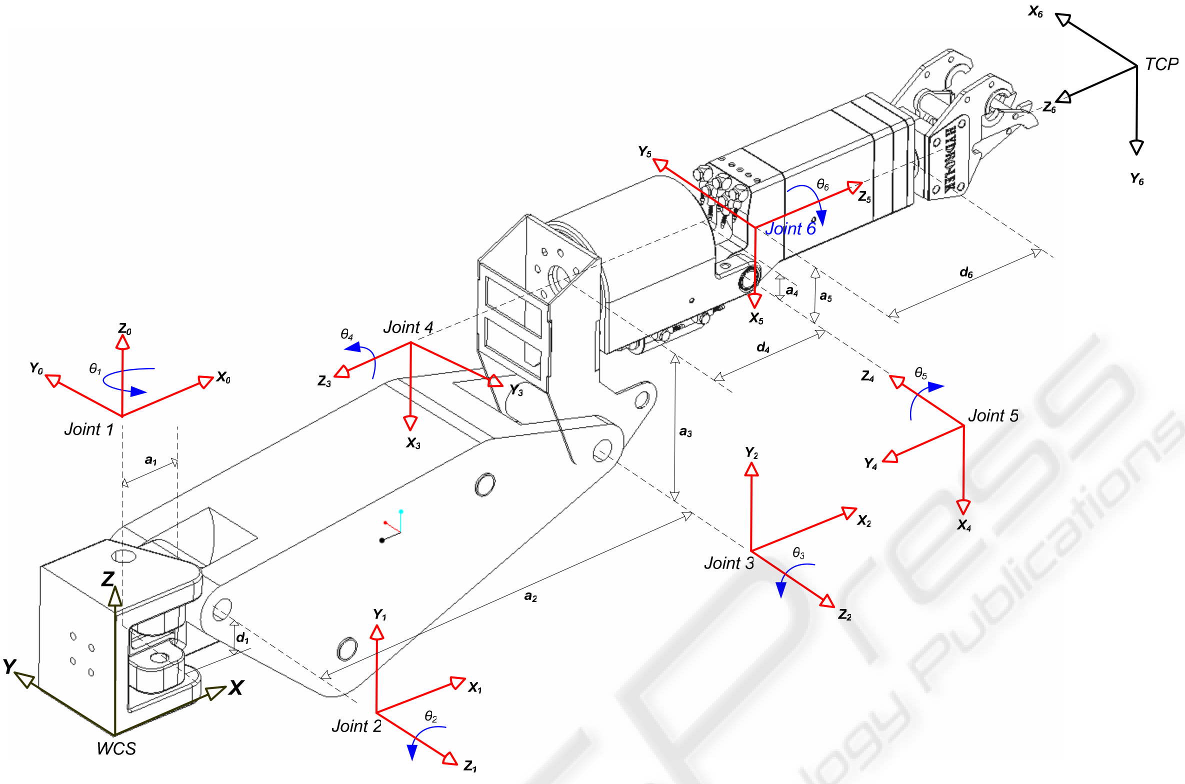

Figure 5: Denavit-Hartenberg Configuration for the Hydro-Lek arm.

Robot manipulators can be considered as a set of bodies, or links, connected in a kinematic chain by joints. Each joint of the robot manipulator exhibits one degree of freedom.

Hydro-Lek manipulator specification:

- Human size arm (900 mm long)
- Approximately 30 kg weight
- 6 function + gripper
- Potentiometer sensor for each joint
- Gripper with force sensor
- Closed loop position control

Both Hydro-Lek manipulators are in the manufacturing stage, they are due to be delivered in two months time. Multi-arm configuration will be set up in order to be mounted to the Brokk 40 friendly mount point.

The Hydro-Lek manipulator structure is kinematically defined by giving each link four parameters (d_i, θ_i, a_i and α_i). The four given parameters shown in Table 3, describe how to get from one joint to another. Neighbouring links have a common joint axis between them.

Table 3: The D-H Parameters.

Joint	θ_i	α_i	a_i	d_i
1	θ_1	90°	a_1	d_1
2	θ_2	0	a_2	0
3	θ_3 - 90°	90°	$-a_3$	0
4	θ_4	90°	a_4	$-d_4$
5	θ_5	90°	$-a_5$	0
6	θ_6 + 90°	180°	0	d_6

The distance along the common axis from one link to the next link is offset d_i. The amount of rotation about the common axis between one link and its neighbour is joint angle θ_i.

The definition of mechanisms by means of these four parameters is a convention called Denavit-Hartenberg (Fu, 1987). The location and orientation of each joint frame is shown in Figure 5 above. In this research, the installation step can be conceived as an integration step within the systems engineering process. This integration step couples the two Hydro-Lek manipulators in a test bed in order to form a multi-arm configuration as shown in Figure 4. A similar project has been undertaken by Daniel Cox (2004).

6 THE MULTI-ARM ROBOT CONFIGURATION

The ongoing research work in robotics at Lancaster University is concerned with advancing the semi-autonomous tele-operated robot for D&D tasks. Figure 6 shows the layout of the two Hydro-Lek arms. The left arm is a complete arm with a gripper and the right arm has no gripper but a simple flange where a cutting tool will be fixed. The purpose of developing the multi-arm robot in this research work is for the arms to have the ability to perform two distinct operations simultaneously or separately. The decommissioning task considered here is pipe cutting where the left arm holds a straight pipe while the right arm cuts it. The left arm then places the cut piece in a suitable waste disposal vessel.

At this stage of the project, the aim is to attach the multi-arm robot on to a Brokk 40 friendly mount point as shown in Figure 7. The primary aim of the research is to develop intelligence in the robot that is similar to the cooperation and communication between the human brain and its two arms; hence the human arm is adopted as the starting point to establish the size and functionality of the proposed system. The next stage of this research work is the identification and development of hardware and software systems such as the National Instruments robotic platform (Lewis, 2004). The NI robotic platform combines hardware interfacing, stepper or servo control, trajectory generation, task level programs, a graphical user interface 3D simulation and a math library. The NI robotic platform implements all these components in a homogeneous architecture that will utilise a single hardware platform (a standard PC), a C programming language and an operating system (LabVIEW Real-Time). This design will lead to a less complex architecture, easier to use and easier to extend.

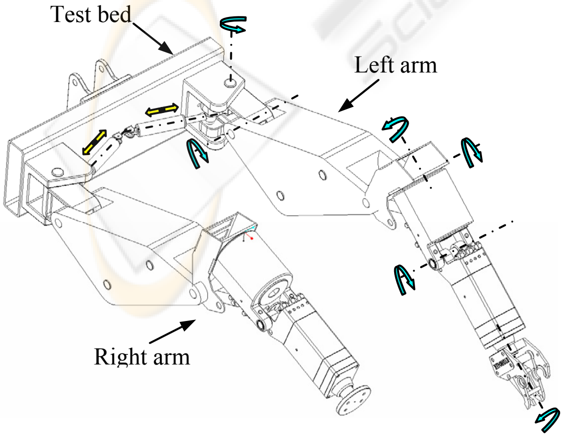

Figure 6: Hydro-Lek arms configuration.

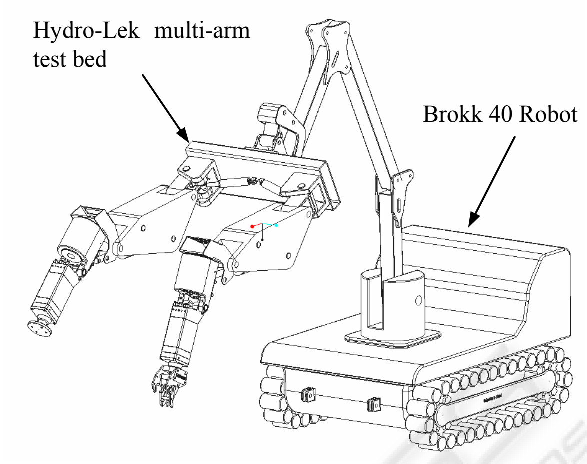

Figure 7: Multi-arm mobile robot.

7 CONCLUSION

Nuclear decommissioning provides a particularly fruitful sector for the advancement of automation and robotics. Earlier generations of nuclear facility have now been closed and many are waiting effective decommissioning. There is a multi-billion pound world-wide market for companies who have the skills and technology to engage with the task. In addition to traditional hazards such as asbestos and PCBs, the key hazard is obviously the presence of significant quantities of radioactive waste material. It is the effective management of this waste which is the crux of nuclear decommissioning. Many projects have been successfully completed and valuable lessons learned. This is a great driver to the further use of automation and robotics in order to reduce the radiation dose to which workers are subjected.

This paper has outlined and discussed the design and development of a human arm-like mechanical manipulator in order to address the complex tasks found in the rapidly expanding field of nuclear decommissioning and the requirements of multi-arm robot architecture for use in decommissioning tasks. The stage so far reached is a manufacturing and integration stage, the next stage of this research will involve carrying out experimentation in order to execute pipe cutting tasks.

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