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Evaluation and Design Recommendations for a Folding Morphing-wheg Robot for Nuclear Characterisation

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Abstract— **This paper explores the design and development of a folding robot required to survey and characterize nuclear facilities only accessible via 150 mm diameter entry ducts. The enclosed legacy facilities at old nuclear sites like Sellafield in the UK have this sort of limited access. When a site reaches the end of its operational life, it must be decommissioned and the resulting waste material must be safely disposed of. The condition, radioactive characteristics, and accessibility of the enclosed environments are unknown; for decommissioning to occur, these environments must be mapped and characterized. For a robot to carry out this task, one of the key requirements is the ability of the robot to traverse rough terrain and obstacles that could be found inside the facility. To accommodate this, while fitting through the entry duct, the chosen design utilizes morphing whegs (i.e., wheel-legs) for locomotion. These are shape-changing wheels that can open out into a set of legs that rotate around an axle, allowing greater traction, diameter, and object traversal ability than wheels alone. The design and morphology of a folding morphing-wheg robot for nuclear characterization, as well as the manufacture and testing of a prototype, is discussed in this paper. A preliminary evaluation of the robot has shown it is capable of climbing up a maximum step height of 150 mm while having a wheel dimension of 100 mm and being able to fit through a 150 mm duct.**

Folding Robot, Morphing Wheg, Characterisation, Nuclear Decommissioning

I. Introduction

With use, nuclear facilities are exposed to radiation and inevitably the buildings and equipment used in the nuclear processes become radioactive. This radioactive material poses a hazard to human and animal life and effectively renders a large area of land unusable if the radioactive material is not successfully removed or rendered safe. These environments are complex and due to the degradation of the facilities, unstructured and unclean. Nuclear decommissioning is the process whereby a nuclear facility is dismantled so that it no longer requires measures for radiation protection. The term encompasses the immediate decommissioning of power plants, the dismantling and demolishing of buildings, the management and disposal of nuclear waste, and the remediation of the land. Nuclear decommissioning is a global problem of enormous societal importance and is set to become increasingly important in the future as Nuclear power becomes more widespread [1].

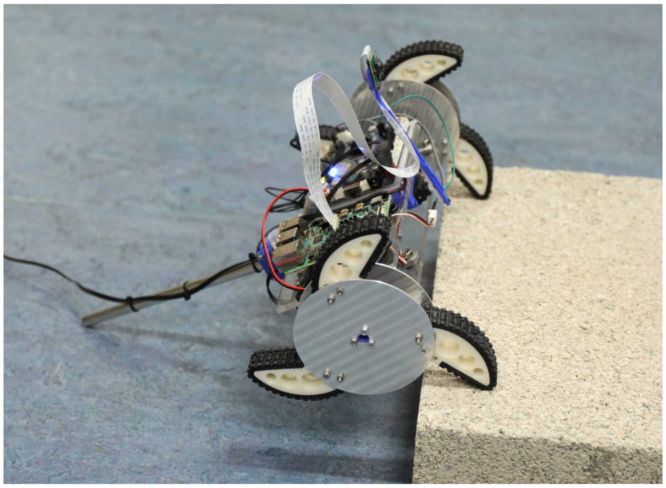

Fig. 1: The robot

For decommissioning operations to be conducted safely and efficiently the state, layout, and radioactivity of the facility must be known. [2] “Characterisation is extremely important because it allows the most appropriate and effective methods of decontamination, dismantling/demolition, and waste management to be subsequently applied and therefore affects decommissioning safety and cost.” [3]

Decommissioning and characterization operations at Sellafield and other nuclear sites are currently carried out manually and with some bespoke mechanical systems. These bespoke solutions are both time-consuming and expensive to deploy, and manual handling is costly, slow, and potentially dangerous. There is the potential to develop less expensive, modular robotic systems that can be used effectively in many nuclear environments. Objects such as pipes, cables, and other nuclear detritus may lay across open spaces and impede the movement of any robot inside.

The nuclear decommissioning industry is a highly regulated and relatively conservative industry, and so far this has prevented the use of many robotic tools, though many are currently in development in academia and industry (e.g., [4], [5], [6], [7]). A high degree of importance is put on the reliability and robustness of processes, as the consequences of a failure can be so high. For this reason, simple tools are preferred and thus far high levels of automation have been rejected to continue the use of traditional machinery. Any

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robotic tool must be designed carefully to be suitable for the industry and task.

This paper presents the design and development of a folding robot for access into nuclear facilities through 150 mm diameter entry ducts (Figure 1). The robot uses a morphing-wheg design to traverse flat surfaces and obstacles of up to 150 mm height.

II. RELATED WORK

A robot that has previously been designed for entry through the 150 mm diameter ducts at Sellafield is the MIRRAX (Miniature Inspection Robot for Restricted Access eXploration) robot [8]. This robot is a 3-segment folding robot with its shape inspired by the Hitachi-GE Nuclear Energy Robot, which is also designed for duct entry. With the robot 'opened up' and the three segments parallel to each other, the robot can move through a duct driven by its four omni-wheels. Once inside the facility, the robot can then close to a 'U' shape providing a stable platform. The robot carries two LIDARs, a camera, and a GM tube. This robot has been designed to be low-cost and is deemed sacrificial. Through discussion with the creators, it had been found that this robot is limited by its lack of ability to move over rough terrain, with omni-wheels only being suitable for movement on flat, smooth surfaces. The design of the MIRRAX robot was inspired by the PMORPH2 and PMORPH2 robots made by Hitachi Corp for use in decommissioning the Fukushima Daiichi Nuclear plant following the 2011 nuclear accident. These are also folding robots designed to move through pipes, as well as move on flat ground. They are tracked robots that perform similar tasks to that required at Sellafield and have been deployed successfully at Fukushima. They differ from the robot featured in this paper in their form factor. One of the requirements given by Sellafield Ltd was that the robot should not be tracked, as this increases the risk of spreading radioactive material. It was chosen not to use a traditional legged robot due to the risk of toppling and the more complex control required. [9] The robot discussed in this paper uses whegs as a means of locomotion, which reduces the potential to pick up and spread radioactive material. This paper builds on the paper discussing the previous prototype [10]. The design has been improved to increase the traction of the whegs and reduce the likelihood of the whegs getting stuck, as well as adding actuation of the tail, a folding camera boom, and the ability to teleoperate the robot.

A. Whegs

Whegs are a system in which legged locomotion is implemented by a number of legs rotating around an axle. The advantage of whegs over conventional wheels centers around the ability of the design to traverse rough terrain and obstacles [11], [12], [13]. Whegs are implemented in two main forms, the first with fast-spinning, flexible legs that cause the vehicle to 'bounce' over objects, and the second with slower-moving, stiffer legs that hook onto objects, allowing the vehicle to crawl over them. For this design, whegs designed to crawl over objects have been chosen. These provide a high ability to traverse obstacles while doing so in a relatively safe manner. The slower more gradual movement allows for more careful route planning by the operator and reduces the risk of the robot tipping over or damaging itself. The slower movement also reduces vibration, aiding the use of sensing equipment and potentially leading to better-quality sensing.

For wheeled and wheged robots, the object traversal ability has a direct correlation with the size of the wheels or whegs. Without significant lateral force to provide friction, wheeled vehicles are not able to traverse obstacles larger in size than the wheel's radius. In practice, this ratio is even smaller for smooth wheels. If whegs are shaped to hook onto objects they can traverse objects of greater size, [14], [15] potentially nearing the diameter of the wheg. Though again, we see that the ability to traverse objects is limited by the diameter of the whegs. For this task the size of the duct limits the diameter of the wheels or whegs that can be entered into it. To work around this problem, and to maximize the obstacle traversal ability of the robot, 'morphing whegs' have been chosen. These are mechanisms that transform between wheels and whegs, with the effect of increasing the diameter of the system, as well as the traction properties on rough surfaces [16]. It is envisaged that the robot will be entered into the duct while in the 'wheel state', as the diameter of the wheels will be smaller than that of the whegs, which would be too large to fit through. Once beyond the duct, wheels and whegs each have use cases depending on the terrain being traversed. Whegs are most useful in crossing uneven terrain, climbing over obstacles that wheels cannot, and generally in situations where wheels lack traction. Wheels are useful where speed is required, as they can turn more rapidly without transferring vibration and jarring forces to the robot, and in situations where more accurate sensor data and odometry is needed, as the jarring movement of the whegs may degrade these capabilities.

III. ROBOT HARDWARE AND SOFTWARE DESIGN

This section describes the design and implementation of the presented folding morphing-wheg duct-entry robot. We describe the hardware design for the overall robot in Section III-A, and give an overview of the robot's ROS-based software in Section III-B. The robot shown here is a prototype built to test the morphology and software, and therefore the materials and design are not expected to withstand the real-world conditions of a nuclear facility.

A. Robot Hardware

A robotic tool for duct-entry nuclear decommissioning has been developed. The robot is connected via a tether to its 'tail' and is able to move around inside to the nuclear environment to gather sensory data for characterization. The robot is a two wheged differential-drive design with a folding tail, allowing it to enter into a duct, as shown in Figure **??**. The shape has been optimized to minimize the projected side-on area when in the folded configuration, allowing the robot to fit into and be pushed through a 150 mm duct. Once through the duct, the robot is lowered to the ground by its tether and can unfold the tail to move about. The robot is able to move on smooth ground while in the wheel configuration, and open up the whegs to traverse rougher terrain when required. Sensing and imaging equipment can be deployed via a hinged arm that swings out above the robot and provides an overhead vantage point, as shown in **??**. This allows unobstructed sensing and imaging for characterization and operator feedback.

A simple way of implementing morphing whegs is to use a wire-pull and opposing spring mechanism. This consists of a wire passed through a hollow axle that can be tensioned to actuate the legs. A 'swivel' or rotary coupling must be included in the wire to allow for continuous rotation of the whegs without the wire becoming twisted or tangled.

A schematic is shown below in figure 2:

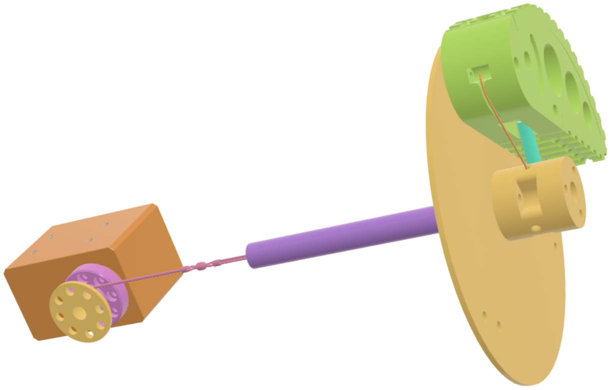

Fig. 2: A diagram showing the wire pull wheg activation mechanism

The robot moves about by rotating the wheels or whegs and dragging the tail behind it. The tail is required to oppose the forward rotary motion of the whegs, without which the main body of the robot would rotate rather than the wheels. Steering is conducted by varying the speeds of the two wheels relative to each other.

B. *Robot Software*

The software runs on a Raspberry Pi 4 single-board computer and an OpenCR control module. This framework allows for control from either a base PC or a Bluetooth controller. The Raspberry Pi runs Ubuntu 20.02 Server which allows for ROS Noetic to be run. ROS integration allows for the inclusion of navigation, mapping, and vision packages. The OpenCR board is used to read and write signals to the motors. More complex computation, such as for image processing and SLAM can take place on the base PC. The teleoperation system uses the ROS package usb_cam to pass image data over WiFi. This is received by the base PC. Control commands are sent via ROS using a custom teleoperation package or via Bluetooth controller and receiver connected to the OpenCR board.

A high-level system diagram can be seen in Figure 3. This figure shows how the individual components link together and interact with each other.

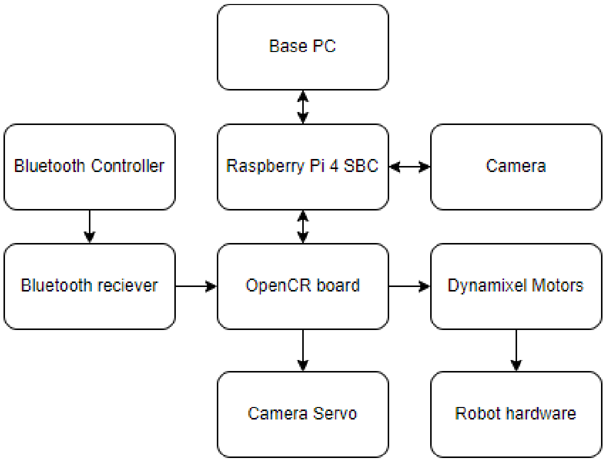

Fig. 3: A diagram showing the system architecture

IV. PROTOTYPE AND EVALUATION

A prototype has been manufactured to test the morphing wheg design and folding concept. The overall robot consists of a chassis constructed from two Acrylic plates, which sandwich the mechanical hardware of the robot. A wire pull mechanism is used to actuate the whegs. This consists of a central capstan rotated by a Dynamixel servo that tensions a wire. This wire is attached via rotary couplings to two wires that run through the center of the two hollow axles and into the wheg mechanisms. Inside the body of the wheg mechanism this wire splits into 3 and when tensioned, actuates the wheg mechanism to open the legs. To close the legs, the tension from the wire is released and springs, which were tensioned during opening, pull the mechanism closed. The wire mechanism is shown in Figure 8. The tail is actuated via a worm drive gear. This provides a large force to open and close the tail, meaning the tail can be opened even if the weight of the robot must be lifted to do so. This is useful for duct entry applications, where the robot may land in an uncontrolled manner and orientation. The camera arm is actuated using a standard RC servo motor, this allows for the arm to be folded parallel to the robot body to reduce the cross-sectional area during duct entry, and unfolded when through.

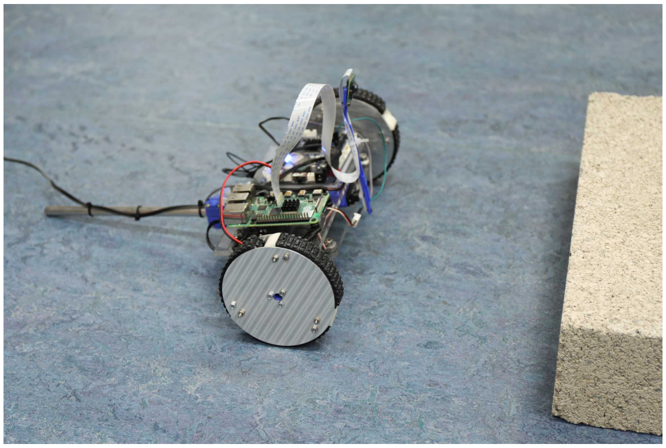

Fig. 4: The robot approaching an obstacle

A. Design Calculations

At each of the wheels, the force required to lift the robot is 7.85 N. Based on a 3 Nm capstan motor and a friction constant of 0.8, the force provided to the wheg tip when opening the whegs is 38.25 N. Hence the robot is easily able to lift its own weight.

$$\text{Maximum wheg tip force during opening of whegs (N)} = (3Nm \times 0.8 \times 0.0065m)/(0.006m \times 0.068m) = 38.25N \tag{1}$$

For forward movement of the wheg, the maximum force at the tip of an extended wheg can be calculated as:

$$\text{Maximum Wheg Tip Force during forward movement} = 3Nm/0.09m = 33.3N \tag{2}$$

This is easily enough to lift the robot when moving over obstacles during forward motion. The maximum moment that can be applied to the tail is 14 Nm. This equates to a 70 N opening force at the end of the tail, which is enough to open the tail when underneath the body of the robot.

The table below shows some of the key physical attributes of the robot.

Parameter	**Value**
Distance Between Wheels	330 mm
Width	140 mm
Tail Length	200 mm
Wheel Radius	52.5 mm
Wheg Radius	100 mm
Weight	1.6 kg

TABLE I: Key physical attributes of the robot

B. Evaluation

The prototype has been tested in a range of scenarios and in both wheel and wheg configurations. Generally, it has been found that the robot operates well and as intended in a range of environments. It was found that the robot could traverse up a step of 150mm in height. The robot could traverse a breeze block of dimensions 100 mm by 200 mm over a period of 11 seconds. On flat ground, without the whegs deployed, the robot can move at a speed of 0.5 m/s, this is limited by the speed of the motors. With the whegs deployed, the robot can move at a maximum speed of 0.15 m/s. This is limited artificially to reduce the reactive forces on the robot during forward movement with the whegs deployed. On a pebbled surface, shown in 5, it was found that the robot could move at a speed of 0.1 m/s. Moving over grass, as shown in 10, the robot could move at a speed of 0.12 m/s.

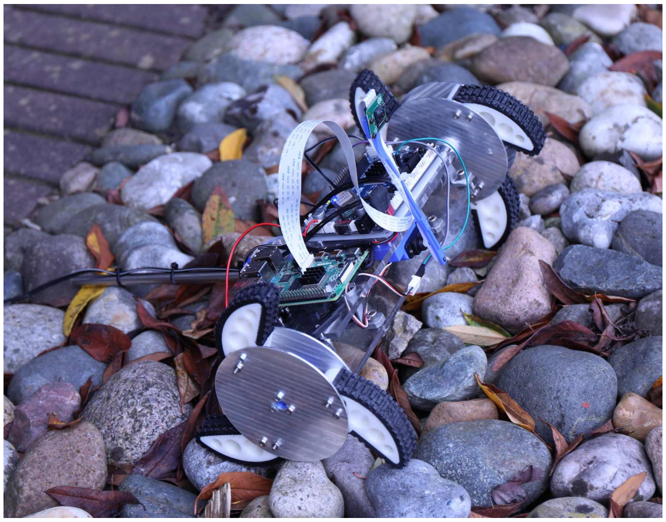

Fig. 5: The robot traversing over large pebbles

Task	**Result**
Step Traversal Height	150 mm
Flat Ground Speed (Wheel configuration)	0.5 m/s
Flat Ground Speed (Wheg configuration)	0.15 m/s
Pebbled Surface Speed (Wheg configuration)	0.1 m/s
Grass Surface Speed (Wheg configuration)	0.12 m/s

TABLE II: Table showing robot performance in different scenarios

Figure 6 shows the robot climbing over a breeze block.

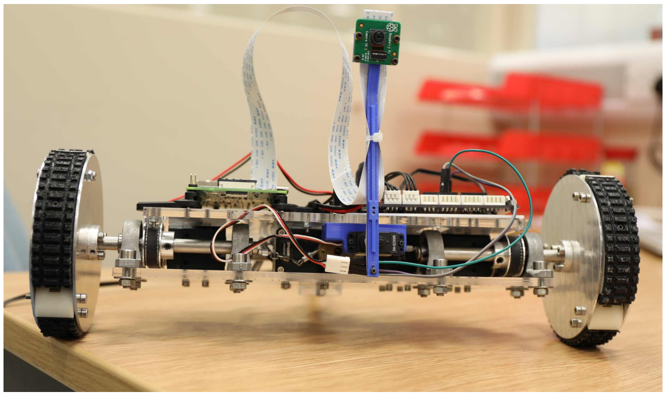

Fig. 8: The front of the robot

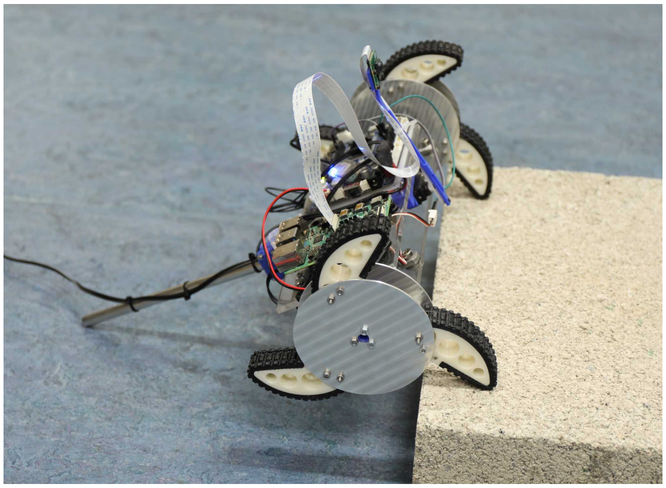

Fig. 6: The robot climbing over an obstacle

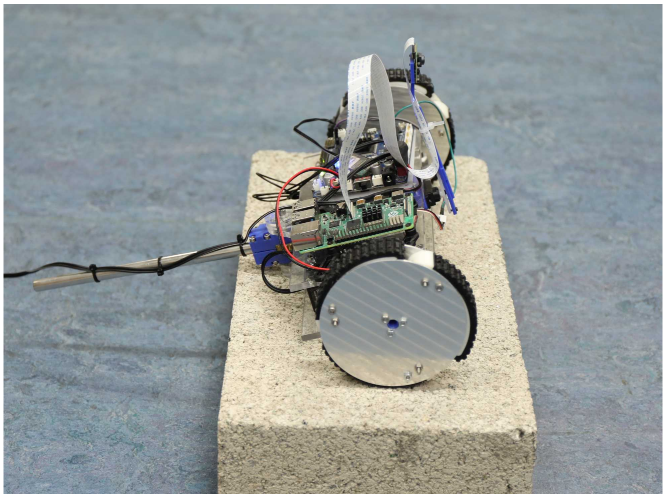

Fig. 7: The robot in the process of traversing an object

C. Limitations and Future Work

One of the predicted difficulties during the operation of the robot is the initial application of the robot through the duct. Figure 9 shows the robot in its folded state, ready to be inserted into a duct. Figure 11 shows the robot being inserted into a duct. The ducts at the Sellafield site are at various angles and positions. For the application of the robot, a duct in the most preferable position and orientation will be chosen. Even with this considered, ensuring the robot reaches a stable and upright position on the floor of the operational area will pose a challenge. An applicator tool will be used to push the robot through the duct and if required, lower it to the ground via the tether. This task will likely require the operator to be trained to effectively lower the robot and use its actuation to orientate the robot in its upright position. Removing the robot via the duct also poses a significant challenge. Prior to removal, the robot will be driven to the area in which it entered the duct. The cable can then be linked to the applicator tool and the slack can be pulled back through the duct. Once the slack is removed, the robot can fold to its ’closed’ position, ready to enter the duct. The tether can then be tightened to remove the slack and the robot pulled tight onto the applicator tool. Once this has happened, the applicator tool and robot can be removed from the duct together. Tether management will also need to be considered when operating the robot within the nuclear facility. The robot can operate via a battery and wireless control, though part of the design brief stipulated the use of a tether, to make removal of a damaged or broken robot possible. When operating a tethered mobile robot in a complex industrial environment, there is the potential for both the robot and tether to become stuck on objects or ground terrain. This risk can be mitigated by altering the driving style and path planning of the robot. Particular movements, such as looping around obstacles, and particular obstacles, such as protruding metal pipes should be avoided. Upon removal of the robot, the robot should be driven back along its operational path, to prevent the tether looping around obstacles. Radiation hardening is possible in future versions of the robot. This will mainly be achieved by preventing the ingress of fluids and dust, and by using shielding to protect electronic components. The design of some systems would need changing to accommodate seals and shielding. This is likely possible without major modifications to the overall design of the robot.

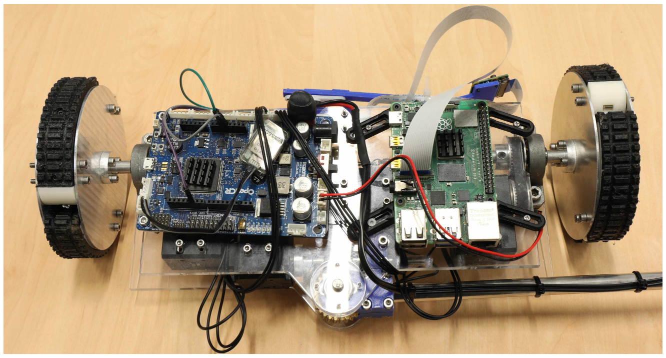

Fig. 9: The robot in its folded state

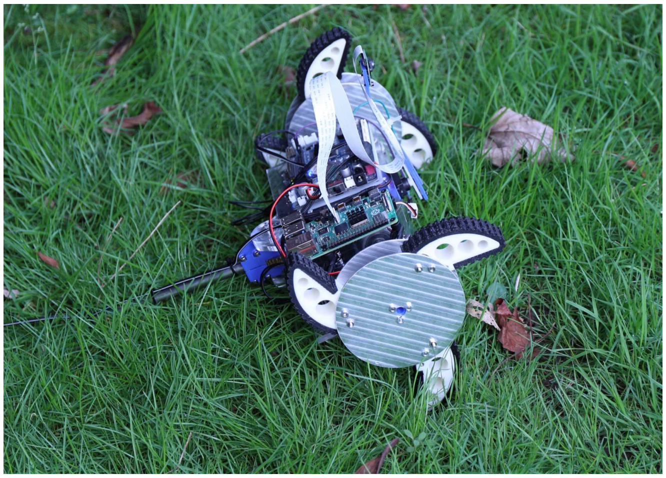

Fig. 10: The robot traversing over grass

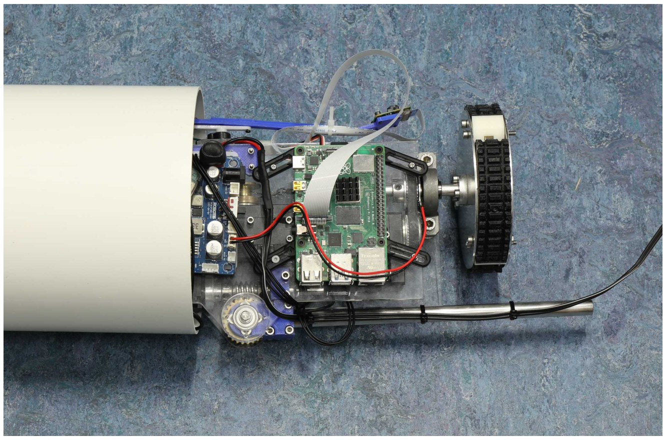

Fig. 11: The robot halfway inside a 150mm tube

V. CONCLUSION

This paper proposes the design and control mechanism of a novel wheged robot for use in restricted access nuclear decommissioning, as well as the design of mechanical systems for morphing wheel-leg robots. The robot proposed is a folding ground-based mobile robot for use in restricted access nuclear environments accessible only via 150 mm ducts. The robot uses morphing-whegs to achieve this. Whegs are systems in which multiple ‘legs’ rotate around an axis, giving a resemblance of legged motion via a simple control mechanism. Morphing whegs are whegs that can transform between wheels and whegs, depending on which state is desirable for a given terrain. An evaluation of the robot has been carried out. The robot has been found to function well in both wheeled and wheged states. In the wheeled configuration, the robot can move quickly on smooth ground, in the wheg state it was found that the robot can climb over a step of 150 mm height and traverse over rough terrain. Further work will focus on improving the mechanical design of the robot to bring it to a state more suitable for commercial use, as well as improving the software for teleoperation and potential autonomy.

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