Novel UAV and UGV Platforms for Physical Interaction with the Environment in support of Nuclear D&D Operations

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Abstract: The current state-of-the-art in decontamination and decommissioning (D&D) remains largely based on manual operations in personal protective equipment (PPE) with human-operated equipment augmenting human abilities, as needed. Increasingly, robotic or remote-piloted equipment, such as back hoes and bull dozers, have been making inroads into conventional construction projects, and these implements are beginning to appear in D&D projects in the nuclear industry. With the potential benefits to worker safety and reduced risk of exposure, we have been working with a broader array of robotic equipment to bring these derived benefits earlier in the process to the realm of inspection and assessment of potentially contaminated facilities.

In this paper, we describe recent demonstrations at the Portsmouth Gaseous Diffusion Plant —and their proposed extensions to more difficult problems —during a U.S. DOE "Science of Safety" exercise to explore new technologies and new applications for nuclear D&D. We first explore the ramifications of a new class of unmanned aerial vehicle (UAV) designed for physical interaction with the environment that permits new levels of fidelity in tasks such as remote swabbing of potentially contaminated surfaces and inspection and sealing of enclosures. We also describe the advanced mobility possible with modular, snake-like unmanned ground vehicles (UGV) and hybrid combinations for advanced inspection and characterization.

The Dexterous Hexrotor, BoomCopter, and Tiltrotor VTOL are example UAVs capable of hovering in place, as well as horizontal flight. With varying degrees of precision, these flying vehicles can apply controllable forces to the environment for a large variety of useful tasks, while still being able to cover significant distances between physical interactions, even with limited battery life. The three distinct flying morphologies represent tradeoffs between the precision of contact forces and the range of coverage with a single battery charge. Example applications of contact-based swabbing of lightly contaminated surfaces; opening, inspecting and sealing electrical enclosures; and inspection of very large structures are examined. This robotic vehicles can keep humans out of hazardous environments while extending their ability to see and feel.

Likewise, the MOTHERSHIP and CMU Snake robots are serpentine, ground-based robots that can explore confined spaces and other unknown or challenging spaces. Modular in design, these robots can be configured for a variety of tasks, leveraging operator skills acquired in one task for other tasks. They can also be combined to capitalize on the heterogeneous nature of the size scales, so composite mechanisms can be purpose-built to fit the task at hand.

Keyword: aerial manipulation, serpentine robots, hybrid locomotion

1. Introduction

The US Department of Energy, Environmental Management (DOE/EM) division mission is extraordinarily large and complex. Cleaning up decades of processing and fabricating nuclear and conventional explosive materials into large-scale weapons will take 60 years or more and cost hundreds of billions of dollars. Yet the real cost of this effort is in the risk of human exposure to these materials and facilities. Radiological and chemical materials present a variety of hazards to human health and human livelihood. We consider such materials *high-consequence materials* because the consequences of mis-handling such materials are high for both the people handling the materials and for the general public that live and work in the vicinity of such handling operations. As a result, the DOE/EM has embarked on a "Science

Figure 1: *The aerial view of the massive Gaseous Diffusion Plant in Piketon, OH, USA shows the scale of the main process buildings, center.*

of Safety" examination to explore current and future robotic and remote handling technologies that can be employed to reduce human exposure and societal risk during the handling and processing of these sometimes hazardous, sometimes beneficial components.

A demonstration of capabilities was carried out at the Portsmouth Gaseous Diffusion plant in August of 2016 that included a dozen projects from eleven performers:

- Purdue University
- Carnegie Mellon University
- University of Texas at Austin
- Johns Hopkins University - APL
- Texas A&M University
- SUNY Oswego / Excelon Generation
- Sandia National Lab
- Savannah River National Lab
- NASA Johnson Space Center(
- Southwest Research Institute
- Open Source Robotics Foundation

Software and hardware projects that spanned the gamut from virtual reality to multi-legged robotic inspection were on display with real application scenarios and real workers [12, 9, 17, 16, 11, 15, 18, 14, 7]. The Portsmouth Gaseous Diffusion Plant presents an enormous facility with a variety of challenges for D & D. With a net length of nearly 2.5 km, the shear size of the main buildings (Fig. 1) complicates the already difficult tasks of demolition with problems of long range communications, battery life issues, and situational awareness.

The work presented here is based on the work of the DOE Science of Safety demonstrations at the Portsmouth site and was previously reported in [16] and [9]. Updates to the ongoing work have been added to this document.

2. Physical Inspection of Large Structures

The Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA is a storage facility for high-level nuclear waste located deep underground. In February, 2014, an incident took place that left the facility out of commission for nearly three years. A chemically-induced energetic event occurred within one of its storage containers that resulted in the release of a small amount of radioactive smoke. For over a month, the DOE was unsure how to proceed, due to a lack of situational awareness 660 meters below ground. (Nobody was in the mine at the time of the incident.) Once it was deemed safe to venture down, it took another 34 months to clean up the facility to remove the traces from the walls, ceiling and floor inside the mine. The enormous size of the facility took a long time to clean, but the exhaust shaft of the ventilation system was the last difficult item on the agenda. At 660 meters (2150 feet) tall and 4.3 meters (14 feet) in diameter, clean up would be extremely hazardous. Non-contact sensing was impractical due to the very low concentrations of possible material and the low energy of americium, which was the primary radiological agent in the ruptured container.

The Portsmouth gaseous diffusion plant was used for production of enriched uranium for the U.S. nuclear weapons program until 2010. At that point, the plant went into shutdown and has been preparing for decontamination and decommissioning since 2011. Inspection of the contaminations and leaks in such facilities requires preparation time and risk to humans in handling materials. We need robotic tools to handle and inspect, working in collaboration with workers. Using robots reduce the risk of getting effected by radioactive materials, reduces the time involved in preparation and safety.

The Decontamination & Decommissioning (D&D) Program at the Portsmouth Site encompasses demolition and disposal of approximately 415 facilities (including buildings, utilities, systems, ponds and infrastructure units). This includes the three Gaseous Diffusion Process buildings. These buildings housed the process equipment and span the size of 158 football fields. These building comprises of cold zones and hot zones, depending the presence of radioactive materials. Cold zones can be accessed by the workers under strict safety rules. Robots becomes the alternative for the workers to inspect and cleanup the facilities. The use of robotic technologies not only increases efficiency, but reduce personnel exposure to hazards.

The PUREX tunnels at the Hanford Site are another example of a large structure that presents complex difficulties for inspection. The recent collapse event that occurred in the small tunnel [8] provides a heightened sense of urgency for such modular robots that can be specially configured for rapid resposne to unusual situations.

Robots are well suited for this kind of cleanup program, where it is difficult for humans to reach. The inspection and cleanup required the robot to physically interact with the surface of the shaft. This is because the quantities and energy levels of some materials is very low to detect with non-contact sensing. The shaft also provides an additional challenge to overcome the turbulence, as it is a cylindrical shaft. In this paper, we present the robots that can be used in this kind of scenarios.

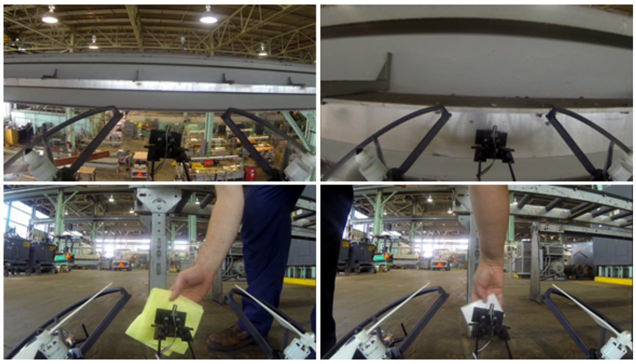

Figure 2: *Sequence of images showing the Dexterous Hexrotor approaching and swabbing the crane rail, top, while quality control personnel wipe the swab surface, bottom. (re-printed from [9]*

3. UAVs for Physical Interaction

3.1. Dexterous Hexrotor

Common UAVs, quadrotors (Drones) in particular, need to tilt their entire body and point their thrust in a particular direction to gain the acceleration. This type of UAV is underactuated for their six degrees of freedom (DoF) mobility in 3-D space. This is because most quadrotors have four fixed pitch propellers with parallel (and vertical) thrust vectors [1]. The standard quadrotor provides linear force along Z, and torques around X, Y and Z axes. Torque around Z is achieved indirectly through Coriolis forces resulting from differential angular velocities of the counter-rotating propellers. But it can't exert linear forces directly along X and Y axes. This locomotion is nonholonomic.

In a nuclear facility, we have harsh environments, no proper lighting, and interaction with the physical environment is necessary. For this purpose, the UAV needs have full control over 6 DoF and should be able to exert forces independently. To explore all six DoF in 6-D Cartesian force space, a new actuation design with nonparallel thrusters has been developed. At Collaborative robotics lab, we developed Dexterous Hexrotor, a fully-actuated UAV platform with nonparallel actuation mechanism, as in fig. 3. The nonparallel actuation is achieved by tilt rotor design, in which the rotor is rotated with respect to their frame at a fixed angle called cant angle [2]. This allows the UAV to explore all 6 DoF in three-dimensional space and is a more stable platform. Desired acceleration can be achieved by simply changing the thrust magnitudes of different rotors. This results in faster response to acceleration, with more keeping precise position in the plane [**Jiang14.**]

3.2. I-BoomCopter

The Interacting BoomCopter (I-BoomCopter) is custom designed for enhanced physical interactions with the environment [10]. The vehicle is based on a Y-shaped tricopter frame with an additional boom mounted in the front of

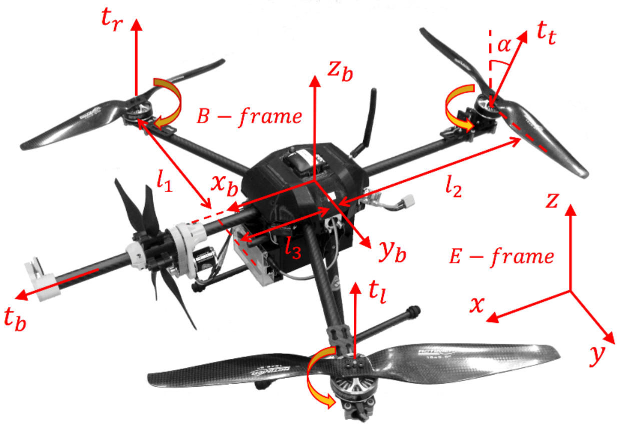

Figure 3: *Free-body diagram of the I-BoomCopter with frames of reference. (re-printed from [10]*

the vehicle. A mechanism, referred to as the boom-prop, is mounted on this front boom that allows a fourth propeller to rotate around the boom. It has been designed with symmetric propeller blades as in fig. 3. Therefore, by rotating either clockwise or counter-clockwise, it can provide thrusts in the vehicle's forward or reverse direction (perpendicular to the main rotors' thrust). Thus, the boom-prop, along with end-effectors attached at the end of the front boom, enable the I-BoomCopter to apply horizontal forces while in a stable hovering configuration, making the I-BoomCopter well suited for performing aerial manipulation tasks.

The I-BoomCopter's airframe, motors, propellers, and power source were each selected to increase its payload capacity and overall efficiency. Its large 15-inch diameter, carbon fiber propellers and 4-cell lithium polymer batteries give the I-BoomCopter a flight time of 21+ minutes and a maximum payload of 1.86 kg. The vehicle also carries a BeagleBone Black (BBB) computer (running Linux and the Robot Operating System (ROS)), which is capable of performing on-board, real-time image processing, in addition to collecting and analyzing sensor data. Thus, the I-BoomCopter can implement vision-based, closed-loop control systems to perform intelligent physical interactions with the environment.

The I-BoomCopter performed a high-speed flight test and an electrical enclosure door manipulation task (see Fig. 4). During the

Figure 4: *Free-body diagram of the I-BoomCopter with frames of reference.*

indoor flight, the boom-prop was engaged to demonstrate the I-BoomCopter's ability to move forward at high speeds without the need to pitch the vehicle forward. In addition, the I-BoomCopter's carefully tuned flight control parameters and standardized radio control system made it possible for some of the union workers present at the demonstration to teleoperate the system. The electrical enclosure door manipulation task required the I-BoomCopter to detect an electrical enclosure, move into position to pull on the enclosure door's L-shaped handle, and then open and close the door. We demonstrated this task with the vehicle moving on the ground (see Fig. 4 for set up details), to focus the demonstration on the physical interaction element of the task. Subsequent work has extended this capability to perform autonomously during free-flight.

3.3. Tiltrotor VTOL

The vast majority of commercial UAVs are quadrotors. They have the advantage of low cost, high maneuverability and user friendly control. However, endurance is their chief limitation, as most of the designs on the market cannot fly more than 30 minutes or so. Unless a revolutionary new design for high-density batteries emerges, the endurance of quadrotors is unlike to improve significantly.

An improved design is to combine the idea of fixed-wing aircraft and multirotor. Such design can maintain the maneuverability of quadrotors and gain efficiency of fixed-wing aircraft. An example is the amazon prime air: it uses one rotor to provide horizontal thrust and eight rotors to provide vertical thrust during the take-off and landing. It can carry up to 5 pounds' cargo to a range up to 10 miles [6]. However, it requires 8 motors to provide vertical thrust only during takeoff and landing. This wastes not only payload mass but also cost extra maintenance requirement. Therefore, developing a UAV with rotors that are utilized both in takeoff and forward flight reduces the actuators weight.

The UAV is comprised of pair of semi-wings, with at least two rotors mounted in the wings. The rotors can rotate relative to the first axis and tilt relative to the second axis. It has two modes: vertical take-off and landing mode, where UAV applies thrust in vertical direction to lift off and land. In this mode it operates same as multirotor and can hover after takeoff. After first mode, UAV transitions to second mode where the thrust is applied in horizontal direction. During the transition rotors start to tilt forward at the same time and change from vertical position to horizontal gradually. After the transition is complete, UAV operates as fixed wing UAV with two motors for forward flight. UAV also comprises at least two through openings within which rotor may tilt to change to airplane mode.

As shown in fig. 11, two tilt-able motors (2) are individually installed on each semi-wing (1). Two servos (7) in the lower surface of the wings provide torque required to tilt the rotational motors which are mounted on support rod (3). Rod (8) connects servo with horn (9) that pushes the rod (3) to tilt the motor. Two similar servos (10) which also located in the lower surface of the wings control the elevens (4) on the trailing edge on the wing. Control horn (12) is used to move elevens by servo. Propellers (6) are mounted to the motors.

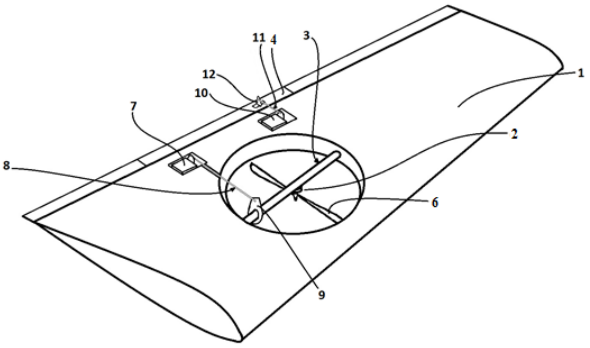

Figure 5: *The novel design of the tiltrotor VTOL embeds the rotors within the wing, itself.*

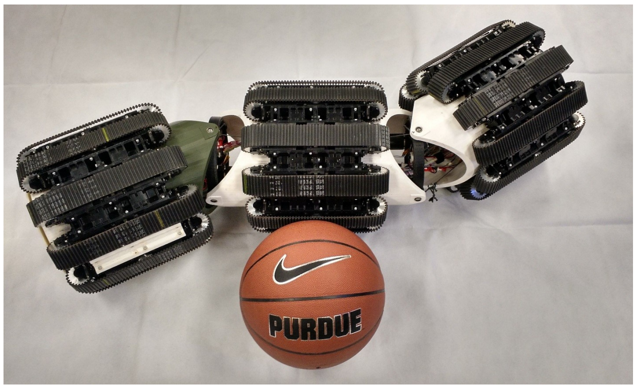

Figure 6: *The MOTHERSHIP is a modular design consisting of 2-D tread modules and 2-D articulating joints. Shown here with a regulation basketball for scale, the modules are roughly 25 cm in diameter.*

4. UGVs for Inspection in Uncertain Environments

4.1. MOTHERSHIP Tread/Limb/Serpentine Hybrid

The MOTHERSHIP (Modular Omnidirectional Terrain Handler for Emergency Response, Serpentine and Holonomic for Instantaneous Propulsion) was designed at the Collaborative Robotics lab at Purdue University. It is a holonomic, thread/limb/serpentine hybrid robot for locomotion in uncertain environments (Fig. 6). This mechanism includes 2-D tread modules connected in line by the articulating joints. Fig. 6 shows the configuration with three 2-D tread modules, but it is expandable to any number of modules, depending on the task [4]. Each module is 25 cm in diameter and 23 cm long. Each articulating joint mechanism is also 23 cm long making the MOTHERSHIPâĂŹs total length 115 cm. Each module has and cross sectional diameter to length ratio of 0.2 and tread coverage of 65%. MOTHERSHIP is designed to be fully holonomic in movement.

4.2. CMU Snake Robot

Several generations of serial-chain and snake-like robots have been developed by Carnegie

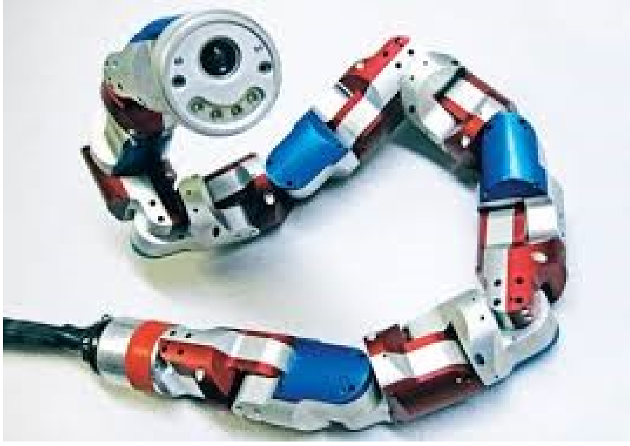

Figure 7: *CMU's snake robot is a modular design consisting of 1-D joints, each one rotated 90 degrees with respect to the prior.*

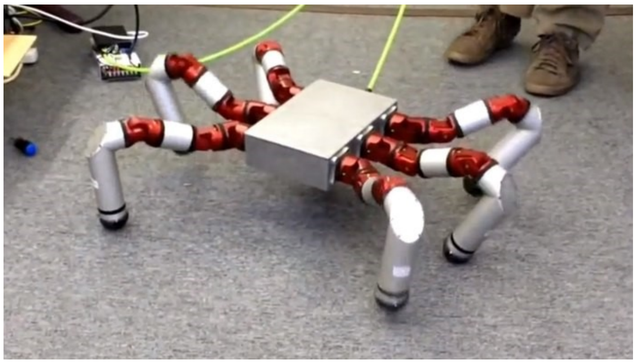

Figure 8: *CMU's hexapedal spider robot is made of the same modular joints as the snake. Many configurations are possible.*

MellonâĂŹs Biorobotics lab. The latest platforms are easily assembled from a set of hardware modules provided by former lab members at HEBI robotics (hebirobotics.com). The two actuated hardware modules include: 1) 1-degree-of-freedom (DoF) S-modules, and 2) 1-DoF X-modules [13]. The snake-like inspection device in Fig. 7 is composed of 6 cylindrical, S-module body segments with a single X-module as its base. A custom sensing module with a camera and laser range sensor serves as an end-effector for inspection tasks.

The hardware modules are designed to allow for rapid attachment and adaptation, so that robots can be re-configured meet to task demands. For instance, end-effectors may be swapped for a manipulator module to support mobile manipulation. Additionally, the robot may be elongated (shorted) by attaching (removing) modules. While the X-modules use a standard bolt pattern, the S-modules are manually screwed together through their black screw collars. By creating custom, passive structural elements to allow modules to attach in more complex, branched patterns, the modules can also generate legged or wheeled robots capable of navigating difficult terrain (see [3]).

In addition to actuation, each hardware module contains a suite of sensors including angular encoders, accelerometers, a gyroscope, and a force sensor. Force sensing is provided by measuring the deflection of a rubber, series elastic element at the output of the drive shaft. The sensor facilitates low-level control over environmental interaction forces during manipulations tasks. Also, compared to traditional industrial manipulators, the series elastic element has the added benefit of compliance. Because of this compliance, the robot in Fig. 7 can safely work around people without risk of series injury. The series elastic element can also absorb large impact forces, protecting the robot from damage.

For ease of interfacing, the hardware modules include on-board controllers that are accessible through standard Ethernet communication protocols. The S-modules automatically share/transfer Ethernet and power connections when screwed together. As shown in Fig. 10, the X-module provides an ideal base attachment point, since it includes a standard power input connection (18-48V) and Ethernet port to connect to any standard router or switching equipment. Once connected to a network, the modules are individually addressable and a HEBI robotics maintains a high-level code application programming interface (API) for simple communication and control for any networked computer (or from the mobile base itself).

4.3. Modular Combinations for Customized Inspection

To enhance inspection capability and to show proof-of-concept, the MOTHERSHIP and the CMU Snake arm were integrated to provide

Figure 9: *MOTHERSHIP and the CMU snake were combined to demonstrate the diverse capability of combining large modules with small. This modular combination can quickly locomote rough terrain and deftly inspect small areas.*

a custom robot suitable for inspections and emergency response (Fig. 9). MOTHERSHIP is 2-D tread mechanism built, in a modular way, for the operator to tailor the configuration for a specific task. While developing hybrid configurations for the tread module, we must consider the regularity, which means, constant frequency of tread modules and limbs. This allows us to expand the number of modules in the MOTHERSHIP, as per the requirement. MOTHERSHIP, with its holonomic mobility, is a mobile base which can navigate through difficult places and off-road terrains. The MOTHERSHIP doesnâĂŹt have a sensor package embedded in it, for inspection tasks, hence the utility of the snake robot with embedded cameras.

Snake robot is small in scale, compared to MOTHERSHIP. It is also built with modularity, allowing us to expand and reduce the length of the robot depending on the application. The end effector can be swabbed depending of the purpose of the task. For an inspection task in a nuclear site need sensors to detect the presence of radioactive materials and also a visual feedback is necessary. Sensing modules such as 3-D gamma ray estimator, camera, laser range sensor, can be set up on to the end-effector. For a manipulation task, a mini scale actuating wrist and gripper can also be attached onto the end-effector. The modular design opens endless possibilities to build the robots for different applications, with minimal efforts.

MOTHERSHIP-arm Combination is well suited for the DOE demo assisting workers in inspection tasks at Portsmouth plant. The MOTHERSHIP gives higher mobility inside the facility. The Snake robot acts as an arm mounted onto the MOTHERSHIP, as shown in Fig. 6, sneaks into hard to reach places and gather information along with the video. The front module of the MOTHERSHIP cases the electronic interface between MOTHERSHIP and snake robot. Mechanically, the Snake robot is clamped, with a custom designed mechanical interface, onto the MOTHERSHIP's front module. The Second module of the MOTHERSHIP cased the electronics driving it. The rear end of the MOTHERSHIP carries battery pack required to drive the MOTHERSHIP and the Snake robot.

The control of the MOTHERSHIP is over ZigBee communication protocol, with a joystick. Whereas the Snake robot connects with an Ethernet cable. So, we created a wifi network using XU4, to which the snake robot is connected and controlled over wifi. We need to have a common communication interface, so the control of MOTHERSHIP will be switched to XU4 over wifi. This integration needs more work to make it fully functional.

5. Discussion

Not all the nuclear facilities are identically constructed. Building a robot which can serve is all possible scenarios is nearly impossible. A step towards making this possible is, if we choose to design and develop the modular robots. The modules, presented in this paper, of MOTHERSHIP and Snake robot, can be assembled into an infinite variety of permutations. MOTHERSHIP with a camera mounted on it, can be used for the application which require visual inspection. Snake robot is used for applications like inspecting tight spaces, crawling over the pipes, etc. The combination of these two modular robots can classify into small/ large snake like robots, mobile robots, rolling robots, etc.

Developing application specific robot from the available modules take less time, compared to that of developing a new robot. Cost for production also reduces, as these modules can be produced in large quantities. Some of the futuristic design are discussed in this section, to provide a picture of how the modularity benefit in building complex structures which meet certain specific demands in terms of inspection or cleanup.

Robots are designed, using the above discussed modules, to meet the requirements of specific tasks. An example of inspection task in a hard to navigate environments is H-Canyon Exhaust Air Tunnel at the Savannah River Site nuclear waste facility [5]. H-Canyon is a chemical separation facility built in 1950s. The exhaust shaft air is passed through a crossover tunnel to a large sand filter through the Canyon Air Exhaust (CAEX). The tunnel, which is made from low grade concrete, is constantly exposed to the harsh environment with alpha contamination, beta-gamma doses and acid vapors. Periodic inspection of the walls of the tunnel is required to make sure of the structural integrity. In the past, there have been successful inspections carried out inside the tunnel using robots as shown in fig. 7. But, the robots could meet limited objectives of inspection and most of them were abandoned in the tunnel. With the extensive scope of modular robots, more inspections can be performed with in less time and collect more information.

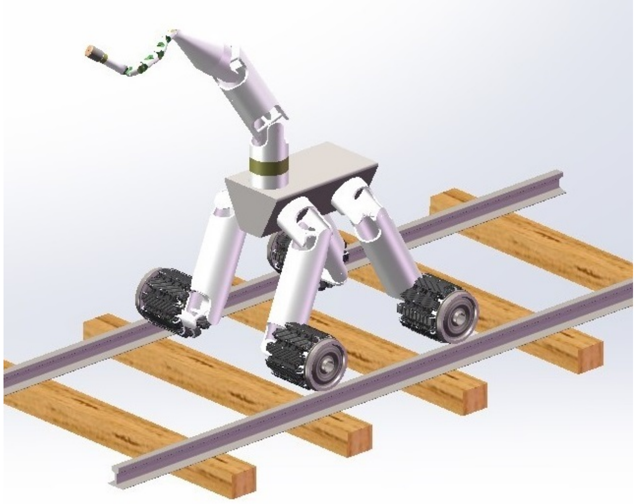

Figure 10: *MOTHERSHIP modules and CMU snake modules assembled in this CAD rendering to create a rolling/walking inspection robot for the long PUREX tunnel.*

Acknowledgments

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