Novel Serpentine Robot Combinations for Inspection in Hard-to-Reach Areas of Damaged or Decommissioned Structures -17335

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ABSTRACT

U.S. government agencies, particularly the Dept. of Energy, need robotic tools to handle and inspect high-consequence materials - materials for which mishandling would result in great risk to both application operators and the general public. The remediation and documentation of nuclear waste has become a problem of national significance and it cannot be addressed without robotic tools. The use of robots bypasses the danger and decreases the preparation time to handle harmful materials. In the 1980's and 90's, the US Dept. of Energy (DOE) invested heavily in robotic technologies as part of a comprehensive program of research and development aimed at enabling safer and more efficient cleanup of nuclear waste sites. For the next generation of harder, more complex clean-up problems, there is a clear need for more R&D.

There is a clear need for flexible, quickly deployable robotic technologies that can be configured to respond to unforeseen situations -- or can be purpose-built for planned activities -- while keeping human workers safe, yet effective. Modularity and interoperability are core capabilities for inspection tasks in contaminated facilities with a large variety of inspection problems. With any tool, familiarity breeds ingenuity, and ingenuity leads to new innovations in efficiency, effectiveness, safety, and performance. For example, the simple screwdriver can be held fourteen different ways by an experienced machinist who knows exactly what he or she wants to accomplish at any given moment. As a tool, robots are no different. To maximize the efficiency, effectiveness, safety and performance, redeployment and reuse of familiar tools is essential. Modularity can assist with re-deployment and modularity manifests itself in both hardware and software.

In some applications of inspection of high-consequence materials, a common concern has been the simplicity of the tool -- often correlated with cost (which is not always accurate) -- in case it becomes unrecoverable. In the case of robots, which have complex user interfaces and complex dynamics of interaction, the lack of familiarity can lead to clumsy operations and reduced accumulation of knowledge. As a result, while incremental successes may be achieved with sequential uses of different robots, there often is little knowledge gain that is generalizable across multiple uses. Total cost often goes down when a more sophisticated, but more familiar tool, can be used more frequently.

An example is the inspection of the H-Canyon Exhaust Air Tunnel at the Savannah River Site nuclear waste facility in the United States [1]. This is a particularly nasty environment, due to the acidic gases, large amounts of erosion and debris, and wet, mucky puddles. Over the past twelve years, six inspections have been attempted with five different robotic vehicles. In fact, these inspections have been successful with their limited, but progressively increasing objectives, although most robots have been abandoned in the tunnel. While each vehicle has cost less than $75,000 (the sacrificial part), the total costs of development have been much higher. The robots used to investigate changed much from iteration to iteration and it is not clear a strong body of generalizable expertise was built up across trials.

The authors of this study demonstrated the combination of two types of modular, serpentine, reconfigurable robots for locomotion over complex terrains and the inspection of hard-to-reach areas. The MOTHERSHIP is a tread/limb/serpentine hybrid robot design for locomotion over complex terrains, while the CMU snake robot provides highly articulated inspection of highly confined spaces. The demonstration at the Portsmouth Gaseous Diffusion Plant involves a combination of the two whereby gross locomotion is achieved with the MOTHERSHIP and the CMU Snake deploys a sensor package to gather data from behind and under obstacles. Although statically configured in its present state, the combined robot is built of individual modules for which reconfiguration has been demonstrated in both labs at Purdue and CMU. In future work, much higher degrees of reconfiguration and re-purposing of both software and hardware are easily achievable with these unique platforms.

INTRODUCTION

Robots and robotics tools make good companions to humans, in performing tasks where there is a high risk involved. Robots don't replace humans, instead they provide assistance to the workers for their safety and perform the operations quicker. U.S. government agencies, like Dept. of Energy, perform activities involving greater risk to workers. Safety plays a big role, this will in turn delay the preparation time for the tasks. Use of robots and robotic tools will reduce the danger and less preparation time to inspect or cleanup harmful materials. Robots deployed in the hazardous environment, will gather important information and also perform certain actions in handling high-consequence materials. Humans' presence in this kind of environment is dangerous to the workers and also to the general human beings.

Handling the nuclear materials needs very high standard safety procedures. Mishandling of the materials, breaches in safety are highly unlikely to happen. But, the consequences of such problems are extremely high for the workers and the general public. DOE sites which hosts the facilities for processing of nuclear materials, handling nuclear wastes, etc are shut down when such problem occur. There is need for inspection and cleanup, before they resume the functionality of the facilities. Sometimes, nuclear facilities get old and need to be decontaminated and demolished. Before demolishing the building, a thorough inspection and cleanup should be performed. To do the inspection and cleanup, it is very dangerous for workers to get involved. Robots do a good job in assisting workers to perform such high risk involved tasks.

Robots are built to do specific jobs under a given environments. So, we need to develop more flexible, modular and easily deployable robots. The robotic technology should be reconfigurable depending on the situations. The worker should be able to assemble the robot modules in a configuration well suited for a particular application. Ingenuity is considered as a major aspect in building the robots. Ingenuity leads to innovative solutions with more efficiency and safety. Consider the example coined in the abstract, the simple screwdriver can be held many different ways by an experienced machinist depending on the task that needs to be done [2]. Modularity allows to redeploy and reuse the robots, to improve efficiency, effectiveness, safety and performance.

Hybrid locomotion and modularity are the major focus of our work presented in this paper. The places where conventional wheeled systems fail to meet the requirements of mobility tasks, the design of advance or Hybrid locomotion is required. Modularity of the system gives additional capabilities and speeds up the development of hybrid locomotion systems. The conventional wheeled systems are easy to control and power efficient, but they require perfect path conditions to more around. For the off-road locomotion capabilities, many robots use the treads. PackBot [3] is a good example among robots, which employed treads and limbs. Robots such as Quince [4], Redback [5], etc., are employed with more independent DoF. These more and bigger tread/limb hybrid have incremental gains in performance, but doesn't make big strides. It is proved that PackBot's ruggedness and simplicity has more advantage over the Quince's incremental mobility gains.

The next generation of hybridization including the modularity are designed to mobilize in extreme terrain, tread/limb/serpentine or wheel/limb/serpentine hybrid. First generation of robots which are built in this type of hybrid form, such as OmniTread, Souryu, and Moira. They are very difficult to control, with almost no payload capacity for additional sensor package. MOTHERSHIP [6] is a holonomic tread/limb/serpentine hybrid which is easy to control by a joystick. MOTHERSHIP has plenty of space for external payloads to carry with it. But it doesn't have ability to manipulate a sensor package for tasks such as inspection.

Modularity of the robots is more advantageous in terms of versatility, robustness and low cost [7]. Easy re-configurability gives more opportunities to explore numerous options. The production can be held in large scale if the robots were designed to be modular, and also allows to make variety of robots by reusing them.

Modularity in the robotics system has more robustness, as it is easy to replace a failed module. In a modular robot, the design of the modules has to be identical, the desired physical configurations have to be identified, create control laws for various behaviors.

The hybridization of locomotion and the modularity in the robots make them better in assisting the workers in nuclear facilities for inspection and cleanup tasks. The Nuclear facilities doesn't always have plain and smooth floors. Some nuclear waste repositories are built several underground, where there is rough terrain. There are requirements for a robot to crawl through narrow spaces, and maneuver in the corners, etc. This can be achieved by the hybrid locomotion is built in MOTHERSHIP [6]. In this paper, we are presenting the MOTHERSHIP robot and its modular design for re-configurability. We also talk about the Snake robot built at Robotics Institute, CMU by Dr. Howie Choset [10]. The integration of the snake robot with the MOTHERSHIP is discussed. The snake robot gives the MOTHERSHIP, its missing ability to hold a sensor package for inspection tasks. We refer to the DOE site visit at Portsmouth as an initial step towards modularity in robots with the integration of MOTHERSHIP and the Snake robot, "MOTHERSHIP-arm".

MOTHERSHIP

The MOTHERSHIP (Modular Omnidirectional Terrain Handler for Emergency Response, Serpentine and Holonomic for Immediate Placement) is built at Collaborative Robotics lab at Purdue University. It is a holonomic, thread/limb/serpentine hybrid style robot (Fig. 1). This mechanism includes 2-D tread modules connected in line by the articulating joints. Fig. 1 shows the configuration with three 2-D tread modules, but it is expandable to any number of link hybrid robot, depending on the task [8]. Each module is 25 cm in diameter and 23 cm long. Each joint mechanism is also 23 cm long making the MOTHERSHIP's 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.

Fig. 1. Three link configuration of the MOTHERSHIP hybrid robot.

The 2-D tread mechanism is a cylindrical arrangement of ten discrete treads that incorporates a dual ring gear differential drive to both actuate the treads to propel the mechanism along the body axis and rotate the entire tread assembly about the core for transverse motion.

The 2-D tread mechanism consists of a series of ten discrete treads spaced evenly around the circumference of a hollow cylinder that rides on a set of idler gears interposed between a pair of ring gears. These ring gears transfer torque from two drive motors to the tread pulleys on either end of the treads. Rather than driving each of the ten treads individually with its own motor and using an additional motor to realize the transverse motion, the 2-D tread mechanism incorporates a novel dual ring gear differential drive system to drive all ten treads in unison and to provide transverse motion from only two stationary motors. With this drive system, the mechanism realizes the desired two degrees of freedom with the minimum possible number of motors. An illustration of this drive system is presented in Fig.2.

Fig. 2. Close-up view of the 2-D tread module, highlighting the gear arrangement.

The structural components of the tread module from Fig. 2, are the motor core (1), torque is transmitted from the motor drive gear (2) to the inner ring gear (4) which is supported on the core by two inner pinion gears (3). Torque is then transmitted from the inner ring gear to a set of intermediate idler gears (5) mounted to the tread assembly. Within the tread assembly, torque is transmitted from the intermediate idler gears to the outer ring gear (6) that passes through all the treads and then to the bevel gears (7) mounted in each of the ten treads. The torque is transmitted 90 degrees to the tread pulleys (8) by a 3D belt configuration, which in turn drives the treads (9). The entire gear train has an effective gear ratio of 1.49 from motor to tread. This gear arrangement is reflected symmetrically on both ends of the tread module resulting in two differentially driven gear sets which gives the module its two degrees of freedom. The motors used to drive the tread mechanism are Maxon DCX32L 48V motors with a GPX32A 28:1 planetary gearhead. This motor was selected under the criteria that the treads be able to reach a top speed of 1 m/s and that the treads be able to propel the tread mechanism up a 35° incline at 0.3 m/s.

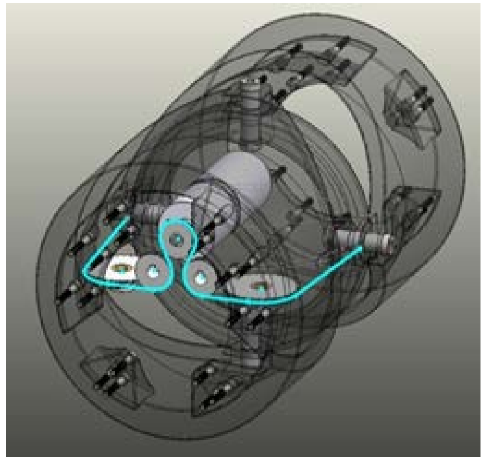

Fig. 3. The universal joint that has been designed and tested for module lift capacity.

The articulating joint of the MOTHERSHIP hybridizes the tread mechanism to enhance its mobility and extend its task space to make it effective. To minimize additional complexity in the system, the articulating joint is implemented as a simple active universal joint as shown in Fig. 3. Being a universal joint it has two degrees of freedom which account for the pitch and yaw motion of the neighboring tread mechanism. To drive the two degrees of freedom there is a cable pulley system at each end of the joint which actively pulls on the opposing half. The motors used in the articulating joint are different from the drive motors in the tread mechanism as greater torque and less speed are required in the joint. The joint motors are Maxon RE30 48V motors with GP32C 66:1 planetary gearheads. These motors were selected under the criteria that they be able to lift a 2-D tread mechanism 40° in one second. The two halves of the joint are held together at the inflection point by steel crossing shafts and a solid ABS ring. The total length of the joint is 31.2 cm but most of this length is contained inside the neighboring tread mechanisms to minimize the distance between treads. In the pulley system a 400 pound test braided Kevlar cable passes through a hubcap on the drive motor shaft and passes over a series of v-pulleys to terminate on the opposite joint half.

The MOTHERSHIP uses the articulating joints to create a reaction arm between modules. By reverting to the zig zag configuration in Fig. 4, each tread module uses its neighboring modules as a reaction arm. Therefore, the MOTHERSHIP can take advantage of the two degrees of motion of the tread mechanism and enable full holonomic locomotion.

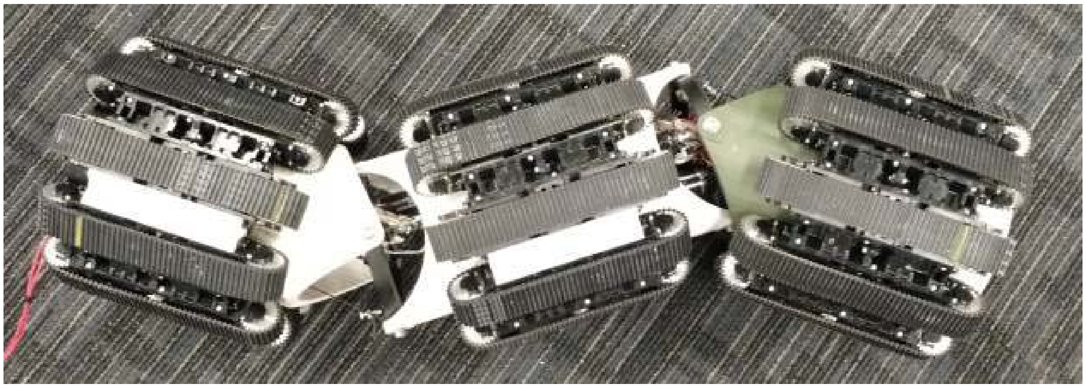

Fig. 4. Zig zag configuration of the MOTHERSHIP with a self-induced reaction arm for transverse motion.

Since both the 2D tread mechanism and the articulating joint limb have two degrees of freedom, the three link MOTHERSHIP consisting of three tread modules and two joints has ten controllable degrees of freedom. It would be quite burdensome for a human operator to have to directly control all ten degrees of freedom and would likely require more than one operator to manage them all. To ease the operational complexity of the MOTHERSHIP, assisted remote operation methods are used to implement shared autonomy control. In this shared autonomy system, the operator provides control at the robot level, designating the desired direction of travel, speed, and rotation while the robot autonomously controls the individual degrees of freedom. (https://youtu.be/Ia7YXx4TzL0)

CMU MODULAR SNAKE ARM

Several generations of serial-chain and snake-like robots have been developed by Carnegie Mellon's 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 [9]. The snake-like inspection device in Fig. 6 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, the end-effectors in Fig. 5-6 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 [10]).

Fig. 5. Modular Snake Robot with tether attachment

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. 5 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. 6, 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).

Attaching to the mobile base, (the MOTHERSHIP) in Fig. 6 required only bolting the robots together at the X-module base and connecting the X-module to the wireless router and power supply (24V). Once installed, it is straightforward to teleoperate the modular inspection device by sending either joint level control commands, which are tracked by low-level PID controllers on board each module. We also use inverse kinematics control strategies where the operator may use a game controller to coordinate desired movements in the end-effector from video stream data sent back to the remote computer over Ethernet. The inverse kinematics strategy finds joint angles for the modules that are near their current angles and (approximately) produce the desired changes in end-effector motion.

Note, to provide greater flexibility and access, it is not necessary to bolt the robots together. In addition to attaching to an X-module and mobile base, the chain of S-modules in the snake robot can be connected tethered to the power supply and communications of the mobile base (see Fig. 5). In this case, the mobile base might carry and release the snake robot at a desired location, and the snake robot can use a number of undulatory, snake-like locomotion patterns to crawl and climb through tight spaces to perform hard-to-reach inspection tasks in and around equipment or piping [11,12] (https://www.youtube.com/watch?v=XdWe9NvTVog).

DOE SITE VISIT - PORTSMOUTH

DOE, office of Environmental management and it Portsmouth/Paducah project office (PPPO) hosted "EM Science of safety: Robotics Challenge" on August 22-25, 2016. This challenge provided us an opportunity to present the robot with modularity, assisting the workers in cleanup and inspection activities remotely. In this paper, we present the modular configuration of MOTHERSHIP-Snake arm robot which we demonstrated in the Robotics Challenge. This work is done in collaboration between Purdue University and Carnegie Mellon University.

The Decontamination & Decommissioning (D&D) Program at the Portsmouth Site needs 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 are accessed by the workers under strict safety rules. The use of robotic technologies not only increases efficiency, but reduces the personnel exposure to hazards. MOTHERSHIP-Snake arm robot assists the workers mainly for inspecting the facilities.

The modular robots with well-defined software and hardware will helps the workers to be more effective in creating remote robots for inspections. The innovation in building the robots has to be encouraged for advanced assistance. The modularity reduces the preparation time for a particular scenario to deploy the robots for inspection or cleanup tasks. We so far have discussed two types of robot which are built in terms of modularity. The functionalities of these robots are completely different. MOTHERSHIP is built to drive through corners and uneven surfaces over longer distances. The snake robot basically crawls and covers the difficult to reach areas. It has a sensor package embedded at the top end, which are primarily used for inspections.

Fig. 6. A modular snake robot attached to the MOTHERSHIP through an X-module base. A camera module with laser range sensor is attached as an end effector to demonstrate highly articulated inspection tasks at the Portsmouth Gaseous Diffusion Plant.

Integration of the MOTHERSHIP and the Snake arm provides custom robot which is used for inspections is shown in Fig. 6. 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 doesn't have a sensor package embedded in it, for inspection tasks.

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.

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 [1]. 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.

2003

2011

Fig. 7. Two of five different robots developed for the H-Canyon Exhaust Tunnel at Savannah River [1].

After the explosion of the McCluskey room at Hanford site, the entire Plutonium finishing plant was decommissioned. During this decommissioning process many maintenance workers have been exposed to radiation. Employment of robot for such activates would have saved many lives. This facility poses a challenge for today's robots in reaching longer distances, inspecting hard-to-reach places. A best suitable robot for this kind of scenarios is shown in the fig. 8. It is built for high reach, combined with walking/rolling with holonomic tread module. This type of design gives the robot to expand its capabilities in any type of terrain and perform the tasks with very minimal constraints. The robot is designed as a horse, with the tread modules as the feet. This gives holonomic motion to the robot. The center body contains the controls, battery pack, etc. Limbs are the articulating joint mechanism which is the MOTHERSHIP joint mechanism. The similar kind of joint mechanism is design in the top of the body which will hold the small robot arms, like the snake robot.

The Hanford site is a single underground storage facility with railroad tracks running its length. The additional set of railings attached at the end of each tread module, would ease the navigation of the robot to the problem areas. The four limbs attached to the tread modules adds more flexibility to the robot in lowering or raising the center of gravity of the whole body. The limb on the top of the body allows the robot to place the Snake robot in reaching higher surfaces. The snake robot bring additional functionality of sneaking in the places where it is difficult to reach. It holds the sensor package, or a manipulator for inspection and cleanup tasks.

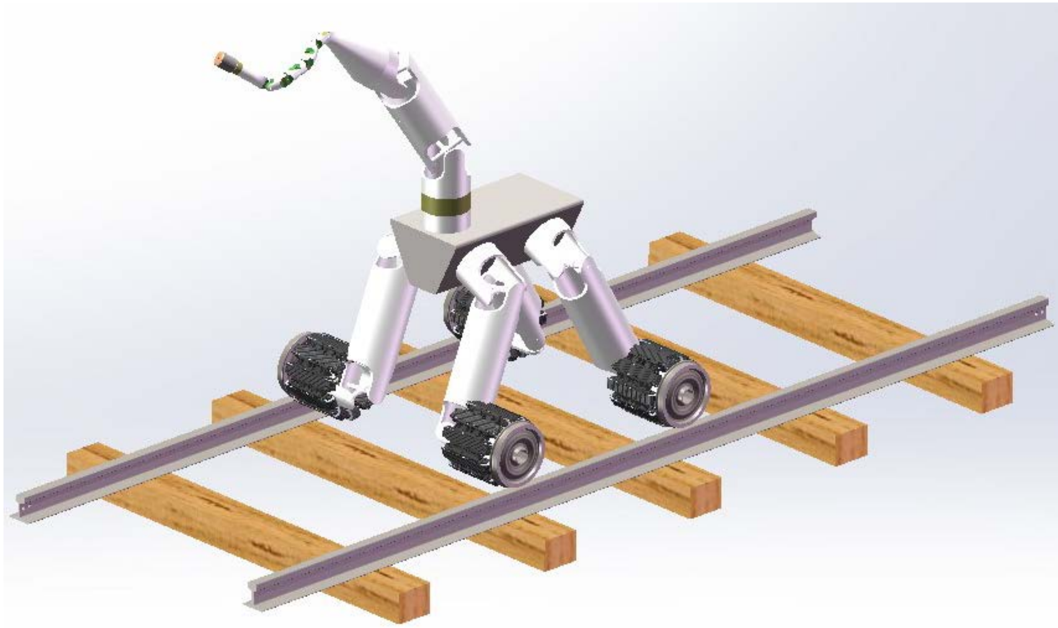

Fig. 8. Combined walking/rolling with holonomic tread modules with High Reach for Inspection of Remote areas.

Another interesting design of the modular robot is as shown in Fig. 9. This is a configuration of MOTHERSHIP which can carry a robotic arm. The two modules in the front are connected with a rigid arm. This is to accommodate the arm inside the core of the two modules, which is folded into a stack. The sensor package at the end-effector can hold sensors like radiation sensor, Kinect, etc. The arm is usually sitting inside the body, projecting the sensors outside. This allows to gather information while locomotion. When required, the arm is projected out and unfolded to reach farther distances for inspection.

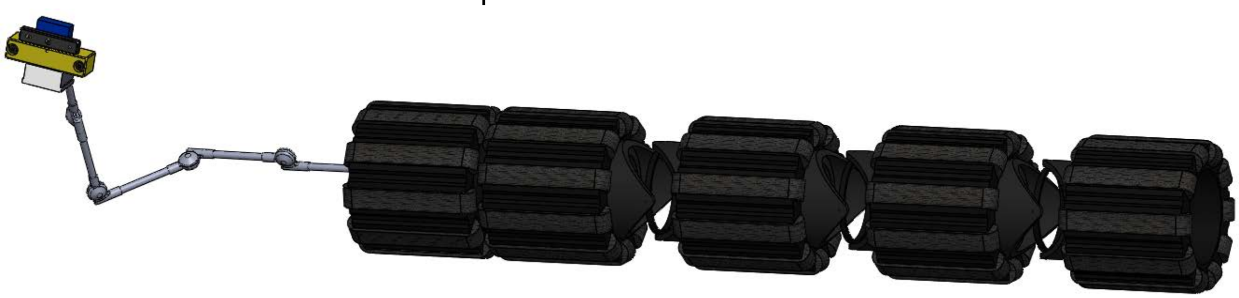

Fig. 9. MOTHERSHIP with 5 modules, 3 articulating joints, 1 rigid joint and extended arm with sensor package.

The configuration discussed above need further research and development. Reconfiguration and reusability of the robots and its parts is possible only when the robot is modular.

CONCLUSION

The aim of our research is to develop robots that can assist workers in gather valuable information from hazardous environments. Robots are not meant to replace workers, instead they assist them to accomplish their tasks more safely and also reduces the preparation time to tackle the environment. This research paper mainly focuses on the modularity and hybrid locomotion in robots to speed up the development process for a specific application and also provide endless possibilities. A tread/limb/serpentine hybrid robot is presented, based on a novel 2-D tread mechanism, combines the strengths of wheels, treads, limbs, and snakes to make effective locomotion. The Snake robot arm with the sensor package for inspection is also presented. Integration of the two Modular robots, one for Hybrid locomotion, another for sneaking and gather information on radioactive elements presence. This paper present one such combination of integrating Modules of MOTHERSHIP and the Snake robot. The discussion section presented some more combinations of integrating the modules for different applications. Robots are meant to work in collaboration with the humans. It is always exciting and motivating for a worker to use robots in their work area. This makes jobs interesting and safe for the workers.

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ACKNOWLEDGEMENTS

This work was supported, in part, by the DOE/EM Science of Safety, by the NSF Center on RObots and SEnsors for the HUman well-Being (RoSe-HUB), and by NSF grant 1450342-CNS.