Modular Platforms for Advanced Inspection, Locomotion, and Manipulation – 17150

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ABSTRACT

Robots can provide remote access, manipulation, and inspection capabilities to augment human workers and improve safety in potentially dangerous decommissioning, radioactive waste management, and emergency response operations. However, such activities may require navigating challenging and unstructured environments, such as those with uneven terrain, obstacles, or loose debris. This remains a difficult task, even for modern robots. What's more, a robot's physical design can inhibit it from accessing hard-to-reach areas such as the tight spaces around, underneath, or inside piping and equipment. To address these challenges, we have developed a series of physically robust hardware modules that can be configured into a variety of robot morphologies, specialized to support different operational needs. Each hardware module consists of a number of on-board sensors and a high performance actuator with a series elastic element to sense and control interaction forces for improved locomotion and manipulation. Using this hardware, we have designed several robotic platforms that support the access, manipulation, and inspection requirements of decommissioning and radioactive waste management. To highlight current capabilities and potential opportunities for technological improvement, we present the outcomes from field demonstrations of our modular platforms at the Office of Environmental Management's Science of Safety Portsmouth Gaseous Diffusion Plant Robotics Challenge. Specifically, results include a serpentine robot climbing vertical structures such as pipes, posts, and supports to demonstrate advanced inspection. Additionally, we discuss field trials of a similar modular configuration that yields a highly dexterous manipulator arm and camera system capable of adding manipulation and inspection functionality to existing structures. Results are presented from inspection tasks in which the manipulator is installed on another mobile robotic platform. Finally, we show our hardware modules can be reconfigured into platforms capable of withstanding significant impacts and of alternative means of locomotion, as may be required to cross terrain too challenging for traditional wheeled robots. Results describe the performance of a hexapod robot that uses proprioceptive feedback to locomote in outdoor trials reminiscent of emergency response conditions.

INTRODUCTION

Nuclear decommissioning involves a number of activities that may be restrictive or otherwise dangerous for human workers. For instance, workers need to inspect in or around dense facility piping, equipment, and environments with hazardous materials. In such situations, robots can serve as vital tools, facilitating access and remote manipulation in dangerous areas, while their operators remain safely out of harm's way. However, traditional industrial robots are often expensive, bulky, and relatively inflexible. That is, the inherent physical (hardware) constraints of such robots prohibit access to tight spaces and limit them to specific tasks, with highly-specialized technical staff required to adapt "canned" behaviors.

To develop more flexible and adaptable robots, our lab, the Carnegie Mellon's Biorobotics lab, and HEBI robotics, a startup founded by former lab members, have designed a series of physically robust hardware modules that can be rapidly assembled into different robot morphologies to support different task needs. The modules can, for example, form highly-dexterous serial-chain manipulator arms that can be installed on any base (or mobile platform). The same modules can be re-assembled into wheeled, tracked, legged, or undulatory (snake-like) platforms that can locomote over rough, outdoor terrain for mobile sensing and manipulation, e.g, in disaster response scenarios [1,2,3] (see Fig. 1).

While physical adaptability is ultimately essential to the development of robots that can support humans in different scenarios, it is of little use if teams of engineers are required to re-program and develop new behaviors for each new robot, i.e., each customized modular configuration. To address this concern, we emphasize principles of modularity and scalability not only in physical design, but in control. The following section will describe a tiered control scheme that is easy to adapt to new robots and behaviors, and computational tools that we have devised to simplify or automate motion planning for relatively complex tasks such as gait design [4,5].

To demonstrate these capabilities in action, the DISCUSSION section describes results from the Office of Environmental Management's Science of Safety Portsmouth Gaseous Diffusion Plant Robotics Challenge. The CONCLUSIONS section discusses future potential and current limitations of modular robots to support tasks such as nuclear decommissioning.

METHODS

The following section describes the modular hardware used to construct the different platforms demonstrated during the robotics challenge. Additionally, we provide an overview of the tiered control system and computational tools we use to simplify the design and planning of new behaviors on new robots.

Hardware Modules

We have designed several generations of modular hardware. The demonstration platforms use two types of actuated modules -- 1 degree-of-freedom (DoF), cylindrical *S-modules,* and 1 DoF, disk-shaped *X-modules* (see Fig. 1), capable of producing in the range of 7 N-m torque, depending on gearing.

Fig. 1. Our set of modular hardware includes active modules, passive structural elements, and sensors (top) [3]. Our newest platforms are composed of 1 degree-of-freedom actuated S-modules (bottom left [2]) and X-modules (bottom right) from HEBI Robotics (hebirobotics.com), a company started by former lab members.

The S-modules are easily coupled to one another by hand tightening their two-inch diameter threaded collars, while the X-modules are attached with standard bolts. We also use a number of passive interfaces to transfer electrical power and communications and to provide structure. The electrical connections between modules and interfaces are made using either spring-pin connectors or standard Ethernet cables. With passive interfaces for each type of mechanical coupling, the modules may be quickly connected and disconnected into complicated, branched structures to create different robotic platforms from both S- and X-modules. The passive interfaces also allow for connection of external devices such as cameras, lidar, or end-effectors for manipulation. Such devices are easily attached and are straightforward to communicate with, since the modules employ standard Ethernet communication protocols.

In addition to actuation, each hardware module is bundled with an accelerometer, gyroscope, angular encoders, and microcontroller for low-level control processing. Our latest hardware also makes use of series-elastic actuation (SEA) [6], in which the actuators incorporate mechanical springs at the output of their drive trains. Incorporating series elasticity into robots has the potential to mitigate problems of traditional robotic actuators, facilitating accurate output torque sensing and absorbing impact loads that might otherwise damage the drive mechanisms [6]. Our SEAs are based on shearing a rubber elastomer that is bonded to two rigid plates [1]. Interaction forces/torques are computed from the elastomer's spring constant and its measured deflection, as obtained from absolute angular encoders on the input and output side of the torsional elastic element. The rubber elastomeric design provides mechanical compliance and energy storage an order of magnitude greater than traditional springs [7]. Further information about the modules can be found in [2].

Control Systems

To simplify control, we use a tiered scheme wherein *high-level* commands, e.g., "go forward" or "look up", specify a set of *mid-level* shapes changes, i.e., body/joint motions, that are designed to enact those behaviors. The desired mid-level shapes are tracked by *low-level* admittance controllers that regulate the forces of interaction and bend and adapt these shapes to allow the robot to respond to rough terrain [8]. In addition to the series elastic elements in hardware modules, the low-level admittance controllers ensure the robots are safe to work around, as they will comply behavior to avoid overpowering or harming humans that the robot comes into contact with.

In this control scheme, designers must specify a set of behaviors for each new robot by prescribing desired changes in the robot's shape. In contrast to directly specifying joint angles, shape specification provides a layer of abstraction that allows for minor variations in robot morphology without having to generate new behaviors. For instance, users can add modules to extend a robot's limbs, e.g., for better inspection or improved locomotion, and the new joints should automatically map to and track existing shape profiles. Thus, the same motion plan may be applied without any re-programming or adaptation.

We have devised a number of tools to simplify the specification of desired shapes (behaviors). For easily specified behaviors, users can manually manipulate (back-drive) the robot's joints into desired shapes, which can be recorded with on-board encoders. Similarly, we have designed a teleoperation mode that allows joystick control of different robot appendages. For intuitive control, teleoperation tasks may be defined in the end-effector frame, any robot body frame, or with respect to a fixed frame in the world. Since it is possible that the end-effectors may rotate as the robot moves, teleoperation software utilizes visual filters to cancel camera rotation and supports precise inspection.

To derive more complicated behaviors, [5] shows robots can learn new motions through a sample-efficient Bayesian process of experimentation. As a benefit, these so called *Bayesian optimization* strategies can be applied in simulation, or on-line, which is useful for adapting, refining, or developing new behaviors with respect to a wide variety of different objectives. Also, we have developed a geometric mechanics framework that simplifies and can even automate complex gait design for different robot morphologies [4].

Employing such methods, it is often possible to rapidly synthesize new behaviors to support new modular platforms. Ultimately, users need only send high-level robot commands to switch between different behaviors, while low-level policies track the evolution of desired shapes, e.g., to locomote, and automate compliant responses to unforeseen disturbances and rough terrain.

DISCUSSION

This section discusses field demonstrations of our modular hardware at the Portsmouth Gaseous Diffusion Plant Robotics Challenge. The challenge included three modular platforms performing distinct tasks. Descriptions of each platform and the corresponding task scenario are in the sections that follow. A video with highlights from the robotics challenge is provided at https://youtu.be/04B-w8VbRpM.

Remote Inspection with a Modular Snake Robot

To demonstrate remote inspection capabilities at the robotics challenge, we tested a modular snake-like robotic platform consisting of a serial-chain of 16 directly connected S-modules with a camera module "head" (see Fig. 2). The robot transmits video signals down its chain of connected modules and through a tether to a computer control box. During the challenge, we used a simple game controller to send high-level commands to coordinate the snake's motions.

To show the capabilities of this morphology, we demonstrated the snake robot locomoting outdoors in tall grass. These relatively complex, undulatory locomotion patterns can be derived and optimized using the geometric mechanics framework discussed in the METHODS section [4]. The demonstration showed a plant worker, who was previously untrained on the robot, could control the robot both to locomote on the ground, and to "look around" in simulated remote inspection tasks that required coordinated motions of the robot's head camera.

As the primary purpose of the demonstration, we showed the capability of the snake robot to climb up vertical structures such as posts or common facility pipe supports. The snake successfully climbed a metal pole of approximately 6" diameter to a height of 10' using only simple joystick commands to coordinate two main behaviors: 1) grasping and releasing the pipe and 2) climbing up the pipe by rolling its body joints along a fixed helical shape (see Fig. 2). Once it reached approximately 10', we commanded the snake to release its head in order to perform teleoperated inspection.

Fig. 2. The snake robot, shown here at the Portsmouth Gaseous Diffusion Plant, can climb on the inside or outside of pipes by rolling in a helix shape. At a desired vantage point, a user can teleoperate the front joints to aim the camera, while the remaining joints hold the pole.

Although we did not have the opportunity to demonstrate the capability at the Portsmouth plant, we note the snake configuration can climb inside piping with bends and turns using similar helical motion patterns. For example, the snake robot has been deployed to inspect inside piping at the Zwentendorf Nuclear Power Plant in Austria (a short video is provided at: https://www.youtube.com/watch?v=QQSHFkITIiI). One of the main benefits of the modular snake configuration is its ability to inspect such tight spaces both inside and around plant equipment. Another benefit is the ease and adaptability of such serial-chain mechanisms. As described in the METHODS section, we can add modules to increase the length of the snake robot, e.g., to climb larger diameter pipes, without any re-programming or changes in control. Our newest SEA modules also allow the snake robot to modulate how hard it squeezes when climbing, bending and deforming its helical body shape to help it navigate bends, turns, and joints in piping.

Disaster Response with a Modular Hexapod Robot

In addition to serial chain platforms, the robotics challenge included a demonstration of a modular hexapod robot [3] locomoting outdoors over debris and difficult terrain. The scenario showed the potential for disaster response, remote access, and inspection in environments that may be unsuitable for wheeled or tracked robots of similar scale. The hexapod configuration is depicted in Figs. 3-4. The silver, metallic components on the legs are passive structural interfaces except

Fig. 3. The hexapod robot walks through piles of rocky debris at the Portsmouth Gaseous Diffusion Plant. A camera is mounted to the head in the configuration depicted; however, its modular design allows any type of end effector, limb, or sensor to be easily attached.

for the rectangular body, which includes an off-the-shelf switch to network the modules. Although communication and power are routed to a control case through a tether, our newest variant of the robot (not yet available at the time of the demo) includes on-board power and wireless communication.

To demonstrate ease of control, we showed a plant worker who had not been trained on the robot, could control it walking over rough terrain. We used a game controller to send high-level, directional commands to modulate the body's ground clearance when walking, and to lean, roll, pitch, and yaw to better position a camera attached to the front of the robot's body. Although we used the camera attachment to illustrate inspection, the attachment is easily replaced with a manipulator arm to support manipulation tasks.

To locomote, we implemented a common alternating tripod gait. However, low-level compliant controllers are critical for navigating rough terrain. They allowed the robot's legs to bend and flex, serving as shock absorbers, so that the robot can absorb forceful impacts and drops. Furthermore, we showcased a control mode that uses sensed forces in the leg joints to switch behaviors (see [9]). Similar to the way a human might stammer backwards when shoved, the hexapod dissipates forces when it is hit or trips by taking a few steps in the direction of the unbalanced force vector. Using these low-level strategies to improve performance in implementing high-level user commands, the hexapod was able to successfully

Fig. 4. A U.S. Department of Energy worker drives the hexapod robot at the Portsmouth Gaseous Diffusion Plant using a gamepad controller. The robot is controlled using high-level commands, while low-level controllers use proprioceptive feedback to react to external disturbances and rough terrain.

navigate over loose gravel, rocks, and obstacles of significant (relative) size.

One benefit of a hexapod configuration that we did not demonstrate at the challenge is redundancy. Because it only needs four legs to locomote, the platform can sustain damage, losing up to two of its legs. Redundancy is ideal for operation in the potentially harsh conditions of a nuclear facility. Also, redundant legs may serve as manipulators while the remaining legs coordinate locomotion.

Rapid Deployment of a Modular Robotic Arm

To support rapid deployment scenarios, we demonstrated a serial-chain modular robotic arm that can be easily installed on both fixed structures and other robots. The modular arm (see Fig. 5) consists of a special, compact end effector module with a line laser range sensor and RGB camera for precise inspection and 3D visualization in tight spaces. The body is composed of a series of S-modules, with an X-module at the base to provide standard Ethernet and 24V power connectors for ease of interfacing.

The goal of the demonstration was to install and deploy the arm on another mobile robot base. In this case, the mobile base, which has been named the *MOTHERSHIP*, was provided by Professor Voyle's team from Purdue [10]. The MOTHERSHIP itself is capable of complex, hybrid locomotion patterns, relying on both internal motions from jointed body segments and rolling treads to traverse

Fig. 5. The series elastic modules are configured into an articulated arm that is readily attached to a mobile base. The end effector, containing a camera and laser range sensor, can be used to inspect confined spaces.

varying terrain.

In preparation, we required CAD files depicting the desired attachment point on the mobile base, since a physical interface is required to bolt our arm to another structure. Based on the CAD files, we machined a simple interface from spare metal components around our lab. We also confirmed that the MOTHERSHIP used standard Wi-Fi for communication and that 24V power was available. In cases where communication and power infrastructure is unavailable, a standard router and 24V battery (or power converter) must be installed along with the arm. Other than these few items of coordination, our engineers had not previously seen or attempted to interface with the MOTHERSHIP before the robotics challenge.

During the challenge, we showed a single engineer was able both to couple the robots and to re-program the arm to carry out an inspection task within 15 mins of receiving the mobile base. Figure 5 depicts the robot inspecting the inside of a drum as it plays out its programmed motion plan. While it may be desirable for a mobile base to coordinate some motion of the arm, e.g., to have it contract before navigating into a tight space, this can be done through the same high-level command API provided for users in teleoperation mode. In general, special software interfaces are not required and, with only simple Wi-Fi communication, the modular arm can be controlled independently of its base. For instance, we demonstrated the ability to pause canned motions to perform teleoperation of the arm from an external computer.

CONCLUSIONS

The Portsmouth Gaseous Diffusion Plant Robotics Challenge highlighted the flexibility of modular robotic hardware. With such hardware available, we showed plant personnel may design custom inspection and manipulation devices, or entire robotic platforms capable of accessing tight spaces with difficult terrain. However, to support the variety of tasks involved in activities such as nuclear decommissioning, there are several challenges that the community should address.

One potential issue is exposure to radiation sources, which can damage electrical equipment as easily as biological materials. Lightweight robotic platforms like the ones demonstrated should, at minimum, use external protective equipment, i.e. a custom personal suit, to operate near radiation sources.

Also, although we have several completely wireless platforms, many of our robots still employ tethers to operate in noisy environments that interfere with wireless communication. It is possible to use external amplifiers and signal boosters in such scenarios. However, more advanced communication paradigms may be necessary to accommodate lossy networks and large amounts of data. Data Distributed Service (DDS) middleware seems a promising technology for managing low-latency communication in such environments and has proven capable in numerous military and space applications.

More generally, it is our opinion that modular hardware is in its infancy, and we are only beginning to realize its benefits. Projects such as H-ROS (DARPA funded) have sprung up to begin to standardize hardware interfacing, with the goal of reducing the time, cost, and complexity of creating or replacing components of robotic platforms. We expect to see more modular hardware components capable of supporting in tasks requiring different scales of actuation and sensing. If only for their capability to rapidly deploy customized inspection and manipulation devices, we believe the hardware discussed here already provides a useful set of tools that can enhance the capabilities of personnel operating in nuclear facilities.

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