

Design and Control of a Second-Generation Hyper-Redundant Mechanism

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Abstract— We present a refined, second-generation design, construction and integration, of a compact hyper-redundant *snakelike* robot, called “Woodstock.” This robot has substantial advantages over our previous design iteration, “Snoopy,” in terms of cost and performance. The robot is composed of six actuated universal joints which are serially chained to construct a twelve degrees of freedom snake-like robot optimized for strength and compactness. Any joint in the robot is strong enough to produce a torque that is capable of cantilevering the entire robot. This paper also presents the low-level system-control architecture, which is based on a high-speed RS-485 data bus; this allows the entire system to be operated with only two power and two data wires. The system is controlled from a remote computer on a wireless network and can also run over the internet.

Index Terms—hyper-redundant mechanism, snake robots, mechatronics, mobile base, mechanical design.

I. INTRODUCTION

Many tasks require manipulation of a device in inaccessible and cluttered spaces. This challenge can be confronted using a controllable highly articulated robot to reach through convoluted volumes accessing locations that people and conventional machinery otherwise cannot; such a robot is formally called a *hyper-redundant manipulator* (Figure 1).

Chirikjian first coined the term *hyper-redundant* mechanisms as a mechanism which has many more degrees of freedom (DOF) than required to perform a certain task. These extra DOF enable the hyper-redundant mechanism to handle more constraints, such as those presented in highly convoluted volumes, while at the same time enabling them to perform a variety of tasks. The versatility of hyper-redundant mechanisms is evident in biological systems: snakes, elephant trunks, and worms, all of which can poke through

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and crawl through crevices as well as manipulate objects.

Over the past 17 years, many researchers have built a variety of hyper-redundant devices. The first true snake robot was built in 1972 by Hirose [1]. His pioneering work in snake robot design was geared towards mimicking the behavior of real snakes while laterally undulating on the ground. The work of Chirikjian and Burdick [2] in the early 1990’s sparked the development of a variety of hyper-redundant robots, calling them snake robots, elephant trunk robots, monkey tails, and tentacles. Since then, many researchers have built snake-like robots, Borenstein, Walker, and Yim, to name a few, [6].

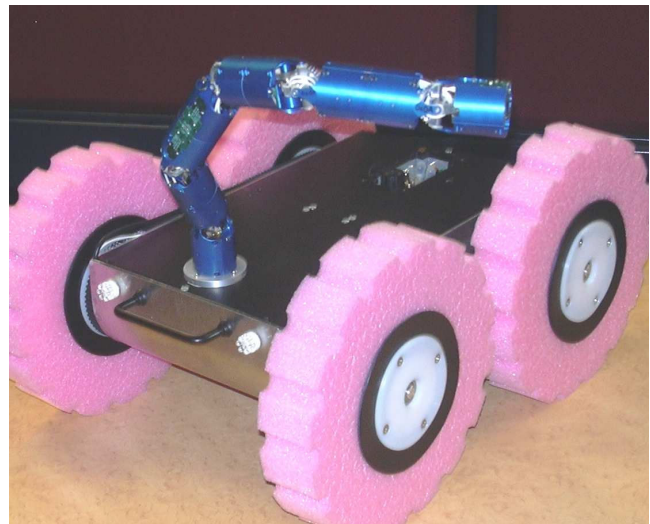


Figure 1: Our hyper-redundant robot mounted on a mobile base

Most of the mechanism designs, however, have been limited to the plane. A few three-dimensional robots were developed but they were somewhat bulky or had limited strength. Inspired by the urban search and rescue application, our design seeks to get both compactness and strength while maneuvering in three dimensions. When designing a hyper-redundant mechanism, we considered several critical design metrics such as: maximum torque-to-weight ratio to allow the robot to support its own weight, minimum envelope diameter to allow it to fit through small cracks and confined spaces, minimum achievable radius of curvature resulting from short links with maximum angular travel between links

(for high maneuverability), and rugged construction. Naturally, we are also interested in optimizing our design for minimum backlash and compliance while maintaining a reasonable speed of motion.

In this paper we introduce a second generation of design for a three-dimensional hyper-redundant mechanism which is composed of six actuated, serially-chained, two-degree-of-freedom joints that have compact structure, and are strong enough to allow the robot to support itself. We compare our new design, Woodstock, with our previous design, Snoopy, and show advantages in terms of cost and performance.

II. PRIOR WORK

Snake robots are the main subject of several robotic researchers who often address them as hyper-redundant robots [2]. The maneuverability inherent in these types of mechanical structures and their ability to conform to environmental constraints, allow them to overcome obstacles of significant complexity compared to conventional robots [3][4]. One of the pioneering works in this area was introduced by Hirose [1]. In this work he developed a device that mimicked the locomotion of real snakes on the ground. Hyper-redundant robot research continued in the early 1990's at Caltech with the planar *hyper-redundant* manipulator by Chirikjian and Burdick. Their contribution focused on novel end-effector placement algorithms for these robots [5] [2]. OC Robotics [20] has built a number of prototype, cable-driven "snake arms" for security, inspection and assembly applications.

Recently, other researchers, such as Yim [6] at PARC, Miller [7] on his own, and Haith at NASA Ames [8], have duplicated Hirose's pioneering work on snake locomotion, where Yim and Haith used Yim's polybot modules to form modular hyper-redundant robot. Modularity clearly has its benefits, but comes at the cost of strength and maneuverability. The electro-mechanical connection between adjacent links is Polybot's innovation, yet it also provides a point of weakness to the mechanism and reduces its maneuverability.

We are interested in building a snake robot which is capable of maneuvering in three dimensions. The Pacific Northwest Labs developed a three-dimensional mechanism which was designed for the delicate task of disarming bombs. Kinematically, the mechanism is a sequence of linearly actuated universal joints stacked on top of each other. Unfortunately the design was too bulky and slow for the present applications. Takanashi developed at NEC [9],[10] a new two-DOF joint for snake robots that allowed a more compact design (Figure 2a). This joint uses a passive universal joint to prevent adjacent bays from twisting while at the same time allowing two degrees of freedom: bending and orienting. The universal joint being installed on the outside rendered the joint rather bulky.

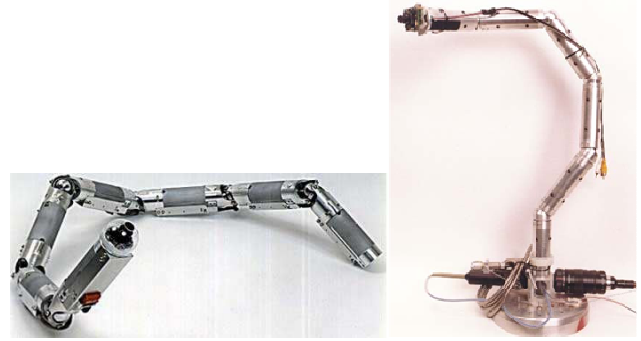


Figure 2: a) NEC Snake Robot b) JPL Serpentine Robot/

Researchers at JPL [11] "inverted" Takanashi's design by placing a small universal joint in the interior of the robot. This allowed for a more compact design, but came at the cost of strength and stiffness (backlash). A small universal joint cannot transmit rotational motion at big deflection angles nor can it withstand heavy loads. Other known designs use cable/tendon actuation systems for driving the robot, yet these designs are somewhat cumbersome and require quite a big external driving system [1] [3] [12] [13].

In a previous paper [19] we described our hyper-redundant mechanism—Snoopy—which was based on actuated universal joints driven by small ball-screw actuators with DC motors. We have since found that the ball-screw units suffer excessive wear under normal operating conditions, although the loads are within the manufacturer's specifications. The wear causes increased friction and loss of efficiency, and the inability to apply the torques needed to lift the mechanism in some loading scenarios. This design also suffered from high cost of components (garmotors and ball-screws), high fabrication costs, and complex assembly (reassembly of ball screw units and intricate wiring). Our new design—"Woodstock"—seeks to achieve better performance and reliability at lower cost.

III. MECHANICAL STRUCTURE OF THE HYPER-REDUNDANT MECHANISM

A major challenge for a hyper-redundant robot mechanism is to be strong enough to lift itself in three dimensions but be small and light enough to be useful in field tasks such as search-and-rescue, battlefield medicine, and engine inspection. Also the robot should be able to achieve a small radius of curvature resulting from short links with maximum angular travel between links (for high maneuverability). Finally, each of the joints should have a reasonable speed of motion. In the next section we present our new hyper-redundant mechanism and its mechanical properties.

A. Mechanical Design

The Woodstock hyper-redundant robot comprises six² actuated, 2-DOF universal joint (U-joint) modules connected in a serial chain. Figure 1 shows the robot mounted on a mobile platform, while Figure 4 is a close-up view of a single module.

Each module comprises two geared actuator units joined by a U-joint. The basic actuator components (motor and gears) are taken from a commercial hobby servo (Hitec HSR-5995TG) and remounted in a custom, aluminum housing that provides the overall structure and appropriate cylindrical envelope. The aluminum housing also serves as a heat sink for the motor and electronics. The HSR-5995TG was selected for its high performance and high-quality components, as well as for the intrinsic engineering at a reasonable cost (<\$100). Figure 3 shows the components of a single actuator module (half of a *joint* module).

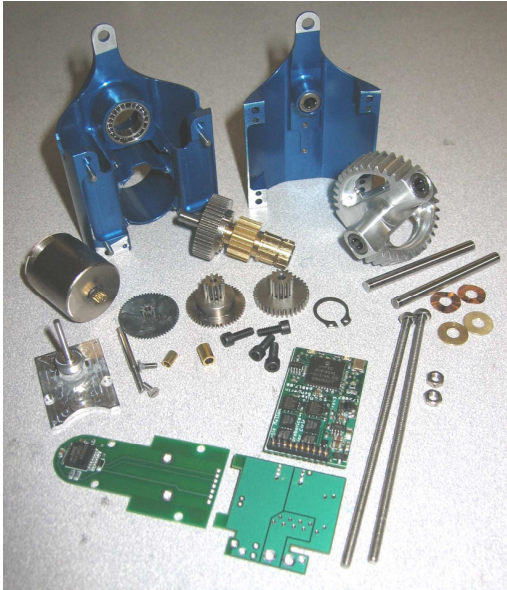


Figure 3: Parts for the Woodstock joint

A cross-sectional CAD model of the actuator mechanism is shown in Figure 5. Torque is transmitted from the coreless DC motor through a 4-stage 305:1 gear train, the standard components of the hobby servo. A custom gear is attached to the servo output gear, and drives one sector gear of the U-joint cross; this provides an additional 40:12 reduction, yielding an overall ratio of 1015:1. The servo output gear assembly rotates on a needle bearing and a full-complement ball bearing. The *gear-cross* has four needle bearings for each pivot, to support the high gear reaction forces and

² The modularity of the design permits the use of whatever number of modules is needed to achieve the desired number of DOF. With six or seven modules, the robot has adequate torque to operate in a fully cantilevered, horizontal configuration.

structural bending loads that can exceed 450N (100#). The inboard needle bearings in the cross are needed to restrict bending of the pivot pins that can cause edge loading and premature failure of the needle bearings. Maximum angular travel of the joint is about +/-50 degrees.

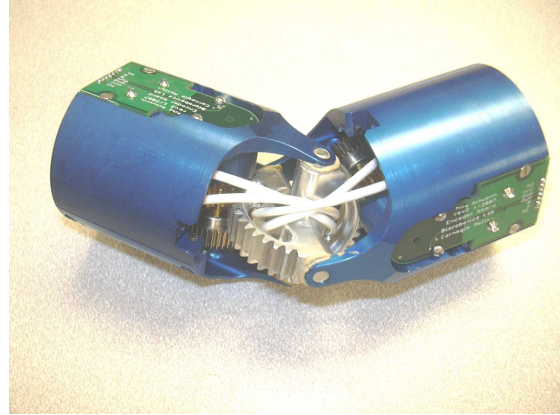


Figure 4: Integrated joint module with onboard electronics.

B. Electro-mechanical performance

A primary objective of the robot design is a high torque-to-weight ratio to enable the robot to move in arbitrary configurations while working against gravity loads on the joint modules and any payload. At the same time, it is desirable to keep the robot profile slender so it can easily “snake” into cramped areas; and to maximize the curvature that the robot can achieve to facilitate maneuverability. Fabrication cost and reliability were further considerations. The use of hobby servo components met these needs.

Gear-cross couples two actuator units and provides joint torque

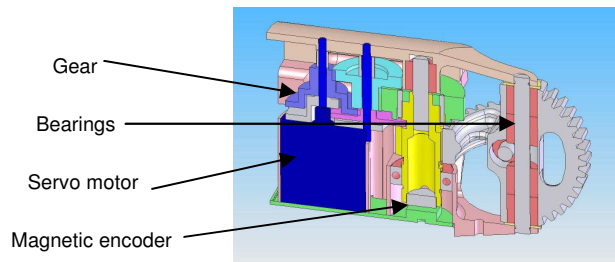
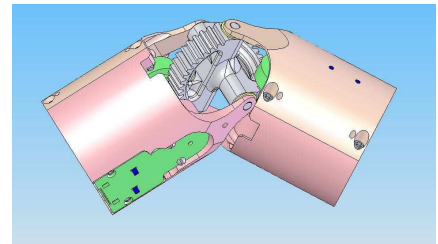


Figure 5: Link details

Table 1 summarizes the performance parameters of the electro-mechanical system. The hobby servo is advertised as having a torque rating of 333 oz-in @4.2A, 6.0V; our tests indicated a value of about 250 oz-in (15.6 #-in or 1.76 N-m)

is more realistic. With the added 40:12 final gear stage, this gives a theoretical output torque of 5.86 N-m (52.0 #-in). Load tests on the joint confirmed that this output torque was achievable for a short duration. Thermal testing has shown that a sustained motor current of about 2 Amps. produced a case temperature of 90C after about 10 minutes of operation. Using the 2 Amp figure as the allowable, continuous current, we conclude that our joint can produce a continuous torque of 3.73 N-m (33.0 #-in).

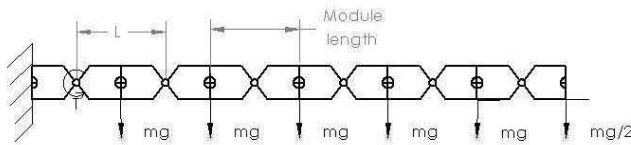


Figure 6: Diagram showing how weights of links produce a torque at the base joint

In order for the robot to move itself through arbitrary configurations, it needs adequate joint torque to support itself in the worst loading case: full horizontal extension, or *cantilever* configuration. Figure 6 shows how the gravity loads are distributed along the robot’s length in this configuration. For N joints connected in a serial chain, the total torque, τ , in the base joint is given by:

$$\sum M_{base} = \tau - mg \left(\frac{1}{2} + \frac{3l}{2} + \frac{5l}{2} + \dots + \frac{(N-1/2)l}{2} \right) = 0,$$

which yields $\tau = \frac{mgl}{2} (N(N-1) + 1/2)^3$. For the present design, the term $\frac{mgl}{2}$ is equal to 0.0876 N-m (0.776 #-in). Based on the available, continuous joint torque of 3.73 N-m (33.0 #-in), Woodstock should be able to support cantilever loading with up to nine modules. Operation with fewer modules would require correspondingly less torque; for instance, seven modules would require only about half the available continuous torque.

Woodstock compares favorably with our previous design, Snoopy [19], in terms of performance and cost. Snoopy was larger in diameter (47mm vs. 41mm); comparable in module length (96mm vs. 101mm); and heavier (220g vs. 177g). Snoopy was designed for significantly higher joint torque than Woodstock (4.5N-m vs. 3.7N-m). However, Snoopy’s performance rapidly deteriorated due to localized deformation of the ball screws at the ball-contact surfaces. While Snoopy was originally able to cantilever seven modules, this was reduced to six or even five modules. We believe that Woodstock will be more robust, and maintain its ability to cantilever nine modules. Further, Woodstock is

³ This equation differs from that derived in our previous paper [19] because the joints are located at the mid-length of the modules, rather than at the ends. That is, the first (base) joint is displaced $\frac{1}{2}$ module length from the base end of the serial chain.

substantially faster: less than one second for full joint travel, under no-load conditions compared to approximately five seconds for Snoopy.

Moreover, Woodstock is substantially lower in cost and simpler to assemble and repair. The entire motor and gear train (hobby servo parts) for each actuator cost less than \$100, with other major components (bearings) costing less than \$50 per actuator. Because of the low part count, assembly and repair are simple and quick. Snoopy’s components (garmotors, ball-screw units, etc.) cost about twice as much; difficult machining of the ball nuts and custom thrust ball bearings was needed; and the disassembly and reassembly of the ball nuts made the assembly process very tedious. A new wiring scheme for Woodstock, described in the System Control section, alleviates much of the effort required for assembly.

On the other hand, Snoopy has a few advantages over Woodstock. The Maxon gearmotor is designed for higher voltage and draws less current (0.56A vs. 2.9A for Woodstock) so wiring can be smaller. This is also reflective of Snoopy’s lower power and speed. The use of 24V or 48V in future versions of Woodstock may mitigate this. Because Snoopy’s encoder measures motor motion (compared to servo output gear motion), it has much higher joint angle resolution: 0.005 degree vs. 0.11 degree for Woodstock. This could present some control problems for Woodstock. Finally, Woodstock has substantially greater joint backlash resulting mainly from clearance in the gears: ~1 degree per module, vs. 0.06 degree for Snoopy. We decided that keeping the gears loose for low friction was more important than minimizing backlash for the typical low-precision, teleoperated tasks of interest.

Performance Parameters for Hyper-redundant Robot (Woodstock)

Parameter	Value
Link diameter	40.6 mm (1.60 in)
Module length	101 mm (3.98 in)
Module mass	177g (0.390 #)
Joint torque, continuous	3.73 N-m (33.0 #-in) @ 2 A (90C)
Joint torque, peak	9.69 N-m (85.9 #-in) @ 5.2 A, 7.4 V
Joint travel	(+/-)50 degrees max.
Joint speed, theoretical no-load	0.42 rev/sec or 0.67 sec full travel (+/-)50 degrees)
Gear ratio, overall	1015 to 1
Angular resolution	3413 counts per rev. at output (0.105 degree)
Joint backlash	<1 degree (due to gear clearances)

Table 1: Parameter values for Woodstock

IV. SYSTEM CONTROL

A. Low-level control

Hard wiring to all 12 actuators and encoders would require 72 (12 x 6) conductors to run inside the hyper-redundant robot envelope. This scheme was deemed infeasible. The solution was to run an RS485 bus through the robot with distributed control circuit boards for each DOF. Each of these distributed controllers provides an H-bridge to drive the motor, quadrature decoding for position feedback, and a 16bit microcontroller which runs a PID loop as well as the RS485 bus protocol. Each actuator also houses a number of sensors for monitoring the temperature of the actuator, the orientation of the actuator (3-axis accelerometer), and the motor torque (motor current measurement). Packaging all these components to fit within the link envelope, and providing interconnects between controllers, are both challenging problems.

The current electronics design includes three custom circuit boards per actuator (six per joint module). One of these boards (back PCB) serves solely as a connector between the other two boards and connects adjacent modules (Figure 7). Electronic modularity is maintained at the “joint” level, allowing disassembly of the modules without desoldering wires. Boards on either end of each link are connected to each other via three hard soldered wires. To remove individual boards (i.e., to disassemble a module itself), some desoldering of wires or pins is necessary. Also, the motors are hard soldered to their controlling boards.

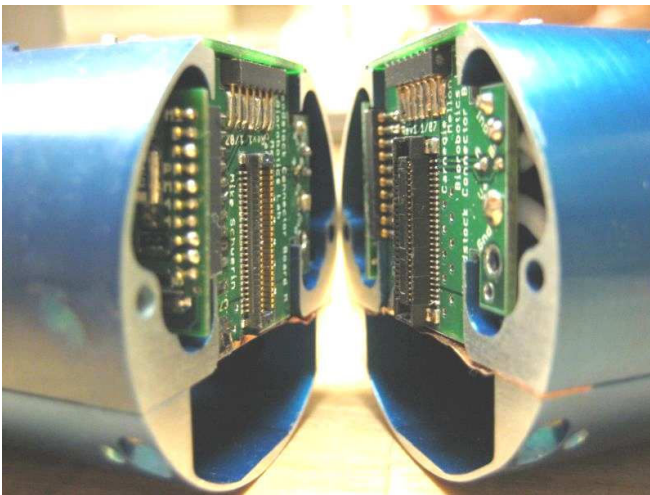


Figure 7: Inter-module connection

The second circuit board (encoder PCB) serves as an interconnection device, linking the motor to the other boards, and also includes a magnetic encoder chip, the AS5040 from Austria Microsystems, which provides feedback on the absolute angular position of the actuator. This is the elongated board in Figure 3 with the rounded end.

The third circuit board (controller PCB) includes a Microchip dsPIC30F3011 microcontroller, which runs the communications, trajectory generation, and PID control loop as well as measuring the outputs from the various sensors including the AS5040 encoder. Because of the amperage requirements of the motor, this board features a discrete MOSFET H-bridge using two Intersil half bridge drivers.

This controller board also houses a number of the actuator sensors. An Analog Devices chip, ADXL330, provides 3-axis accelerometer readings. Motor current is measured across a low resistance sense resistor and then amplified by a TI INA197 current sense amplifier chip. An LM20 chip provides thermal feedback to protect the electronics and motor from the dangers of overheating. In addition to these sensors the board also houses a number of voltage regulators. An LT3470 switching regulator provides 5v to the digital electronics. There is also a 3.3v low dropout precision regulator to power the analog components and a 12v linear regulator to provide the gate drive voltage for the H-bridge.

In order to meet the tight space requirements and high peak current requirements (as high as 5A) .050” headers are used to interconnect the boards, but are soldered on both ends of a male header rather than using mating connectors. The inter-module connection between adjacent joints is made by a .5mm pitch 50 pin board to board connector. The majority of these 50 pins are used to carry the positive voltage bus, while the actuator housings are used as the negative (ground) voltage bus. Phosphor bronze spring washers at the U-joint pivots provide a low-resistance, conductive path (“slip ring”) through the joint. The two differential RS485 lines are also coupled through the 50 pin connector and then pass through the joint in a shielded twisted pair cable.

The firmware running on the microcontroller includes support for the bidirectional RS485 protocol. Moreover, the code performs trapezoidal trajectory generation and provides a PID control loop for the connected motor. For this use, the PIC reads the joint angle (quadrature encoder counter), and drives the H-bridge amplifier with a PWM signal according to the desired trajectory. This trajectory is generated based on a desired goal, a ramp time, and a time to goal value, all of which can be specified dynamically over the RS485 bus. The controller also has the ability to communicate with the host computer over the bus and provides, upon request, the readings of any of the on-board sensors. The RS485 bus is running on at 320 kbps allowing for quick updates and lower command latency on the bus. The PID control loop on board the PIC microcontroller runs at a 1 KHz rate.

B. High-level control and user interface

Many of the user interface features for this system were well established during the development of the Snoopy

robot. The key features are based around the knowledge of the kinematics of the robot and the information provided by the encoders. One of the most important features is the rotation of the image retrieved from the camera at the end of the snake. Without this feature it would be very easy for an operator to get disoriented or confused about what they are looking at, but this function of the software ensures that up in the image correctly corresponds to up in the real world.

Similar information is used in another key feature of the software, the ability to move in the camera plane. All of the motion profiles the operator can use to control the system are rotation compensated to match the image, but there are two modes of motion that take things one step beyond this. These are the capabilities to move in and out along the camera axis and to move in the plane of the camera image. These two complex motion profiles involve solving inverse kinematics to calculate the correct joint angles to provide the desired movement.

One new feature which has enhanced the usefulness of the system is the ability to record and play back waypoints. This is useful in many situations including repetitive operations as well as operations in confined spaces.

By recording waypoints as the operator threads into a convoluted space the job of getting back out of that space is trivialized by enabling the operator to simply replay these waypoints in reverse to extract the robot from the environment.

For repetitive tasks such as engine inspection the operator could build up a library of configurations which they could play through to give them complete coverage of the inspection task without having to manually drive the robot to each inspection point.

V. CONCLUSION

In this paper we presented a new design of a compact hyper-redundant robot. The robot has 12 degrees of freedom yet it is still compact and strong enough to allow the robot to cantilever-lift itself. The new robot, Woodstock, is similar in size and performance to our previous design, Snoopy. But the use of high-performance, hobby servo components—rather than expensive ball screws and servo motors—reduces component and fabrication costs, as well as assembly time. We expect improved reliability and longevity from the new design as well.

We also presented the low-level system-control which is based on a high-speed RS485 data bus. This enabled us to maintain compact structure. The system is composed of 12 embedded mini circuit boards, each containing a microchip microcontroller, a driver, and a counter, which run the PID control loop for each motor.

Another important application of hyper-redundant robots is urban search and rescue. Already, we have deployed our mobile base carrying a hyper-redundant robot in a collapsed

building in August of 2003 in Lebanon, Indiana. The deployment was part of an exercise organized by the *Center for Robotic Assisted Search and Rescue* and the Indiana Task Force I. Although our device performed quite well, we learned that there are still many features that the robot requires; most importantly, we have to update our current device so that it is water-resistant so that we can clean the robot after each deployment. We also have to add additional sensors for search and rescue.

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