A Novel Architecture for Modular Snake Robots

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Abstract—**We have designed a snake robot, a hyper-redundant serial linkage of many actuators, that uses a modular architecture. Our design considers size, power, weight, and trade-offs among these criteria. We chose a modular architecture to allow a single joint design to simply be repeated to achieve the sixteen degrees-of-freedom (DOF) the robot normally consists of. At the core of the module is the "Super Servo 2," a modified hobby servo, with custom electronics for sensors to monitor current and temperature, a communications bus, and a programmable microcontroller. This combination of the mechanical and electrical architectures results in a robust and versatile robot that is capable of a wide variety of tasks from swimming to climbing flag poles. In this paper we discuss the trade-offs considered in the design, the mechanical and electrical architecture, and the reliability of the modules.**

Index Terms—**Snake Robot, Hyper-Redundant, Modular, Servomotor**

Fig. 1. View of a snake robot crawling inside of a turbine.

I. INTRODUCTION

SNAKE ROBOTS unique shape and ability to navigate challenging environments, such as the turbine in Figure 1, make them suitable for a broad range of tasks including search and rescue, inspection, and reconnaissance missions. In a highly cluttered environment such as a collapsed building or mine only a robot with a small cross sectional area can pass. Moreover, such environments often have several twists and turns, thus requiring a highly flexible robot. A snake robot is both small and flexible, but perhaps a more important feature is the snake robot's versatility in locomotion. Our prior work has demonstrated that snake robots can climb poles, swim in ponds, crawl up stairs, and traverse uneven terrain [1]. We argue that perhaps snake robots may not be the "best" robot for each of these tasks, but to our knowledge no other type of robot can do them all.

The contribution of this paper centers on a modular design, composed of single-DOF modules with special modules at the head and tail of the robot. Modularity has several advantages, including adjustable length, cheaper manufacturing, and easier repair. Adjustable length, by adding or removing modules, is important because some applications may call for a shorter or longer robot, depending on the size of the environment the robot is working in. Manufacturing and design become cheaper because of the many identical parts. Finally there is a large advantage to having every segment be identical so that a single set of spares can replace any broken segments. One disadvantage is that it is harder to have specialization, such as one module for power storage and another module for sensors.

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Our modular design addresses the issues of size, range of motion, reliability and modularity. The success of our design can be seen in its performance on a variety of obstacles. The robots have climbed the inside of a 12" pipe and also the tight interior of a steam turbine. They can climb flagpoles over a wide range of diameters as well as highly irregular structures such as human legs. They can navigate man made obstacles such as stairs in addition to natural obstacles like brush and mud. This versatility is what makes these snake robots so useful.

At the core of each module the servo, which we call the Super Servo 2, provides actuation to the DOF of each module. The architecture also includes sensors distributed throughout the snake that provide valuable feedback. In addition to enabling more intelligent locomotions, the Super Servo 2 monitors these sensors to detect and prevent failures. This paper will cover some related work in Section II, followed by the mechanical and electrical design in Sections III and IV, respectively. Then we will present a brief discussion of reliability issues in Section V, and then a summary of the features of the Super Servo 2 in Section VI. The final section will discuss some conclusions and future work.

II. RELATED WORKS

The modular snake robots described here draw inspiration from two fields: modular robotics and snake robotics. Recently, especially within the past decade, interest in modular robotic systems has increased [2]. These systems have certain advantages such as low cost, robustness, and versatility [3]. Mark Yim's PolyBots [3] [4] [5] have greatly inspired our work.

PolyBots are versatile modular robotic systems that feature 1-DOF joints and two connecting ports per segment. The 2"x2"x2" modules allow the robot to support a number of configurations which include snake, spider, and rolling modes. One special module that they call a node has 6 connecting ports to allow more than two segments to join together. The robot is tethered to an external power supply, as they point out that "portable power is very difficult to incorporate into modular systems" [3].

One focus in this line of research is a particular subclass of modular robotic systems known as self-reconfigurable robotic systems, including further work by Yim [5]. Murata et al. [6] further divided this into two subtopics: lattice type robots and string type robots. The lattice type systems, defined by their spatial symmetry and crystal-like structure, have limited motion generation capabilities but make up for it with their easy reconfigurability. The self-reconfiguring molecules from Rus [7] have many similarities to some of our designs in the past, but were designed to function as a lattice type system. In contrast string type robots, consisting of a string of many joint modules, can generate a wide range of motions, but it is harder to have a self reconfigurable system. Our robots fall into this second category, as do all snake robots.

One self-reconfiguring robot is the SuperBot from the University of Southern California [8], which features 3-DOF modules. Each module has two 3.3"x3.3"x3.3" lateral joints connected by a central pivot, making the overall module size 3.3"x3.3"x6.6". There are 6 docking faces on every module, which allow for a wide variety of topologies including snake, biped, and other configurations. The face plates include a communication interface over IrDA. Every module contains a 11.84 Wh LiPo battery to power the motors and electronics.

In addition to modular robots, prior work in snake robots have influenced us, including the undulatory snake robots that were pioneered by Hirose starting in the 1970s [9]. Hirose mimicked the lateral undulation motion of real snakes by creating the ACM line of robots and developing the serpenoid curve. To achieve this motion the robots feature small wheels that allow for easy motion in one direction while providing friction in another. These robots have come a long way resulting in the most recent version, the ACM-R5 [10]. This robot includes fins which serve a similar purpose as wheels when the robot is in the water. Other undulatory snake robots that use wheels include the AmphiBot II [11] and Gavin Miller's snake robots [12].

Wheels can cause problems, however, because they hinder many more interesting means of locomotion. Wheels allow a robot on a flat surface to move in a smooth and continuous manner, but are ineffective on less smooth and non-planar surfaces. Robots that use passive wheels in this way would not be able to easily climb the inside of a pipe and would have difficulty in an outdoor environment. To locomote, our robot relies exclusively on body shape changes, typically generated by a discretely sampled sinusoidal wave moving through groups of modules. Every module is assigned a different phase of the sine wave and the sine wave propagates along the robot to cause the motion. A previous paper [1] gives a much more thorough description of our snake robot locomotion.

Fig. 2. Progression of modular snake robot development - older robots are at the bottom of the image.

The University of Michigan and SAIC have taken a different approach that does not exclusively use undulatory locomotion. Their robots use an active tread, like the OmniTread OT-4 [13], or a toroidal skin, like the SAIC snake robot [14], both of which provide direct forward propulsion for the mechanism. The OmniTread robots have treads that run the length of each module and between each module is a 2-DOF pneumatically actuated joint. In addition the OT-4 robot is unique among the robots listed here in that the modules are highly specialized. For example two of their modules are power modules, and contain two batteries each totaling 81 Wh. Meanwhile the SAIC snake robot has a toroidal skin that covers the entire exterior of the robot and is propelled forward by internal motors. This allows them to push through cluttered environments without getting stuck on debris. After traveling the length of the robot the skin is pulled in and recirculates to the front of the robot in a continuous fashion. Inside the skin are 2-DOF conventional actuators that were also used in the elephant trunk robot Woodstock [15], which was developed in the same lab as the snake robots described in this paper.

Active skins, while able to speed the completion of certain tasks, may have unnecessary mechanical complexity. These skins do not significantly increase the types of obstacles that the robot can overcome, but do help in some cases. Tasks that require motion along the direction of the skin gain a significant performance benefit from having a direct means of locomotion, while other tasks are hindered by the robots weight and size increases. Addition of a complicated skin drive mechanism also adds a number of potential points of failure which could lead to a less reliable robot.

III. MECHANICAL ARCHITECTURE

The snake robot presented here is made up of a string of 2"x2"x2.25" modules with special modules at the head and tail. Each module functions as a single rotational joint with 1-DOF. We assemble the modules such that each module's axis of rotation is perpendicular to the length of the robot and rotated 90 degrees from the previous module. The modules can then be divided into two groups based on their axis: horizontal and vertical.

The powerhouse of each joint module is the Super Servo 2, a modified hobby servo, which controls its one DOF. The Super Servo 2 relies on a heavily modified Hitec HS-5955TG servo, utilizing its DC motor and gear train with our electronics to control the motor according to outside commands. The output shaft protrudes from the servo and has a range of motion between -90 and +90 degrees relative to center with a resolution of .35 degrees. The Super Servo 2 is capable of rotating 360 degrees continuously, but the mechanism and software limit its range of motion to 180 degrees.

We designed the Super Servo 2 with a servo that could deliver the maximal amount of torque to allow the snake robot to do as many tasks as possible. One way to measure this strength is by measuring the *characteristic torque*, or number of modules that can be cantilevered by a single joint [3]. We have found that a single Super Servo 2 can lift the entire robot (15 remaining modules) with a current limit set as low as 65% (for a discussion of current limits, see Section IV-B). For comparison the characteristic torque of some of the other robots listed in the related works section are: one module for Rus's molecule (2-DOF/module) [7], three modules for OmniTread (2-DOF/module) [13] and SuperBot (3-DOF/module) [8], five to eight modules for the PolyBots (1-DOF/module) [3], and nine modules for Woodstock (2-DOF/module) [15].

In addition to the strength of the joint, we also carefully considered the structural requirements and have designed a three piece design: the servo, the servo back, and the U-case (Figure 3) . The servo body is primarily composed of the stock servo case, while the servo back has been completely redesigned. The new back design gives extra space for the electronics and permits us to use a specially designed bearing system. This bearing system lets the U-case screw firmly in to the back but still rotate freely around the servo. The U-case itself is, as the name suggests, shaped like a U. It has one arm attached to the output of the servo and the other attached to the servo back. The U-case moves in conjunction with the output shaft of the servo. The modules connect together via screws, which secure the back of each module to the U case of the previous module.

In our experience, protecting the wires that are critical to the functioning of the robot is hard to do well. Attached to the sides of the servo are plastic wire sheaths that house the cables that run from module to module. They were designed to prevent cuts, nicks, pinches, and other damage to the wires in the robot. In addition they help hold the connectors in place and guide the wires to the next module.

The modules are designed to link primarily to other modules. However the rear of the robot must have additional functionality in that they must interface both with other modules in the robot and with the controlling computer, over either a wired or wireless connection. We primarily operate in a tethered configuration (like [3] and others), and the tail module converts the wiring inside the robot to a tether connection. The tail features a slip ring to allow the robot to rotate relative to the tether, which is crucial for climbing and rolling gaits. In addition to interfacing with the tether we are in the process of adding a camera to the tail module. This will allow the user to lift the tail and see how the robot is sitting in its environment for easier tele-operation.

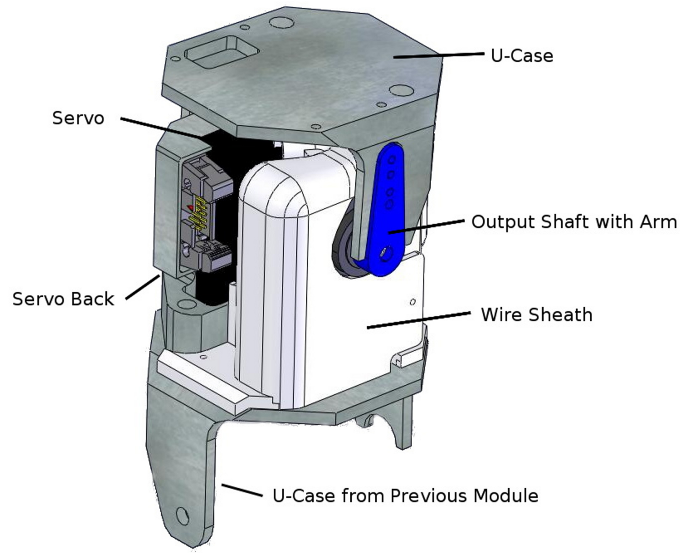

Fig. 3. CAD model of a snake robot module.

At the other end of the robot is the head module, where we can attach any application specific payloads. For many applications, a color camera with artificial illumination is all that is required. In general the snake robots are intended to operate in confined spaces with little lighting so having adjustable headlights around the camera helps the operator control the robot in an unknown environment.

IV. ELECTRONICS ARCHITECTURE

With this sturdy mechanism in hand we sought to create a comparable electronic package whose goal is to reliably control and monitor the actuators and sensors. Our design consists of three circuit boards per module – a controller board, a power board, and a sensors board, whose functions are summarized in Figure 4. The controller board has an Atmel microcontroller (as in [8] and others), as well as the electronics for the communications, H-bridge, temperature, voltage, and current sensors. The power board is simply a switching power supply, and the sensors board has a second Atmel microcontroller to monitor the remaining sensors, such as the magnetic encoder and the accelerometer.

The main microcontroller permits the module to perform all of the local computations (like PID control) internally. The gaits, meanwhile, are generated and coordinated by an off-board personal computer (as in [7] and others). Thus the PC coordinates this hierarchical system. For example, the PC may send a command to a module to move to a given position or specify a current limit. The module then does the calculations to actually turn to that position or keep its current draw below the specified limit.

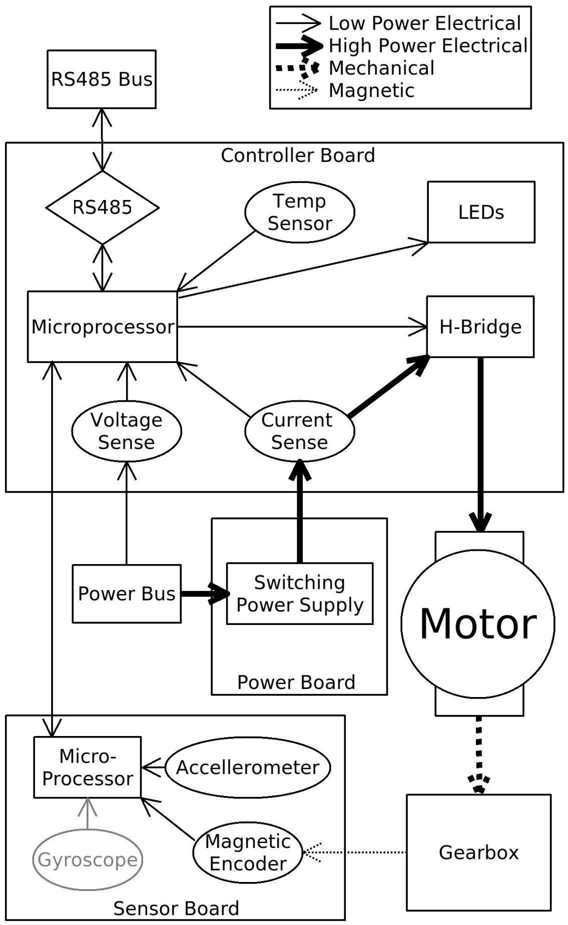

Fig. 4. Block diagram of Super Servo 2 internals.

A. Communications

In order for the commands to and from the PC to reach the modules in a reasonable amount of time a relatively high speed communications bus is needed. The communication is broken into per-module packets. The PC sends out packets containing the desired state (position, current limit, temperature limit, etc.), while the modules respond with a packets containing their state (actual position, current, temperature, etc.). The PC communicates with a repeater, which in turn communicates with the robot modules. An RS485 bus (as in [7] and others) connects the repeater to all of the slave devices – snake robot modules, in our case. A separate line is run through the length of the robot for video, which is then passed through a balun (for improved video quality over twisted pair wire) to either the same PC or a video screen. A summary of the communication and power connections can be seen in Figure 5.

Between the computer and repeater, we have a USB connection emulating a serial port. Over this connection the PC sends and receives large constant-length packets which begin with two synchronization bytes and contain a 16-bit cyclic redundancy check (CRC). These larger packets contain the information for all of the robot modules. Packets are sent and received continuously and since each packet contains all of the most current information, there is no need to build retries into the protocol as any dropped packet will be made up for by the next one.

The repeater breaks up each packet from the PC into individual constant-length packets to send to each slave. These packets are made up of 9 bit serial frames. The first frame of each packet is an address on which the 9th bit is set high to indicate the beginning of a new packet. This allows the slaves to easily ignore packets not addressed to them. The packets contain a 16-bit CRC and do not need a synchronization byte because of the 9 bit protocol. The repeater sends a single packet to one slave and then allows enough time for the slave to send a response. If a response is received the current state for that module is updated. The repeater then proceeds to the next slave until it has sent a packet to every module on the robot and the process repeats. As with the PC to repeater communication, this simplifies the handling of dropped packets by not requiring a retry in the event of a dropped or corrupted packet.

Between the repeater and the modules is an RS485 connection with a bus topology running at 250 kilobaud. Since the data rate is not exceptionally high, we take the “big bits” approach to communication: we assume that there are no propagation delays or reflections over the length of our bus.

B. Controller Board

Once the packet reaches a module, the main processor on the controller board (on the left in Figure 6) must independently execute the command from the communication packet and return its status. The processor runs a motion controller to set the module to the desired angle. Along with using PID control to regulate the position of the module, the motion controller can also limit the electrical current drawn by the motor. This is achieved by maintaining a duty cycle limit on the motor which is then increased or decreased when the motor current is above or below the current limit, respectively. Due to the essentially linear relationship between current draw and torque, limiting current effectively creates a torque limit; this limit allows the snake robot to comply with the external environment and helps keep the motor from using too much power and overheating when it is stalled. Sometimes the robot will need more torque, however, and the current limit can safely be turned up as needed.

Since we have developed our own motion controller, we can tune many parameters to affect how the snake robot interacts with its surroundings. For example, a mostly proportional controller or a low current limit will cause the servo to comply more with its environment. A proportional controller cannot overcome a steady state disturbance and thus may allow the robot shape to be affected by an uneven environment. A more integral controller will eventually overcome errors and force the snake robot into the commanded position, even if that means fighting back against the environment. The current limit also puts an upper limit on how hard the robot can push, which is important especially when it would be undesirable to exert too much force, such as climbing a human leg. The operator or gait may switch between gains for the PID controller during

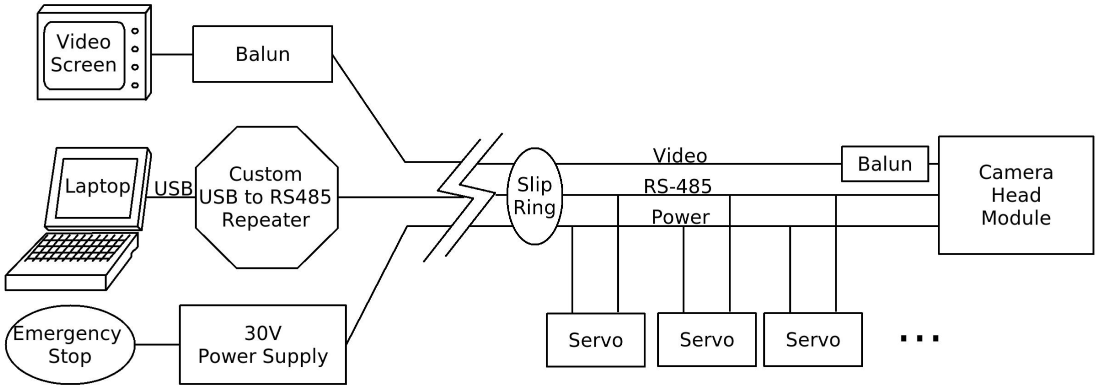

Fig. 5. Overall wiring of the robot.

operation. This allows the robot to use more conservative gains for normal operation, and more aggressive gains for crossing difficult terrain or climbing large pipes.

By using a trajectory generator our position commands may take a time parameter as well; thus the user may specify how long the servo should take to reach a position instead of only having the option to immediately send a servo to the specified position. Currently the only trajectory available is a trapezoidal velocity profile, however in the future we may develop sinusoidal or Bezier curve trajectories. Without a trajectory generator the module will try and reach a commanded position as fast as possible, which may cause jittering, use more power, or put more stress on the mechanism.

C. Sensor Board

In order for the position controller to know the output shaft orientation, we use a magnetic encoder (as in [15] and others) on the sensor board (on the right in Figure 6). We glue a diametrically polarized magnet to the output gear from the servo; the magnet protrudes into the space that the potentiometer would have occupied in a stock servo. The magnetic encoder chip sits inside the servo on a circuit board situated near where potentiometer had been and senses the direction of the magnetic field. These modifications provide digital, absolute position feedback as well as continuous rotation. Furthermore since the magnet does not touch the magnetic encoder chip, the system does not wear out or develop dead spots as is the case with potentiometers.

In addition to the magnetic encoder chip, the sensor board has a three axis accelerometer. The accelerometer data can be fed back to the user for on-line or off-line processing. Currently, we use the accelerometer to detect a gravity vector and this is used to infer which way is “up” as well as to provide feedback on the robots motion. This is important when working in remote, dark, and confined spaces. The sensor board can also accommodate a two axis gyroscope, but we have chosen not to include this part due to cost constraints.

D. Power Board

One of the problems we have encountered repeatedly in previous generations of snake robots is the high current draw at the relatively low voltage of hobby servos. To meet the power requirements that the servos demanded, we used large wires (12AWG) that took up space and restricted motion. To solve this problem, we designed a switching power supply board (in the center in Figure 6) which fit inside the servo case allowing us to run the servos efficiently at voltages anywhere between 10 and 36 volts as opposed to the relatively small 7.5 volts that the motor is designed to handle. The switching regulator allows us to use thinner wire between the modules and enables each individual module to better handle voltage fluctuations due to the current draw of other modules.

It is important to note that on board power is extremely hard to implement correctly on a limited budget. In addition our focus is on the design and control of these snake robots, and not how best to add and manage batteries. We have in the past had designs that include their own power sources, but have decided that they are not a priority for our applications at the moment. Thus our power is supplied by an off-board source.

V. RELIABILITY

A. Mechanical

The mechanism design has improved the reliability of the system in a variety of ways. For example all of the corners on the structural pieces have been reinforced to resist twisting and fatigue. We anecdotally tested these components by extreme tensional, longitudinal and impact loading, and the modules showed no significant damage. The bearing connection between the back and the U case reduces rotational friction so the servo can move more freely while absorbing the longitudinal and torsion forces on the snake robot. Overheating has been a problem, but the new back is made of aluminum instead of plastic and significantly aids in removing heat from the motor. The wire sheaths were added to cover and protect the servo wires running from module to module. Protecting wires and connectors is important because the snake robot experiences many dynamic interactions and impacts. All together, these changes help the snake robot run longer and survive more damage without failures. The weakest point in the current mechanical design comes from the stock servo gearboxes, which can fail when the robot is dropped from a sufficient

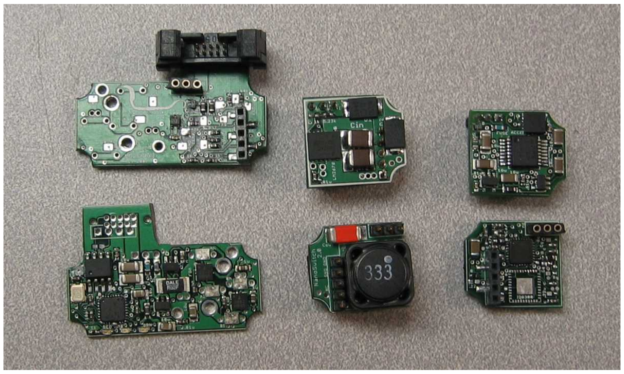

Fig. 6. The Super Servo electronics. Left to right: Controller Board, Power Board, Sensor Board.

height. Under normal conditions, however, we have had few problems with these gearboxes.

B. Robust Electronics

As with many electrical systems we must concern ourselves with how large current requirements will affect the components. A stalled motor draws a large amount of current which causes both the motor coils and the MOSFETs in the H-bridge to heat up. The excess heat will eventually cause a failure. The MOSFETs that originally come with the servomotors exacerbated this problem, since they are not rated to enough current. The new electronics are rated well above the current that the motors are able to draw, significantly reducing electrical failure. In addition to H-bridge improvements, a current sensor on the controller boards allows the microcontroller to limit current draw, which helps protect the servo motor. If the software detects that the motor is drawing too much current, it will reduce the amount of power given to the motor until the current is within an acceptable range. As noted in Section III, a module set to 65% of maximum current can cantilever the entire robot, so turning down the current limit does not prevent us from realizing adequate torque. As an added protection for the motor and electronics, the Super Servo 2 has a temperature sensor that reports to the user the temperature of each module. This will let the driver know which modules have been overworked, and allows the microcontroller to automatically turn the motor off if it rises above a user-defined threshold.

In addition to ensuring the reliability of the motor and H-Bridge, several steps have been taken to ensure the reliability of the other electronics. The Super Servo 2 uses fault-tolerant RS-485 chips that can survive being shorted to power or ground. The new design also has a reduced part count which leads to fewer points of failure as well as more board layout space. In particular the least reliable parts of the original Super Servo have been removed in the new design. Lastly, the three boards now have stacking connectors that reduce the strain of soldering and unsoldering fixed pins on the boards, in addition to making manufacturing easier.

C. Wiring

Individually wiring each module would make them easy to control, however the number of wires would then have to grow with the length of the robot. With an RS-485 bus the snake robot is controlled with only two conductors in a single cable. This makes wiring the robot easier and significantly reduces the chance of a wire breaking. The connectors between the modules can also be a lot smaller and stronger if they only have to have two signals passing between them. The connectors we use do however have 4 signal conductors which allows for a camera signal to be passed through the length of the robot.

In addition to reducing the number of wires, we use high quality silicone insulated wires with a high strand count. Because of this, they can flex well without breaking. For signal wire we initially used headphone cable, but the cable proved too prone to breaking. To remedy this we now use a cable with higher flexure life. Silicone insulated wire is, however, prone to slicing and pinching. The plastic sheaths protect the wiring from these mechanical failures, as described in Section III and seen in Figure 3.

The servos themselves do not have any wires coming in or out of them. Instead of soldering the bus wires directly to the boards inside the servo, a single external connector can provide the servos with power and signal lines. Additionally, with this design the wires themselves are easier to maintain or replace, and the mechanical stresses of soldering the wires to the boards is avoided.

Even with all of these improvements the most common failure we see on the robots is with the wiring. This rate has been greatly reduced by the various features listed above, but it has not been eliminated. Protection of the critical wires within the robot continues to be a priority in our continued work.

VI. Summary of the Super Servo 2

The Super Servo 2 is core of our robot modules, and can be thought of as an independent, feature packed actuator package. For convenience here is a summary of the features of the Super Servo 2:

- High performance hobby servo built on Hitec HS-5955TG servo, with custom electronics
- Microcontrollers in every module talking on RS485 bus and running custom control laws
- Current and temperature sensing and limiting for improved performance and reliability
- Magnetic encoder for higher precision and continuous rotation (range limited in snake robot)
- Switching power supply to run off 10-36VDC
- H-Bridge that wont burn up under a heavy load
- LEDs for status feedback
- Integrated 3 axis Accelerometer and support for a 2 axis Gyroscope allow for more advanced sensing of the world
- Fault tolerant communications chips that wont fail due to wire breaks or shorts
- Stacking connectors and more test points for easy problem solving and fewer strains on the boards
- Single external connector means that wires are easily replaced without having to open the servo case

VII. CONCLUSIONS AND FUTURE WORK

In developing the current modular snake robot design, we considered several factors such as size, weight, and power while producing the necessary torque in every joint. The presented design juggles these constraints and maintains a relatively high level of reliability. This has resulted in a versatile robot that can function in a wide variety of environments. The development of the Super Servo 2 has been an integral part of the achievements of our robot.

While the current implementation has been quite successful, more development is necessary to achieve a fully functional and robust robot. Future designs will most likely no longer make use of hobby servos due to the lack of reliability, inconvenient form factor, and inefficient motor, among other reasons. Using higher voltage motors will eliminate the need for such high current switching supplies. Eliminating our dependence on hobby servos allows a more flexible mechanical design as the module shape and cross section will no longer be constrained by the shape of the hobby servo.

Several payload modules for the head and tail of the snake robot are in development. These will help the robot achieve a wider variety of tasks, including debris removal, pipe cleaning, chemical detection, antenna placement, and advanced vision capabilities. We are also in the process of developing hardware that will allow the robot to run off of much higher voltage to allow even smaller tethers.

On our current robots we are continuing to work with the various sensors in the modules which could be used to achieve much more advanced behaviors, instead of just simple user feedback. This information can be used to estimate which parts of the snake robot are contacting the ground, or to classify different gaits based on sensor signatures.

VIII. ACKNOWLEDGEMENTS

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