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Design and Architecture of a Series Elastic Snake Robot

David Rollinson, Yigit Bilgen, Ben Brown, Florian Enner, Steven Ford, Curtis Layton, Justine Rembisz, Mike Schwerin, Andrew Willig, Pras Velagapudi and Howie Choset

Abstract— **This paper details the design and architecture of a series elastic actuated snake robot, the *SEA Snake*. The robot consists of a series chain of 1-DOF modules that are capable of torque, velocity and position control. Additionally, each module includes a high-speed Ethernet communications bus, internal IMU, modular electro-mechanical interface, and ARM based on-board control electronics.**

I. Introduction

Snake robots consist of a series chain of actuated links, sometimes referred to as hyper-redundant mechanisms [1]. Their small cross section and snake-like motions make snake robots applicable to a diverse set of tasks such as urban search and rescue, mine rescue, industrial inspection, and reconnaissance. This paper details the latest iteration of our lab's modular snake robot, the *SEA Snake*, which builds on the experience and advances of previous generations [2], [3].

Like previous generations, the *SEA Snake* robot consists of a number of identical 1-DOF modules in which the actuated axes are oriented in the lateral and dorsal planes of the robot. Most notably, this latest generation contains a series elastic actuator in each module. This enables compliant motion and fine torque control on each joint. Additionally, each module contains a 32-bit processor and 100 Mbps Ethernet data bus, a 400X improvement in bandwidth over the RS-485 serial communications of the previous generation robot, the *Unified Snake* robot [2]. The modules also have greater torque output, improved sealing, and a rugged tool-free interface. Table I presents the specifications of the *SEA Snake* robot.

II. Related Work

The field of snake robots was founded by Prof. Shigeo Hirose in the 1980's [4]. Since then, work has continued in both the design and control of snake robots. Of note are a long line of snake and snake-like robots by Hirose et al. [5], robots with tactile sensing by Liljeback et al. [6], and full-body tracked robots by Borenstein et al. [7] and McKenna et al. [8]. Work in the field of modular robots [9] has served as an inspiration for the design of the last several generations of our group's snake robots.

Series elasticity was first proposed by Pratt and Williamson [10] as a means of achieving compliant motion and force control with traditional stiff actuators such as highly geared motors. Since then, the design and control of series elastic actuators has been primarily focused on the fields of legged locomotion [11], [12] and humanoid robots [13]. The *SEA Snake* robot uses a rubber-based torsional spring similar to the design presented in [14].

The authors are members of The Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, 15213

Fig. 1: Photo of a *SEA Snake* module. The module is 5 cm (2 in.) in diameter and provides a 1-DOF rotary motion of +/- 90°. Each module has a maximum torque output of 7 N-m, and perform fine torque control via series elastic actuation.

III. Mechanical Overview

Each module possesses a self-contained 1-DOF joint, allowing for a full 180° of rotation. Modules are interfaced together and alternately aligned in accordance with the robot's lateral and dorsal planes. A typical robot consists of 16 modules linked together, with unique head and tail modules.

TABLE I: Overview of *SEA Snake* robot specifications.

Dimensions	Diameter: 5.1 cm Length (module): 6.4 cm Length (full 16 module robot): 1.174 m
Mass	Module: 205 g Full 16 module robot: 3.657 kg
Actuation	Max Torque: 7 N-m Max Speed: 33 RPM
Power	48 V Current (resting): 40 mA Current (max): 600 mA
Communication	100 Mbps Ethernet
Sensing	Angular Position and Velocity Output Torque 3-axis Accelerometer 3-axis Gyro Temperature Voltage Current

Fig. 2: Photo of a *SEA Snake*.

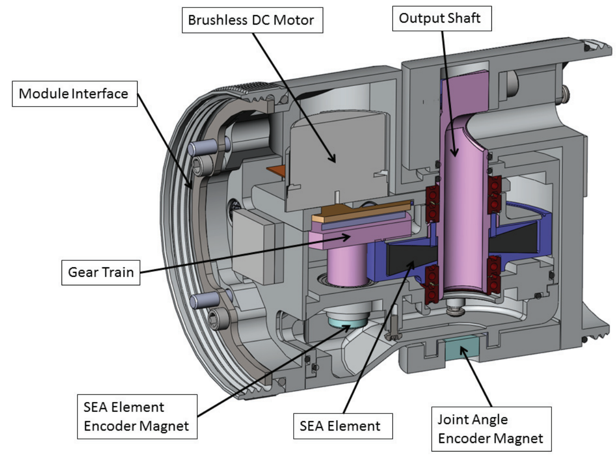

Fig. 3: CAD model cross-section of a *SEA Snake* module.

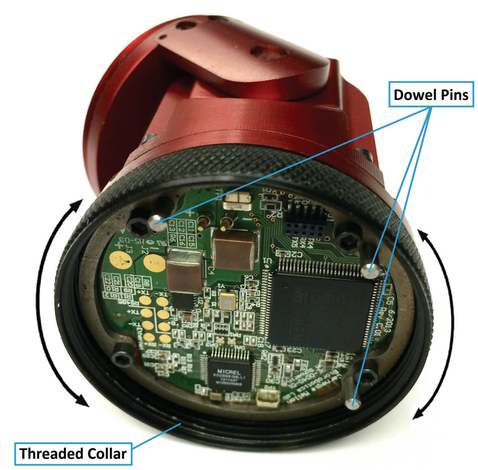

Fig. 4: Photo of the *SEA Snake* module interface. Dowel pins provide alignment while the threaded collar mechanical secures and seals the modules. The electrical connection is made with spring-pin connectors touching target areas on the control board.

A driving design requirement of the *SEA Snake* robot was ease of customization. In addition to the 16 rotary DOF design, modules can be added, removed, interchanged, or replaced with novel mechanisms. Any device meeting the interface requirements can be included in the chain.

A. Motor-Geartrain

The *SEA Snake* modules are driven by a modified Maxon EC 20 flat motor with a nominal speed of 9300 RPM. The steel pinion gear on the motor's output shaft transfers rotation through a geartrain containing 3 steel and brass compound gears. The cumulative gear ratio is 349:1 to create high-torque joints. This motor and geartrain combination provides a maximum output torque of 7 N-m and a maximum speed of 33 RPM. The geartrain has been designed to be back drivable, and as such experiences 2-4° degrees of backlash. While significant, this backlash is of limited consequence to normal snake locomotion, due to the relatively low controller gains on each module, and other modifications that are presented in Section V-C.

B. Sealed Housing

The housing of each module is machined from 7075 aluminum and anodized red to prevent wear and corrosion. Components are densely assembled inside to minimize volume, as illustrated in the module cross-section in Fig. 3. O-rings laid in machined grooves seal the module at each interface. The robot meets IP66 standards, meaning it is splash-proof. Future iterations will aim for IP68, or water submersible. Additionally, an effort was made to minimize external fasteners in the design. The previous snake robot, the *Unified Snake*, has 14 external fasteners per module, while the *SEA Snake* modules have only 4.

C. Modular Interface

The intermodular interface features a rugged, tool-less design. Modules are aligned with dowel pins and matching recesses. A freely-spinning threaded collar, held in place by a retaining ring, is turned by hand to lock adjacent modules together. The collar is knurled to ensure that the surface is easily gripped and can be rotated by hand. An electrical connection is made between two modules with spring-pin connectors on the interface board touching target areas on the control board.

O-rings seal the collar at both ends. Modules can be connected and disconnected quickly and repeatedly. The connections are secure and resist shock and stress. Any device with matching threads, 48V and Ethernet compatibility can be interfaced with a module, allowing for freedom of design and customization. A demonstration of two modules being assembled is in the accompanying video.

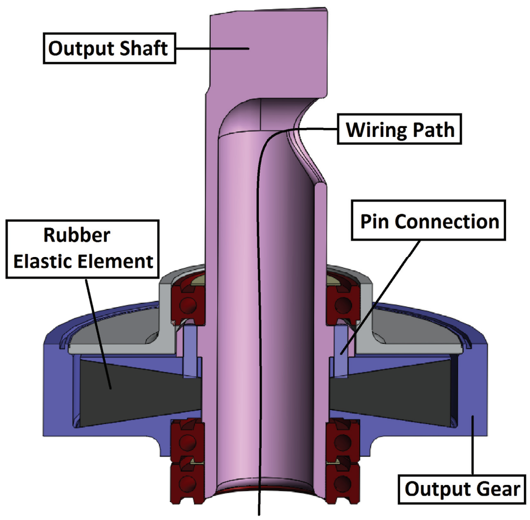

Fig. 5: CAD model cross-section of a module's output shaft assembly. The rubber is bonded to the tapered surfaces of the output gear and top washer. The output shaft is hollow, allowing wires to pass through the center of rotation of the module. A series of dowel pins transfers torque from the spring to the output shaft.

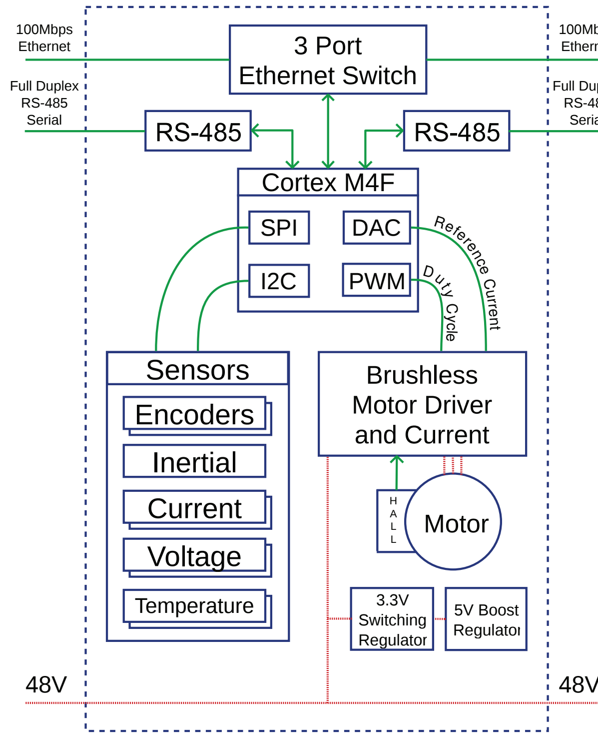

Fig. 7: Module Electronics Block Diagram.

D. Series Elasticity

The *SEA Snake* robot features series elastic actuators. A rubber elastomer bonded between two rigid plates is torsionally sheared during actuation [14]. The elastomer's tapered conical cross section shown in Fig. 5 is similar to the constant-shear-stress design introduced in [14]. The spring design of the *SEA Snake* robot is different in that it is molded directly to the output gear of the module's geartrain. The rigid plate on top is then attached to the output shaft of the system through a number of pins. Another plate is swaged onto this assembly in order to keep the output gear and output shaft aligned with the rest of the geartrain.

The elastomer is molded from Natural Rubber of Shore A Durometer 50. As a torsional spring, its stiffness is roughly characterized by a spring constant of 12 N-m/rad and a maximum rotational deflection of approximately 0.6 radians. Our research is currently exploring ways to estimate the output torque from the elastomer deflection and how to calibrate its parameters online [15].

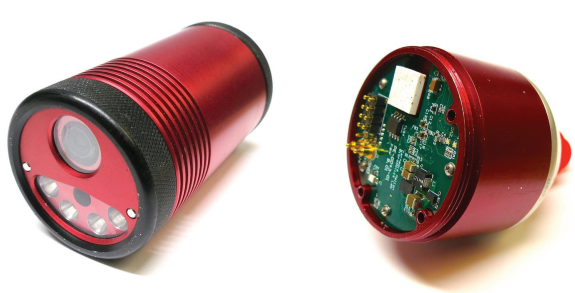

Fig. 6: Photos of *SEA Snake* head and tail modules.

E. Head and Tail Modules

Both a head and tail module were designed utilizing the custom modular interface and they are pictured in Fig. 6. In addition to providing their specialized functions, these modules demonstrate the potential for the use of other modules that could easily be integrated into the *SEA Snake* system.

The head module includes a high-definition camera to provide the user with a live video feed while the four LEDs are available for illuminating darker environments. The head module housing is designed with fins to increase surface area and improve heat transfer from the electronics to the surrounding environment. The LEDs are protected by an o-ring sealed acrylic window while the camera's lens is protected by an o-ring sealed sapphire glass window.

In order to connect a tether to the snake, we custom-designed a tether connector that is sealed and load-bearing. The connector uses keys and keyways to provide a quick and very easy blind connection. Additionally, there are spring-loaded pins within the connector which ensures that the connector's housing bears all of the load. The tail has this connector as well as a slipring integrated within its design.

IV. Electronics Overview

While the electronics in the *Unified Snake* robot were robust, we set out to design the *SEA Snake* robot electronics with a focus on ease of software development to facilitate future research, such as more advanced control algorithms and onboard sensor fusion. To this end, we moved from an 8-bit AVR processor to a 32-bit ARM Cortex M4F running at 7X the clock speed. We also wanted to enable higher frequency external control and sensor feedback and to move from analog to digital video. To satisfy these increased data requirements we moved from a 250kbps half duplex RS-485 bus combined with analog differential video to a switched 100Mbps Ethernet network. Both of these configurations use 4 wires in twisted pairs.

A. Communication

One hindrance to adopting Ethernet in compact embedded devices is the size of the isolation transformers typically required. The solution developed for the *SEA Snake* robot was to integrate a three port Ethernet switch into each module. This kept the wire length down to a few centimeters, which is far shorter than the electrical propagation distance during a 10ns bit period. This allowed us to relax the controlled impedance requirements, and to replace the transformer isolation with capacitive isolation, which has a far smaller PCB footprint. We do provide transformer isolation in the tail module to ensure signal integrity over the tether. In addition to the Ethernet link, each module has a dedicated full duplex differential serial connection to each neighboring module. These serial connections are used for configuration discovery, as described in V-E, and may have additional future applications.

B. Interface

On the *Unified Snake* robot, the module interface was along the axis of rotation, requiring us to create a custom connector to fit around the coaxial magnet used for position feedback [2]. The *SEA Snake* robot design moves the module interface away from the axis of rotation which has many advantages for the electrical interconnection. Because we have a broader, flatter design space for the electrical interface between modules, we use spring contacts that mate with gold plated PCB pads instead of very thin pins. This arrangement is much more tolerant to misalignment and uses connectors that are rated for a much larger number of connection cycles, eliminating the problem of bent, broken, or worn pins. The new design also moves the intermodule wiring terminations as far as possible from twisting motion caused by joint rotation, greatly reducing the risk of fatigue failures at the crimp/solder connections.

C. Motor Control

The *SEA Snake* robot is the first generation of our snake robots to include a brushless motor. We drive the motor with an integrated single chip solution to which we add current sensing. The series elastic member also required the addition of a second magnetic rotation encoder which allows us to measure the deflection. We use a 48V system voltage and overdrive a motor that is nominally wound to run at 36V. This slight over-voltaging with onboard thermal modeling allows the system to safely exceed the continuous operation ratings of the motor for brief periods.

D. Sensors

The *SEA Snake* robot has benefited from rapid development in inertial sensor technology driven by consumer electronics, with the current generation featuring a single chip solution with 3-axis gyro, 3-axis accelerometer, and 3-axis magnetometer. We retained all the other sensing present in the *Unified Snake* robot including voltage and temperature monitoring, and we also added a current sensor to measure the consumption of the entire module in addition to the motor current measuring circuit. This generation also adds externally visible PWM controlled RGB status LEDs, without sacrificing environmental sealing, to provide immediate feedback on module status.

E. Camera Head

The use of Ethernet as the standard communication interface between modules enables the use of readily available, IP security cameras as the basis for the head module of the snake. In the Unified Snake architecture, the video was transmitted over a dedicated, analog bus that supported only standard definition video. By moving to an Ethernet-based camera, the video stream is piped over the same set of cabling as the motion control commands. In addition, the bandwidth that is needed to transmit a high definition video stream is a fraction of the total bandwidth available on the system, paving the way for the use of multiple cameras and additional sensors.

The camera module that has been designed to be used for the *SEA Snake* robot is primarily built around the circuit board and camera that were harvested from a commercially available security camera. A custom circuit board was designed to provide power to the camera, to support additional sensors such as an IMU and a pressure sensor, as well as to control high-brightness LEDs for camera illumination. The camera and electronics were packaged into a simple aluminum tube featuring the same standard mechanical and electrical interface as the regular snake modules.

V. Firmware Overview

The *SEA Snake* robot is a research platform and is constantly reconfigured to support new physical configurations, module types, and sensor types. In addition, researchers with a range of experience must be able to use the platform for research in controls, perception, and planning. To support these research goals, we developed a modular firmware that provides an API supporting both high-level and low-level control abstractions.

A. OS and hardware abstraction layer

The core of the firmware is an RTOS that separates the setup and upkeep of various hardware modules into separate threads. ChibiOS/RT[1] was selected due to its out-of-the-box support for STM32 Cortex processors and a hardware abstraction layer supporting peripherals such as Ethernet (via

[1] `http://www.chibios.org/`

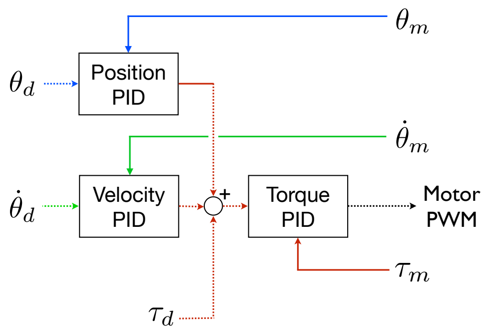

Fig. 8: Cascaded PID controller used for joint actuation.

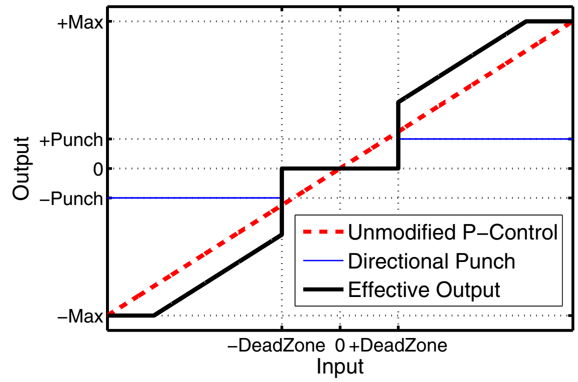

Fig. 9: The modified proportional controller, showing the effect of the deadzone and punch parameters on the output.

the lwIP[2] stack), serial, analog-digital conversion, and pulse-width modulation.

B. Communication

Modules communicate with each other and client software via Google Protocol Buffer[3] messages. Protocol Buffers define an efficient serialization format for typed data structures that is supported across multiple computing platforms and programming languages. We currently use the standard C++ bindings for Protocol Buffers provided by Google. The library includes features such as endianness conversions and support for backwards compatibility between message versions.

We use a common approach in which we define a single "meta"-message that contains several optional sub-messages that encode module parameters and data streams. Any computing environment with Protocol Buffer support can then interact with the robot by sending and receiving streams of these meta-messages. The messages are fundamentally stateless and can be handled transactionally, naturally supporting multiple concurrent connections. Our current implementation is CPU bound and can handle UDP requests at 3-5 kHz depending on the optimization flags during compilation.

The protocol is exposed identically over TCP sockets, UDP sockets, and the serial interface between modules, allowing a variety of flexible communication strategies to be used in various situations, depending on available bandwidth, required level of control, and interface hardware. Modules can propagate local information over the serial interface to neighboring modules, and this is currently used to automatically discover the configuration of the robot. In the future, this could allow simpler "dumb" modules which contain only low-speed microcontrollers to be bridged to Ethernet via neighboring modules to implement low-cost special-purpose functions.

C. Motion Control

Modules support angular position, velocity, and torque control through cascaded PID control, as shown in Fig. 8. Each PID controller runs at 1kHz, although target setpoints may be updated less frequently, typically at 100 - 200 Hz. Independent position and velocity outer loops generate torque commands, which are combined with a desired feed-forward torque to define a setpoint for *output* torque which is maintained by the inner torque controller. The module's output velocity is estimated by numerically differentiating encoder measurements and smoothing the result with a steady-state Kalman filter to reduce noise.

The inner torque controller is able to directly compare desired and actual output torque by directly observing spring deflection as the difference between the two encoder positions. This error is used to compute a PWM command to the motor which applies appropriate torque to the input of the spring and gear train.

In the proportional controller, additional features were added to help compensate for common geartrain nonlinearities, as illustrated in Fig. 9. To prevent oscillations due to gear blacklash and sensor noise, we added a 'deadzone' within which errors are assumed to be zero. To overcome geartrain stiction, a 'punch' factor (directional offset represented by the blue dotted line) was added to help with stiction in the gear train. Finally maximum output limits are also set for each controller. The dashed red line in Fig. 9 shows the output of a theoretical proportional controller, the black solid line shows the output of the actual implementation with these modifications. To mitigate windup of the integral term we limit its output to the difference between the PD output and the a set output level [16]. For example, using this method, if PD control already reaches this level the integral term is reduced to 0.

A common motivation for using SEAs is the ability to store energy from the robots motions, making them theoretically attractive for dynamic walking and running robots. With snake robots, our goal for using SEAs is primarily for torque control and shock protection, with energy storage and recovery being of secondary importance. This has led us to tune the control of the *SEA Snake* actuators less aggressively, and with more damping, than is typically done with SEAs [11], [17]. To characterize the torque bandwidth of a SEA Snake module, we clamped the output and commanded sinusoidal oscillations of increasing frequency, as shown in

[2] `http://savannah.nongnu.org/projects/lwip/`
[3] `https://code.google.com/p/protobuf/`

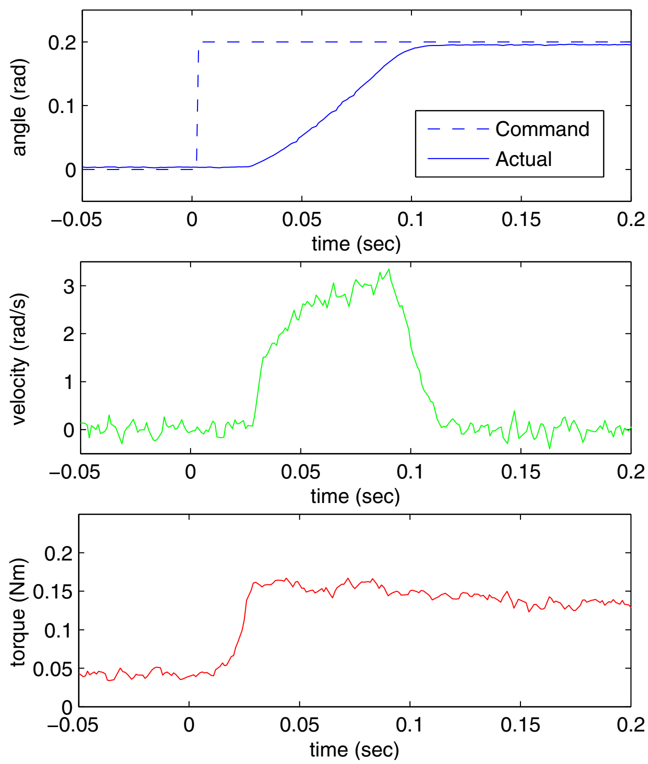

Fig. 10: The response of the angular position (top), velocity (middle), and torque (bottom) to a step input in position. This was performed on an unloaded module, and as such the torque readings mostly reflect the static friction of the module's shaft seals.

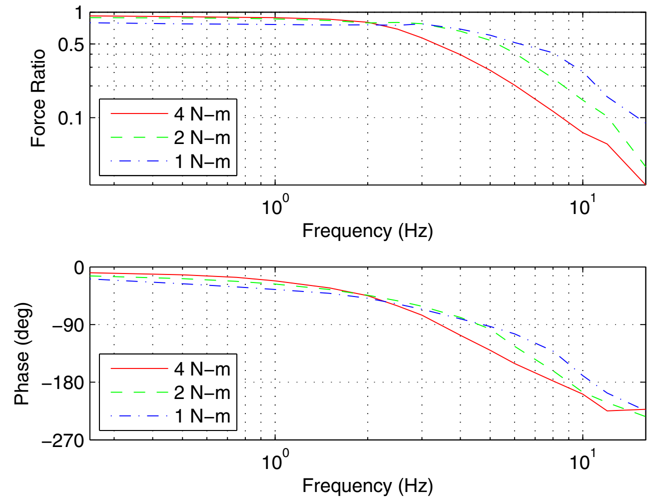

Fig. 11: Torque bandwidth of the a *SEA Snake* module. The actuator's torque bandwidth is limited to about 2Hz (the natural frequency of the the internal motor and spring), although at smaller forces it can provide slightly faster actuation. The controller and SEA are tuned to be damped in order to avoid oscillations during operation.

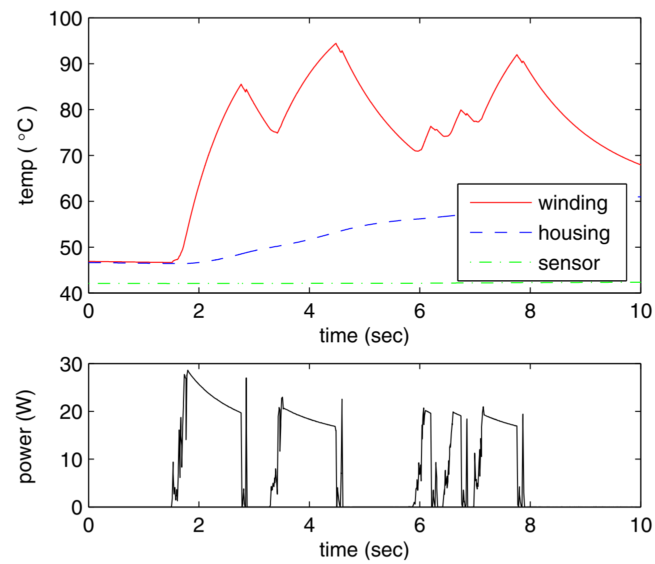

Fig. 12: Top: Estimated temperature of the motor windings in a *SEA Snake* module, based on the thermal model. Bottom: Dissipated motor power based on the measured current draw and the resistance of the motor's windings.

Fig. 11. At large torques, the bandwidth of the actuator is limited to the natural frequency of the internal motor inertia and the elastic spring, approximately 2 Hz.

D. Thermal Management

An important challenge for mobile robots is to safely extract as much performance as possible out of their actuators. For brushless motors, the primary limitation on performance is heat buildup in the motor windings [18]. We use online estimation of each module's motor winding temperature to fully exploit the motor's performance envelope beyond the continuous duty ratings. Figure 12 shows a plot of the power dissipation and estimated temperature of the motor windings while the motor is repeatedly stalled. The estimated winding temperature is based on a temperature sensor near the motor, the sensed current draw of the motor, and a model of the internal thermal resistances and capacitances of the motor similar to the method presented in [19]. Additionally, critical electronic components are sunk to the module using thermal pads, and the board level temperature is monitored to ensure safe operation.

E. Addressing and Configuration Discovery

The Internet Protocol (IP) and Ethernet require each module to have 2 addresses, a fixed 6-byte MAC address and a variable 4-byte IP address. We automatically derive the MAC address by combining our manufacturer's ID with a hash of each processor's unique ID. The IP address is requested on startup via the Dynamic Host Configuration Protocol (DHCP). Clients can discover active modules using UDP-broadcast.

In addition to Ethernet, we use the RS-485 serial connections between modules for a local exchange of address information, allowing us to determine the configuration of the robot at runtime. With this system, instead of having to manually program the position of each module in the robot, we can now seamlessly switch modules in and out of the robot without additional overhead or manual configuration.

F. Torque Estimation

To improve the torque sensing of the modules, the linear spring constant of the elastic element is calibrated online

[15]. The material properties of rubber are sensitive to environmental changes such as temperature, duration of use, and previous peak deflection amplitude. Our approach uses recursive filter and a heuristic function that takes into account the motor's motion and current draw. By selectively sampling motor current only when it is trusted as an accurate estimate of torque, the spring constant is automatically adjusted over time. The module's estimated output torque is calculated at 1 kHz, using the updated linear spring constant and the observed spring deflection. This estimate is the 'measured' torque that is used by the inner-loop torque PID controller (Fig. 8).

VI. Conclusion and Future Work

The *SEA Snake* robot currently consists of a series of extremely capable 1-DOF modules. However, there are a number of avenues of future work. These consist of ongoing improvements to the existing modules, mostly in firmware, and the development of different modules that share the electrical, mechanical, and software interface detailed in this paper.

A. Motion Control

Improvements continue to be made to the low-level motion control of the modules. In particular, future work will look at more sophisticated modeling and trajectory generation that takes into account the motor and spring dynamics, compensating for backlash [20], and different formulations of the torque, position, and velocity control loops [21].

B. Additional Modules

The most exciting avenue for future work will be the creation of a number of new modules for the snake robot, based on the modular interface. Possible future modules include different head modules with cameras and other exteroceptive sensing, battery and wireless communication modules for tetherless operation, tracked or wheeled modules for improved mobility in rough terrain, and 'hockey puck' modules that expose general purpose inputs and outputs to easily test external sensors like force sensing skins.

Finally, we feel the architecture we have developed is general-purpose enough that topologies other than a snake may be feasible. For example, connecting a number of these modules together to a central chassis would enable the rapid prototyping of a field-ready legged robot with torque and position control on each of its joints.

VII. Acknowledgements

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