Laboratory on Legs: An Architecture for Adjustable Morphology with Legged Robots

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ABSTRACT

For mobile robots, the essential units of actuation, computation, and sensing must be designed to fit within the body of the robot. Additional capabilities will largely depend upon a given activity, and should be easily reconfigurable to maximize the diversity of applications and experiments. To address this issue, we introduce a modular architecture originally developed and tested in the design and implementation of the X-RHex hexapod that allows the robot to operate as a mobile laboratory on legs. In the present paper we will introduce the specification, design and very earliest operational data of Canid, an actively driven compliant-spined quadruped whose completely different morphology and intended dynamical operating point are nevertheless built around exactly the same "Lab on Legs" actuation, computation, and sensing infrastructure. We will review as well, more briefly a second RHex variation, the XRL platform, built using the same components.

Keywords: Legged Robot, Modular Payload, Flexible Spine, Robot Architecture, Actuator Selection

1. INTRODUCTION

Despite images of agile humanoid or animal-like robots long held in the public imagination, legged robots capable of autonomous dynamic locomotion over general terrain have only recently been developed*. At the same time, advances in rapid mechanical prototyping,[2] non-traditional assembly and integrated fabrication methods[3] and the adoption of novel materials[4] are all transforming the landscape of mechanical design for robotics, including platforms intended for such challenging applications. The era of modular robotics has almost arrived,[5] wherein even high performance, dynamic operation can be approached using general morphological modules.[6] However, morphology, fabrication, and assembly represent only a few of the many dimensions along which robotic modularity is desired. Different tasks also entail very different power regimes and impose diverse sensory requirements. Not even the specification, much less design techniques for realization, nor still less the modularization of such realizations are well studied within the robotics literature. The integration and operability of sensorimotor functions in laboratory robotics, even the most modularized, still seems to rely on layers upon layers of home-built, one-off interfaces, code, and electronics. Because the problem of specifying a task's required sensorimotor endowment remains so poorly understood, attempting the modularization of a robot's sensing, actuation, and computational resources raises interesting new opportunities for the research community.

This paper describes our initial attempt at a modular architecture for sensorimotor integration that encourages an effort to specify, design around, and explore the empirical consequences of selecting the distribution of a robot's bit rates and power densities. This problem is distinct from—rather than in opposition to—the distribution of its mechanical degrees of freedom, their material realization, and method of assembly which we touch upon only incidentally (thereby enjoying the greater mechanical robustness and selectable power densities of point-solution mechanisms not yet offered by any morphological modules yet proposed). Toward the goal of easily reconfigurable perceptual processing, control function, and scientific data collection in dynamic legged robots, we propose a modular sensorimotor architecture comprising a shallow integration layer for commercially

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* Some of the material in this paper was first presented in a technical report[1] that presents in greater detail the specific design choices for X-RHex (the first robot to utilize the component-based architecture described).

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available units of actuation, computation, and sensing, assembled to produce a variety of high performance legged robotic platforms.

The RHex robot[7] is an example of an early dynamical machine built as a point solution, a hexapod with a single, unrestricted rotary actuator per leg. While mechanically simple, this design has achieved a variety of interesting locomotion tasks, including walking, running,[7] pronking,[8,9] leaping and flipping,[10] climbing stairs,[11,12] recovering from failures,[13] and even running upright on (modified) rear legs.[14] Due to its success, subsequent robots have duplicated or adapted the RHex morphology, including: Research RHex;[7] Rugged RHex,[15-17] a hardened, commercialized version built by Boston Dynamics, Inc.; EduBot,[18] a classroom machine developed at the University of Pennsylvania; AQUA,[19] an amphibious version developed at McGill University; and SensoRHex,[20] a recent update from Bilkent Univerity focused on sensor integration.

We first describe in this paper the application of this modularized architecture for sensorimotor integration to the development and implementation of the two newest descendants in the line of RHex robots, X-RHex and X-RHex Lite (XRL). These new designs represent a thorough and substantial update of the Research RHex platform,[7] illustrating the benefits of modularity by incorporating commercial off-the-shelf (COTS) components— unavailable at the time of RHex's invention a decade previous—to produce compact yet powerful designs featuring the reuse of actuation, computation, and sensory components. Second, we illustrate the generality of the modules by documenting the development of and earliest operational data produced by a (morphologically and functionally) entirely new robot, "Canid", whose power distribution scheme introduces a mechanical energy storage element as an essential new design component. Specifically, Canid represents the first prototype of a quadruped with an actively driven compliant spine intended to increase dynamic locomotion performance. While this prototype does not specifically benefit from emerging new technologies for rapid mechanical prototyping[†], we believe it exemplifies the opportunities and benefits of modular architectures for sensorimotor integration in prototyping for dynamic legged robots[‡]. We emphasize that the term "sensorimotor integration" is intended to encompass not merely the perceptual, motor and computational resources required to run a set of targeted behaviors on an autonomously functioning machine but additionally connotes the complement of data logging, collection and export applications required to promote their study. The architectural design for this collection of functions yields what we term a "laboratory on legs", allowing us to not only rapidly prototype the robot designs, but also develop robot behaviors and study their performance through a component-based software architecture coupled with a modular payload specification allowing the rapid exploration and characterization of new, empirically vetted concepts in legged robotics.

2. A LABORATORY ON LEGS

Using the approximate mass and length scales of Research RHex[7] as a target, we have developed modular units of actuation, computation, and sensing, comprising COTS components inserted at as high a level of functionality as possible without compromising performance or flexibility of use. In this section we highlight a few of the key design decisions underlying this architecture, offering some brief commentary regarding the selection and integration of specific components for actuation, power, control, and sensing. A more detailed account of the development of the architecture and its application to one platform is available in the X-RHex Technical Report.[1]

2.1 Actuator Selection

Motor sizing for legged robots poses challenges distinct from those presented in most other systems that perform mechanical work. Traditional methods,[23] involve selecting an actuator with an appropriate power rating geared to work on a load specified at one or a very few fixed operating setpoints (paired speed torque operating values). For example in order to select a motor for an industrial robot arm, the maximum weight of the payload will

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[†]It might be argued that the reliance on cheap, relatively fast turn-around water jet cut frame components and compliant leg and spine materials offers some useful lessons in effective mechanical prototyping, but this is beside the point of the present paper.

[‡]While RHex's most dynamical regime of operation appears to crucially entail the appropriately timed transfer of battery energy into its leg spring compression,[21] there is a large quasi-static operational regime as well wherein the motors simply act to turn the half-circle shaped legs.[22] In contrast, Canid's compliant spine precludes the possibility of any useful quasi-static regime.
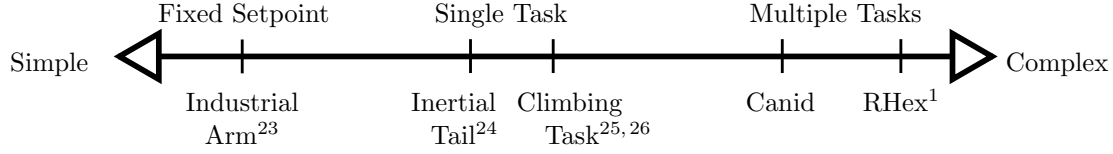
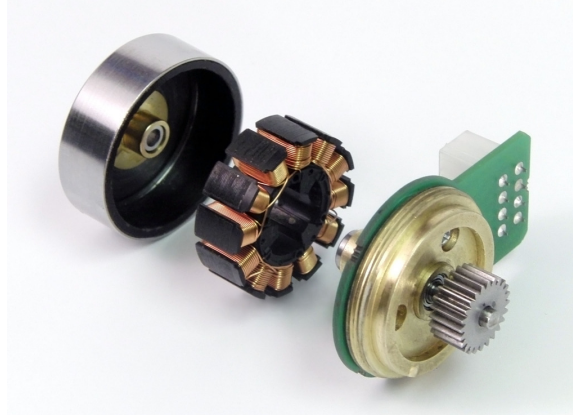Figure 1: A summary of the different types of motor selection techniques with some example domains.

Figure 2: A disassembled view of the brushless motor.

dictate the required torque, which when combined with the desired speed of operation will provide a set operating point, whereupon the choice of a motor (and gearbox) that can meet this demand is straightforward.

As suggested by Figure 1, systems required to deliver multiple or more complex work loops will not present the designer a single operating setpoint. For example, the robotic tail task,[24] to be discussed further in Section 2.4.2, does not entail any particular minimum torque specification (e.g. as might be required were there a need to work against gravity), but, instead, imposes an overall completion time for repositioning a specified inertial load, in a manner most succinctly expressed by a dynamical control problem whose solution imposes a non-trivial functional constraint on the motor parameters. In the somewhat more complex problem setting of vertical running,[26, 27] the imposition of a target task dynamics conferred by an identified template[28] provides a dynamical work-loop specification. It can be shown that these dynamics offer a precise enough task specification as to imply the necessity of additional passive dynamical elements in the power train mitigating peak power requirements otherwise unachievable by any COTS actuator.[25] In such settings, task specification via target dynamics (typically along with various problem-specific constraints) still yields a tractable design problem, affording direct comparison of the relative performance on some task metric of very different motors by relaxing the requirement that they all complete the task in the same way (i.e., via some artificially imposed trajectory on the speed-torque plane).[26]

However versatile robots such as RHex or Canid are from their very inception intended to perform different tasks at different times. Balancing the performance requirements and constraints of multiple tasks performed in a variety of operational environments precludes using either the fixed setpoint or single dynamical task specification methods. RHex[7] must actuate its limbs over an unusually wide operational range, including slow speed activities requiring large leg torques, such as clambering over rocks and climbing stairs, as well as high speed activities with moderate torques, like running at high speeds or walking with high duty factor gaits, all without overheating.[1, 22, 26, 29] There are few non-robotics applications in which a motor operates at both its stall torque and its no-load speed within a short period of time. This spectrum of motor selection tasks is summarized in Figure 1.

In the absence of a general design methodology for robot motor sizing, the most reliable understanding of a RHex-like machine's operating regime comes from Research RHex data. Therefore the leg motors used in

X-RHex and related robots were chosen by comparison to those of Research RHex, as explained in further detail in the technical report.[1] This led to the selection of a 50W brushless "pancake" style motor, shown partially disassembled in Figure 2, which dramatically exceeds the Research RHex motor in its achievable stall torque (limited here by the motor controller) and maximum continuous torque (limited by thermal considerations), though it has a slightly lower no-load speed (limited by bus voltage). In principle, the X-RHex motor is capable of much higher power output than its predecessor. However, motor thermal constraints pose real operational limitations and are harder to assess without a specification of the target task domain. The parameters for our chosen motor are shown in Table 3.

Nearly as important as the selection of the motor is the selection of a gearbox to accompany it. There are a variety of techniques to choose the gear ratio optimally for fixed setpoint or single task scenarios,[26] however absent a precise dynamical task specification, they do not apply. We initially chose an 18:1 gearbox as this results in dramatic, across-the-board improvements to the speed and torque capabilities. However, when tested in X-RHex, the motor current had to be restricted to 9A peak for thermal safety. This handicap manifested itself during high-torque, slow speed maneuvers such as standing up or turning in place. In order to boost torque and shift peak power output to lower speeds, a 28:1 gearbox with an identical form factor is used instead for X-RHex, while the 18:1 (or in a different variant a 23:1 version) is still used for the lighter XRL robot. The increased gear ratio ensures that the motors are able to supply about the same amount of torque as Research RHex at low speeds and significantly more torque than Research RHex at moderate speeds, with top speed suffering slightly. A further comparison of the motor performance, and careful discussion of the thermal issues, is given in.[1]

2.2 Electrical Subsystems

The electrical systems of our modular architecture communicate over the Universal Serial Bus (USB)[§], while relying upon COTS components for general computation, network communication, and actuator control. Additional custom components, for power management and motor controller interfaces, have been developed and applied in a variety of form factors to encourage reuse across multiple robot designs.

Contemporary COTS motor controllers offer a wide range of capabilities and high performance while limiting the necessity for custom designs, thus shortening development time. Impressed by its efficacy in the the RiSE V3 design,[30] we chose the Advanced Motion Controls (AMC) DZRLATE-20L080 motor controller[¶] as an appropriate match to our power and weight needs that also supports both brushed and brushless motors. This motor controller closes a low-level feedback loop internally at a rate of 20kHz, permitting rapid and accurate command of motor current — albeit inaccessibly to the user — highlighting the tradeoff between flexibility and ease of use when designing with COTS components. In addition to control loops, these controllers handle the sinusoidal commutation of brushless motors, and provide sensor feedback for position, voltage, current, and temperature of the motor every 2.5–4ms (depending upon total information in each update), vital proprioceptive measurements which (other than position and temperature) have heretofore been unavailable in the RHex family of real-time robot controllers.[13, 29]

The next layer of our electronics subsystem is a controller interface board that relays communication between a central CPU and the motor controllers, breaking out standard connectors for motors and sensors. The simplicity of this design affords easily varied instantiations of this board: we have constructed versions that incorporate one, two, and three individual motor controller interfaces, providing a variety of form factors for different applications. A battery management board provides the final piece of the electronics infrastructure, allowing a safe and monitored connection to a 10-cell lithium polymer battery, chosen for high power and energy density for a given weight. No suitable COTS solution was available that could handle the current and voltage of these batteries in a small form factor, as these batteries are very large relative to the space allocated to battery monitoring and protection, and so a custom board is required. The battery supply is protected by an output diode that allows multiple boards to be connected in parallel without damage. In addition to monitoring the total battery voltage, this board includes COTS 5V and 12V DC power regulators for onboard components, and is able to communicate with the central computer via USB. The motor controller and battery interface boards, while custom designed

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§Universal Serial Bus Community Website, http://www.usb.org
¶ADVANCED Motion Controls DZRALTE-020L080, http://www.a-m-c.com/products/dzr.html

and manufactured, are based on manufacturer provided reference schematics and described in more detail in the X-RHex Technical Report.[1]

The selection of USB as the common communication bus confers great benefit respecting the interface to additional electronics (both those arising from the various necessary embedded systems within the robot, as well as potential payload sensors, many of which standardize on USB), but incurs some unfortunate cost in actuator control bandwidth, due to slight delays as USB hub chips buffer data for up to 1 ms before sending. This delay increases latency such that real-time 1kHz control is not possible with our architecture, a tradeoff justified in our view by the benefits arising from so widely adopted a bus standard and mitigated by the consequent ability to distribute highest bandwidth loops out to the capable COTS motion control boards.

2.3 Software Architecture

An additional component of our laboratory on legs is a software architecture, *Dynamism*[‖], that encourages rapid prototyping of robot behaviors through distributed real-time control along with scripting language bindings. The core of Dynamism consists of a real-time database,[31] implemented in the C programming language, to allow high frequency sensing and control with great flexibility. This database, a set of key-value pairs encompassing the entire state of a robotic system, can be read and written at rates appropriate for real-time control, including potential synchronization over a network interface. As such, with only minor changes to the robot software, real-time control can be performed within the same process or amongst multiple processes on the robot host, or even amongst multiple hosts on a network, allowing great flexibility in rapidly developing real-time software systems. Furthermore, unlike message passing systems commonly used within the robotics community[32, 33], the real-time database approach provides a compendium of system state available to the distributed pieces of software, while maintaining timing constraints on database operations.

Coupled with language bindings for scripting languages such as Python[**] and MATLAB[††], robot behaviors can be rapidly prototyped, with real-time control performed over network connections. Furthermore control code can be readily ported between languages with minimal changes necessary due to syntax differences. Compared to alternative software approaches commonly found within the robotics community, Dynamism offers great flexibility with respect to language choice and network topology, constrained only by the requirement that all components of robot state be updated and exchanged via the real-time database.

For the laboratory on legs interface and control code, we have developed software modules for the motor controllers, battery management nodes, various sensors, and robot behaviors. Each component consists of a self-contained library, typically written in C, with a small set of code to interface with data from the Dynamism database. In addition, the robot software takes advantage of the scripting language bindings by storing configuration data and some control commands within Python scripts, including separate configuration scripts for individual platforms, robots, and experiments.

2.4 Modular Payload System

Development of advanced sensor-based behaviors on portable, highly-dynamic legged robots is a primary goal of our laboratory on legs. While essential sensors (motor and battery feedback sensors and inertial measurement units) are often located within the interiors of the robots we have designed, the choice of additional sensors largely depends upon robot activity, yet the specifications of a desired sensor package may vary with changing research needs and advancing sensor technologies. To address this issue, we introduce a modular payload architecture to allow users to easily change payloads and rapidly develop behaviors in natural, outdoor environments as easily as on a lab bench, our "laboratory on legs". Fig. 3 shows an example configuration of the X-RHex robot carrying a large number of payloads. X-RHex has been used for experiments with up to 5kg of payloads,[22] and has at least stood up with 10kg, though naturally there will be degraded performance with excessively heavy payloads.

[‖]Dynamism, `http://kodlab.seas.upenn.edu/Gch/Dynamism`

[**]Python, `http://www.python.org/`
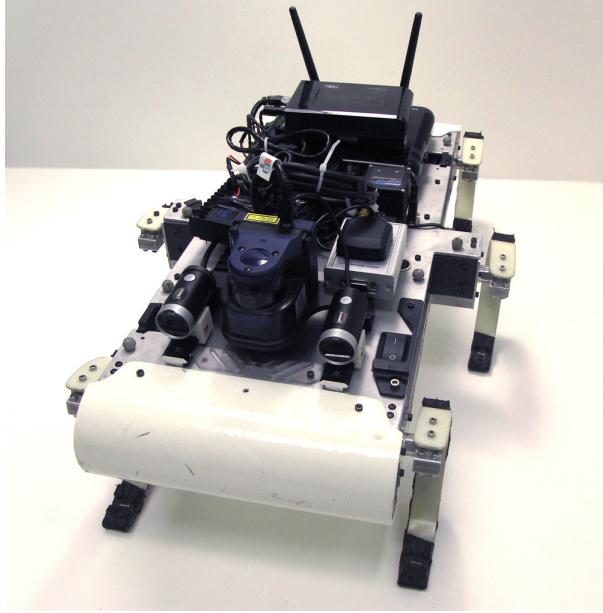
[††]MATLAB, `http://www.mathworks.com/`

Figure 3: X-RHex outfitted with multiple payloads attached to Picatinny rails. Payloads shown include (from front to back) two forward-looking cameras, a laser scanner, a GPS, an IMU, a payload computer, and a wireless access point to boost wireless signals.

2.4.1 Payload Specification

Our X-RHex and XRL robots are equipped with two Picatinny rails[34] as a universal payload mount. While commonly found on handheld weaponry, Picatinny rails have been adopted by robots such as DragonRunner[35] and PackBot,[36] among others. Two parallel rails, 40 cm long and spaced at a center-to-center distance of 14 cm, span the length of the each robot's body. Payloads equipped with Picatinny mounts can be placed on a single rail (off-center) or with mounts spanning both rails.

In addition to a standardized mechanical mount, our design provides an electrical interface to sensors and payloads through a series of standardized connectors placed on its top frame. Multiple USB connectors and an Ethernet port allow direct communication between payloads and the robot's on-board computer. Power is provided via an 8 pin DIN locking connector[‡‡] that is capable of delivering various voltages to payloads, providing up to 2A at 5V, 2A at 12V, and 4A at battery voltage (37-42V), all generated by the onboard battery management board. The pinout for this connector is specified in Table 1 (see manufacturer's datasheet for pin locations and specifications).

Pin	1	2	3	4	5	6	7	8
Function	12V Gnd	5V Gnd	37V Pwr	5V Pwr	37V Pwr	12V Pwr	37V Gnd	37V Gnd

Table 1: Pinout of payload power interface, based on manufacturer's pin numbers

2.4.2 Payloads Used

The modular payload system permits researchers to switch, with minimal downtime, between distinct experiments that use the same mobile platform. Here we describe several existing applications, as well as future application scenarios we envision, in addition to those payloads previously described.[1] Many sensors can be added as payloads, including cameras, laser scanners, RGB-D sensors, and more. A laser scanner and an IMU have been

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[‡‡]CUI Inc. part number SD-80LS, `http://products.cui.com/CUI_SD-80LS_Datasheet.pdf?fileID=7839`

(a) X-RHex   (b) XRL

Figure 4: Two instantiations of the RHex robot, utilizing our modular architecture.

used to enable the robot to autonomously navigate multifloor stairwells and forested hillsides,[12] while unpublished work* has shown the application of the X-Box Kinect RGB-D sensor for person following.

Computational payloads have also been integrated, including a rail-mounted Mac Mini, for instance, to provide additional computational power beyond the PC/104 computer within the robot. One significant advantage for computational payloads is access to processing via GPUs, such as the use of the Nvidia CUDA[37] programming architecture for intensive computation, a focus of potential future work.

In addition to sensory and computational payloads, the robots can also support actuator payloads, such as a modular tail.[24] This tail mounts onto the rails at any point along their length, includes the same motor and motor controller as the legs, and interfaces via the payload power connector and USB. The payload system can also support manipulators or other "arms".

3. X-RHEX AND X-RHEX LITE (XRL)

3.1 Mechanical Design: X-RHex

The main objectives for the mechanical design of X-RHex (Fig. 4a) were to improve frame durability (both in resistance to fatigue and impact) and overall robot serviceability while achieving similar or better performance to past robots. The overall dimensions (57x39x7.5 cm) were intended to maintain as much similarity to Research RHex (54x39x13.9 cm) as possible. The most notable difference is that the X-RHex frame is much shorter at a total height of 7.5cm. Lateral inter-leg distances are identical, but longitudinal inter-leg distances are slightly greater to fit the internal components. Research RHex leg design[11, 38] was preserved, and since the leg mounts are nearly centered on an overall thinner body, the robot can operate with greater ground clearance even when in an inverted state.

The X-RHex frame is light and stiff to optimize locomotive performance, and sufficiently strong to protect hardware and maintain structural integrity even when subjected to severe impacts.[1] A multi-component frame is constructed using top and bottom cross pieces, spanning the length and width of the body's frame, coupled with motor mount assemblies to connect between top and bottom frames (thus dual-purpose as both motor mounts as well as structural members, a departure from the design of Research RHex). Carbon fiber panels were added to increase frame stiffness and to protect the robot from obstacles while not significantly increasing body weight.

Within the body of X-RHex are cavities to slot load two 10 cell lithium polymer batteries, as well as locations for two electronics stacks (each controlling 3 motors) as well as the PC/104 control computer. Payload interfaces, through standardized plugs and Picatinny rails, are located on the top face of the robot.

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*See video `http://www.youtube.com/watch?v=kOd_kaAUjr4`

Attribute	Research RHex	Rugged RHex	Edubot	X-RHex	XRL
Body Height (cm)	12–13.9	14.8	6.3–10.8	7.5	10.0
Overall Width (cm)	39	46.5	34	39	40.5
Body Length (cm)	54	62.3	36	57	51
Leg to Leg Spacing (cm)	20	23.5	15.5	22	20.5
Ground Clearance (cm)	11.5	10.6	7–9	12.5	11.0
Inverted Ground Clearance (cm)	9.5	10.6	N/A	12.0	11.0
Leg Diameter (cm)	17.5	19.5	10.8–11.7	17.5	17.5
Total Weight (kg)	8.2–8.9	15	2.5–3.6	8.6–9.5	6.7

Table 2: Comparison of Physical Properties.

3.2 Mechanical Design: XRL

X-RHex Lite (XRL)[39, 40] (Fig. 4b) is a design study in methods of utilizing the same laboratory on legs components as X-RHex, in a slightly different configuration to simplify fabrication, while minimizing weight. XRL is designed with once again near identical spatial dimensions as Research RHex, but is constructed via an interlocking design of flat aluminum pieces, all machined using a waterjet cutter, rather than CNC milling. Surrounding the robot's frame is a complete shell of carbon fiber (similar to "Shelly-RHex" variant[16]), serving both as a protective shell as well as a structural member, particularly for stiffening loads upon the cantilevered leg mounts.

XRL, as a lighter weight cousin of X-RHex, uses only a single battery compartment, provides space for the same PC/104 control computer, and utilizes three electronics stacks (each controlling two motors), spaced evenly throughout the body, all mounted on the waterjet cut frame. Through the use of a USB bus as the common communication method within the robot, these changes in electronics are easily performed across robots.

3.3 Comparison with Prior RHex Robots

In this section we compare X-RHex and XRL with prior RHex-like robots[†], with a focus on Research RHex,[7] but also considering Rugged RHex[15–17] and EduBot.[18, 41] Each of these platforms was developed through multiple iterations — differences between these versions account for the range of values presented for certain parameters. This section is not intended to demonstrate the superiority of any one platform; instead we aim to highlight the similarities and differences between platforms. Further discussion on the differences between various versions of RHex is presented in.[1]

Compared to the original RHex, the X-RHex and XRL robots have about the same footprint, and are a little shorter in body height (See Table 2). The scale of Research RHex has proven to be an excellent compromise and suitable for both the laboratory and field; its inter-leg distances and frame geometry make it adept at traversing obstacles (including stairs), while still being small enough and light enough to be easily carried by a single person. X-RHex was designed with size and mass similar to Research RHex to capitalize on these advantages of scale. XRL, as the name suggests, is lighter than either of those variants (20-30% lighter), while maintaining the same legs as both and the same motors as X-RHex.

The actuator selection for X-RHex, summarized above and explored in more detail in,[1] resulted in the selection of a nominally 50W brushless motor with a 28:1 gear ratio (see Table 3). Because it is lighter, while using the same motors as X-RHex, XRL instead uses a lower gear ratio (either 18:1 or 23:1). Both X-RHex and XRL have many per-leg sensors in addition to an encoder, including current (I), voltage (V), and temperature (T), and, for X-RHex, include an absolute encoder on the output shaft that eliminates the need to calibrate the leg orientations on startup.

Both X-RHex and XRL use 10 cell lithium polymer batteries, which provide great energy density (as shown in Table 4). X-RHex is capable of carrying either one or two batteries internally, doubling its power capacity without sacrificing any additional space, hence affording much longer runtime than any other RHex version.

[†]There is insufficient information available in the open literature to provide a comparison to the SensoRHex[20] or AQUA[19] platforms.

Attribute	Research RHex	EduBot	X-RHex	XRL
Motor Type	Brushed	Brushed	Brushless	Brushless
Listed Motor Power (W)	20	11	50	50
Gear Ratio	33:1	24:1	28:1	18:1–23:1
Motor and Gearbox Mass (g)	292	126	288	288
Encoder Type	Optical	Optical	Magnetic	Magnetic
Encoder Precision (cnt)	500	512	1024	1024
Leg Calibration Sensor	Hall	None	Absolute Encoder	None
Other Motor Sensors	T	None	I, V, T	I, V, T
No-Load Speed (Hz)	6.86	6.45	5.95	7.24–9.26
Achievable Output Stall Torque (Nm)	8.1	1.7	15.4	9.9–12.6
Max Power Output (W)	111	17	342	342
Cont. Power Output (W)	30	9.9	84	84
Max Motor Power Density (W/kg)	380	135	1190	1190
Max Robot Power Density (W/kg)	78–84	28.2–40.8	216–240	306
Cont. Motor Power Density (W/kg)	103	79	292	292
Cont. Robot Power Density (W/kg)	20.4–22.2	16.8–24.0	52.8–58.8	75.2

Table 3: Comparison of Motor Properties. Rugged RHex uses 70W brushed motors, however the remaining parameters are not available and its column has been left out. Note that while motor power densities are listed for an individual motor, the robot power density compares the sum of all 6 motors to the entire robot mass (such as during a leaping task).

Attribute	Research RHex	Rugged RHex	EduBot	X-RHex	XRL
Battery Type	NiMH	NiMH,LiIon	LiPo	LiPo	LiPo
Bus Voltage (V)	24	48	14.8	37	37
Battery Capacity (Wh)	72–120	86.4	20–30	144	83.2
Battery Quantity	1 set of 3	1 set of 2	1–2	1–2	1 set of 2
Battery Dimensions (mm, each)	157x47x25	127x112x63	66x27x34–50	136x70x43	104x34x41
Battery Mass (g, each set)	1200–1475	1760	122–160	880	588
Robot Mass Dedicated to Batteries (%)	14.6–16.6	23.4	3.6–8.9	10.2–18.5	8.8
Battery Energy Density (Wh/kg)	60–81	49	158–187	164	141
Robot Energy Density (Wh/kg)	8.1–13.5	11.5	5.8–16.7	16.7–30.3	12.4

Table 4: Comparison of Battery Properties. Rugged RHex is assumed to use its two batteries in series.

XRL, intended primarily for the exploration of agile behaviors, sacrifices total battery capacity in exchange for a lighter body than X-RHex[‡] which in contrast is better suited for long missions with many payloads.

As mentioned before, the electronics, including motor controllers, battery management, and CPU, are the same on XRL and X-RHex, with additional information available in technical report format[1] on comparisons with past versions. Performance tests, such as runtime and peak efficiency, have not been completed on XRL at the time of this printing,[40] however given that it uses the same motors as X-RHex on a lighter body we expect a noticeable performance benefit.

[‡]XRL is so light it can carry additional batteries as payload and still end up with lower total mass than most other RHex variants.
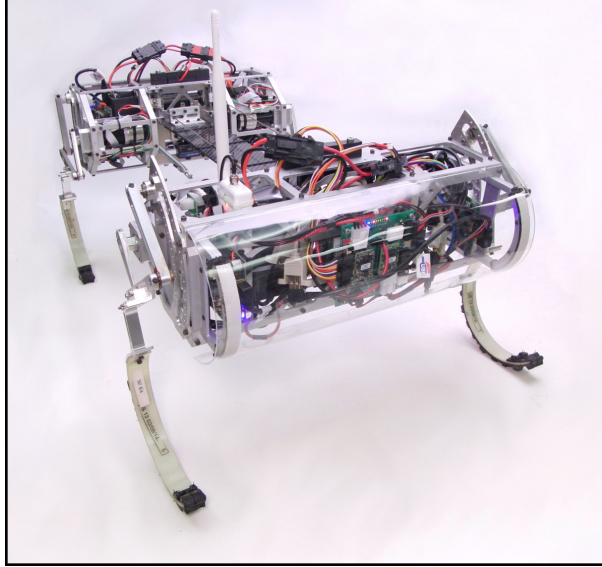
Figure 5: The Canid robot, composed of two body sections connected with a actively-driven, compliant spine.

4. CANID: A QUADRUPED WITH AN ACTIVE, COMPLIANT SPINE

The Canid robot (Figure 5) is a quadruped designed to test hypotheses regarding dynamic bounding using an actuated compliant spine mechanism. Canid was created under the Robotics Collaborative Technology Alliance (R-CTA) between the US Army Research Laboratory (ARL) and the University of Pennsylvania amongst other institutions[§]. By utilizing the modular components of actuation, computation, and sensing developed for the X-RHex robots, Canid has been rapidly prototyped using existing components, resulting in a faster design cycle and initial build. Similar in component design to RHex, both having six motors and precisely one motor per leg, Canid replaces RHex's two middle legs with a doubly actuated, compliant spine for the specific purpose of exciting high speed bounding gaits.

We hypothesize that locomotion with a high-power actuated compliance located at the body core can offer significant speed and endurance benefits. Arguably, the speed limit repeatedly encountered throughout our experience in tuning up RHex's steady state gaits[42] was determined by the no-load speed of the recirculating legs of the alternating tripod gait[¶]. Yet gearing up RHex actuators any further would compromise performance in the high-torque, quasi-static regimes listed in the introduction. The design of Dynoclimber, a bioinspired vertical runner, was predicated upon placing an appropriate compliance in parallel with the actuators so as to lower the required peak torque load, allowing a choice of gearing that permitted the higher no-load speeds needed to achieve the targeted animal-similar limb frequencies.[25] Similarly, one of the central hypotheses motivating the Canid design is that placing a compliant element in series with a spine actuator will supplement the forces it can apply to the body masses that must be necessarily limited by the gearing required to achieve the high no-load speeds we desire.

Bounding and galloping quadrupeds are the fastest mammalian runners[43] and a growing volume of robotics research has focused on this style of locomotion. Raibert pioneered the first dynamical quadruped,[44] while Buehler *et al.* produced a power autonomous version[45] that ran at 2.5 body lengths per second (BL/s) with a specific resistance of $\varepsilon = 1.4$. Additional results with RHex, using only four of RHex's legs to perform a bound (the two legs inactive), produced similar results of more than 3 BL/s and $\varepsilon = 2.1$.[46] In the Canid design, we explore the value of re-directing those two motors' power outputs into actuated body compliances that amplify

[¶]The certainty with which such claims can be made is diminished by the very complicated relationship between the gait parameters, the work imparted upon the robot's COM by the stance legs, the aerial phase that results, and, hence, the time interval available for leg recirculation in flight[21]

Attribute	Canid	Attribute	Canid
Body Size (each) (cm)	14x21x40	Body Weight (no batteries) (kg)	10.3
Overall Length (cm)	78	Battery Capacity (Wh)	166.4
Ground Clearance (cm)	19.5	Battery Weight (kg)	1.17
Leg to Leg Distance (cm)	47	Max Robot Power Density (W/kg)	179
Spine Size (cm)	0.32x7.6x44	Cont. Robot Power Density (W/kg)	43.9
Spine Cantilevered Stiffness (N/m)	161	Robot Energy Density (Wh/kg)	14.5

Table 5: Physical Properties of the Canid Robot.
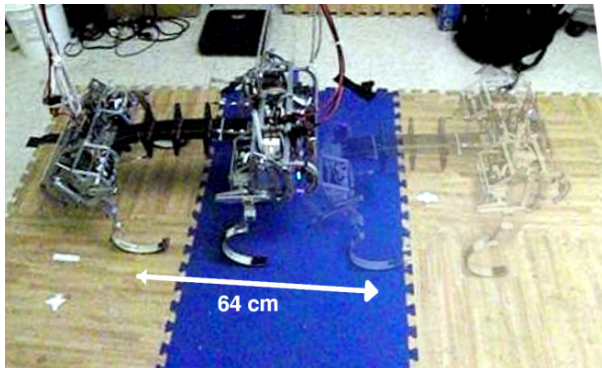
Figure 6: The Canid robot about to perform a leap. The post-leap image is superimposed to demonstrate an estimated, presently working, leaping distance of 64 cm (in 0.6s) or 0.82 body lengths (at 1.4 BL/s).

the force at the desired speed of locomotion according to the overarching "spring assisted actuation" hypothesis just described.

The body of Canid is similar to XRL, built from waterjet cut aluminum pieces, interlocking as a frame on which electronics and actuators are mounted (see Table 5 for dimensions). Canid is separated into two nearly identical bodies with an actuated and compliant spine between them. Antagonistically mounted cable-drive motors allow the spine to flex both up and down, storing (and retrieving) energy with the spine as necessary. A carbon-fiber leaf spring comprises the principal spine component, with a specific mode of bending in the sagittal plane, matching the style of bending commonly used by mammalian quadrupedal runners. Additionally, Canid's legs are actuated via a four-bar mechanisms, providing a variable transmission to affect the speed and torque of legs throughout a stride, aiming for high torque and low speed during the nominal stance stroke of a leg with fast recirculation during nominal swing stroke.

At a systems level, even as Canid consists of a different morphology from RHex, it is able to make use of the same actuators, electronics, and software components as both X-RHex and XRL. The electronics (identical to those utilized in XRL) are mounted within its frame, including a total of 6 motor controllers, across the two body segments. While each body segment contains its own battery power and battery management board (and thus each is isolated in terms of power), a single USB cable traverses the length of the spine to allow a single PC/104 computer to communicate with both body segments. Because of the modularity allowed by the X-RHex architecture, Canid is essentially two robots connected by a flexible spine and a single USB cable. With several different modes of motor excitation desired in the operation of Canid—executing open-loop trajectories akin to RHex gaits vs. operating with closed-loop torque sensing and control—the options available via the COTS motor controllers provide a great deal of benefit without much additional cost.

Early empirical results[||], leveraged upon our experience tapping into actuator power density through the AMC drive electronics accrued during past experiments with X-RHex and XRL, have shown that Canid is capable of appropriately explosive motions, launching from standstill into a leap in the air from which it lands after a suitably extended aerial phase in a trajectory of postures that suggest an effective steady state bounding gait

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[||]For these initial trials, the batteries are not carried on board.
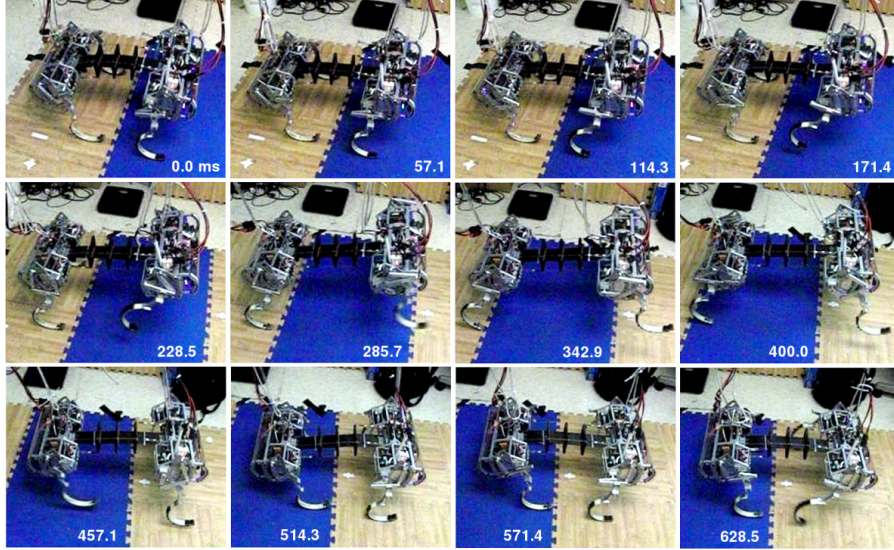
Figure 7: Time ordered images from a leap sequence using the Canid robot.

may be possible. Preliminary leaping results are shown in Figures 6-7, in which the robot preloads energy into its elastic spine before releasing the spring potential, while thrusting its legs, to vault into the air. Ongoing work is attempting to assess the locomotive characteristics, as well as to investigate possible steady state bounding gaits that exist for this class of mechanisms and can be supported by the Canid sensorimotor endowment.

5. CONCLUSIONS

We have introduced a series of robot designs all built using a common modular architecture of actuation, computation, and sensory components. This laboratory on legs infrastructure has encouraged the rapid prototyping and development of both dynamic legged robot designs, as well as robot behaviors, in consequence of the favorable morphologies, sensorimotor capabilities and behavior development environment this modular architecture affords. We describe both the X-RHex and X-RHex Lite robots as updated instantiations of the RHex design, and introduce the Canid robot, with its entirely novel morphology and power distribution scheme, developed using identical systems level components.

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