Rapid Pole Climbing with a Quadrupedal Robot

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***Abstract*— This paper describes the development of a legged robot designed for general locomotion of complex terrain but specialized for dynamical, high-speed climbing of a uniformly convex cylindrical structure, such as an outdoor telephone pole. This robot, the RiSE V3 climbing machine—mass 5.4 kg, length 70 cm, excluding a 28 cm tail appendage—includes several novel mechanical features, including novel linkage designs for its legs and a non-backdrivable, energy-dense power transmission to enable high-speed climbing. We summarize the robot's design and document a climbing behavior that achieves rapid ascent of a wooden telephone pole at 21 cm/s, a speed previously unachieved—and, we believe, heretofore impossible—with a robot of this scale. The behavioral gait of the robot employs the mechanical design to propel the body forward while passively maintaining yaw, pitch, and roll stability during climbing locomotion. The robot's general-purpose legged design coupled with its specialized ability to quickly gain elevation and park at a vertical station silently with minimal energy consumption suggest potential applications including search and surveillance operations as well as ad hoc networking.**

I. Introduction

We are working toward the goal of dynamic legged robots, capable of rapid and nimble locomotion, on challenging vertical terrains in addition to complex level ground surfaces. This paper highlights a series of mechanical improvements that have allowed a prototype robot to exhibit rapid upward locomotion on a wooden telephone pole without recourse to specialized appendages or idiosyncratic kinematics that would preclude general level ground operation as well.

The key innovation of this design is a variable transmission leg linkage that allows climbing-targeted leg motions—high torque during stance, high speed during leg recirculation—with near-constant motor velocity, while maintaining the general purpose morphology of a functional quadruped. A second contribution is the design of a separate variable transmission actuator, the leg abduction/adduction degree of freedom, for which a compliant linkage allows the actuator to modify its transmission ratio to deliver normal forces suitable for gripping climbing surfaces. These actuator improvements, combined with a specialized climbing behavior, accommodate the daunting requirements of rapid 90° vertical climbing.

The design of a climbing robot with general terrain capability is a current challenge in robotics. While many robots have relied upon surface-specific attachment mechanisms—such as magnets ([1], [2]), suction ([3], [4], [5]), or the use of handholds to grip ([6], [7])—we believe the most useful climbing robots will be capable of locomotion on a variety of surfaces, particularly common building materials. Accordingly, we have built a series of successful robots, capable of quasi-static climbing[1] on building surfaces such as brick and stucco, as well as climbing the trunks of trees [9], [10], [8]. The current prototype, RiSE Version 3, shown in Fig. 1, is built with the goal of adding to the RiSE V2 behavioral repertoire the capacity to climb a similar diversity of surfaces with a much faster "dynamic" gait. Indeed, this new machine is designed with enough power per leg—an order of magnitude over RiSE Version 2—to theoretically produce an aerial phase during vertical locomotion. In this early report, we document our preliminary success in achieving significantly faster climbing with the new platform. We remain convinced that subsequent effort will establish that the new machine exhibits dynamical climbing behavior as well, however issues of substrate attachment and detachment must be resolved

Fig. 1: Dorsal and lateral views of the RiSE Version 3 climbing robot. Four powerful legs, each with two actuators, grip a wooden telephone pole using claw-like appendages.

[1]RiSE Version 2 [8] has typically achieved its peak recorded speeds of 10-15 cm/s with a 3.8 kg, 40 cm long body on a carpeted surface, however with much slower speeds on surfaces such as tree trunks or poles.

to determine whether stable aerial phases are possible on natural, unprepared surfaces with this platform.

Robotic pole climbing has applications ranging from cleaning [11] to surveillance and networking operations. Compared to solutions involving kinematic graspers specifically designed for a pole [12], [11], or to snake robots that wrap around poles to climb [13], [14], we have designed the RiSE robot with a goal of reproducing ground reactions forces observed in climbing insects [15]. While we have chosen to utilize legs for their general applicability to locomotion strategies, this paper focuses specifically on the task of pole climbing. The RiSE robot is, however, capable of many other forms of legged locomotion.

In this paper, we focus on the novel mechanism designs that allow the legged robot to climb rapidly, exploiting kinematically programmed legs, driven by power-dense actuators, with compliance properties that match requirements of the climbing task. With our prototype machine, we demonstrate experimental results of sustained rapid locomotion, climbing up a wooden telephone pole at 21 cm/s.

II. RiSE Version 3

Given a basic goal of rapid pole climbing, we focus on several critical design details that attempt to maximize power delivery during locomotion. Foremost is the design of actuation and transmission systems that deliver sufficient power and force to support our desired climbing speed target of 25 cm/s while minimizing weight. These actuators are designed into a unique body morphology that affords effective foot placement on a pole. To achieve these goals we have built a prototype four legged robot which measures 98 cm long (including a 28 cm tail appendage), weighs 5.4 kg, and makes use of tuned kinematic and force sensitive transmission elements to deliver both the high force and power required by climbing while simultaneously enabling rapid limb movement when recirculating individual legs.

A. Mechanism Design

The morphology of RiSE V3 (shown in Figs. 1 and 2) consists of four legs, each containing two active degrees of freedom, attached to a body with an additional central degree of freedom to change posture. The fore hips have lateral spacing of 27.5 cm (51.5 cm from toe to toe with legs fully sprawled), while rear hips are separated by 18 cm (toe distance of 39.5 cm when sprawled). When considering a typical pole diameter of 25 cm, this design allows front legs to partially reach around a pole, thus combatting the natural tendency due to gravity for the robot to pitch back during climbing. The robot's centralized body degree of freedom further allows the robot pitch to be adjusted during climbing. With an adjustable body, combined with the four actuated legs, the robot has kinematic freedom and range of motion to allow effective climbing of poles. The two degrees of freedom on each leg are oriented in the hip abductor/adductor and in the traction directions, carving a near cylindrical shape for each toe's workspace, relative to the body (highlighted for the front left leg in Fig. 2). The hip abductor/adductor allows legs to move $+30°$ to $-90°$ from horizontal, driven by a 30W brushless DC motor (Maxon 200142) with a 60:1 attached to the motor output. The traction degree of freedom uses a 50W brushless motor (Maxon 251601) with a 25:1 gear reduction. Both actuators additionally make use of kinematic linkages to generate variable gear ratios useful for climbing. The body degree of freedom allows for $\pm 90°$ of pitch offset between the front and rear body segments and is controlled by a 50W brushless motor (Maxon 251601) with 40:1 fixed gear ratio.

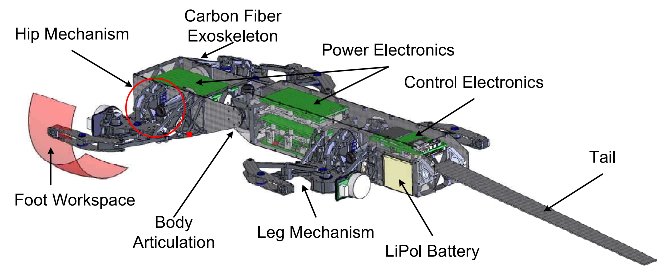


Fig. 2: Overview of the RiSE V3 robot design. Batteries, computation, and actuators are placed near the center of the body. Leg linkages are used to specifically design the workspace and torque/speed generation of each leg.

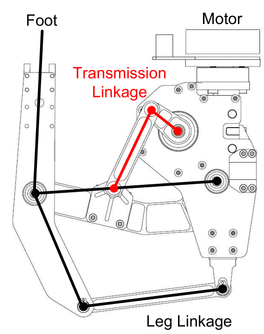


Fig. 3: A single left leg, seen along the dorsoventral axis, showing the single degree of freedom traction linkage that dictates fore-aft toe position. A single joint spins to generate a toe motion that mechanically produces high torque during stance, high speed during leg recirculation.

Traction actuator: The primary design constraint for the traction actuator is that feet must perform a significant amount of mechanical work during stance, carrying a large fraction of body mass, yet rapidly recover during flight, subject only to foot and leg inertia. With a single fixed transmission, compromise must be taken in either one or both of these two dramatically-different behavioral phases. Instead, we have chosen to utilize a non-linear reciprocating transmission system to program into the mechanism the distinct high force and high speed behaviors. Fig. 3 shows a schematic representation of this transmission (an overhead view of a single left leg shown in Fig. 2). The motor, seen at the top of the figure, is coupled through a worm gear to drive the transmission linkage which in turn drives the leg linkage and the foot. The resulting kinematic relationship between

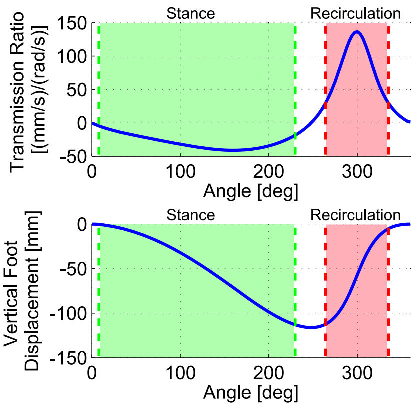


Fig. 4: Transmission ratio of the leg linkage (top) and vertical foot displacement (bottom). The linkage (Fig. 3) is designed to produce a lower transmission ratio, and consequently high torque, during typical stance regions, with a fast recovery during typical recirculation.

motor angle and foot position as well as the associated transmission ratio are shown in Fig. 4. The net result is that the motor can deliver high forces at motor angles ranging from 0 through 225 degrees, while it can produce extremely high foot velocities between 275 and 350 degrees. The reciprocating nature of the transmission linkage makes it possible to reduce overall motor power requirements because the linkage obviates the need for motor reversal during each stride. Properties of the linkage and transmission were chosen specifically for modification of transmission ratio, as well as for the nearly linear toe path produced by the traction actuator.

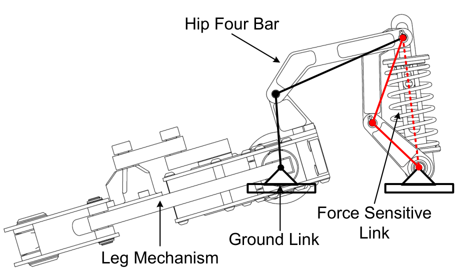


Fig. 5: Leg, as seen along along anteroposterior axis, showing the compliant hip mechanism that governs leg grip on pole. A force-sensitive link both adds compliance to the joint, but also modifies the transmission ratio of the motor based upon load. Under high loads (when a leg is in stance) the motor is able to generate greater forces, as is necessary for gripping a pole while climbing.

Hip abductor/adductor actuation: Design of the other leg actuator faced a similar challenge of needing to generate high forces during stance to ensure adhesion yet also needing to produce fast leg/foot motion during flight. Unfortunately the uncertainty about the location of the pole relative to the robot body makes a fixed kinematic solution, such as was used for the traction degree of freedom, unworkable. To overcome this we have chosen to make use of a force responsive variable transmission system modeled after the one described in [16]. The transmission, shown schematically in Fig. 5, utilizes a compliant element within the four-bar structure to effect a nearly 2:1 change in the transmission ratio of the linkage as a function of foot force. This "automatic gear shift" effectively doubles the available force which the robot can apply to squeeze the pole, ensuring ample normal force at the contact point in order to avoid slipping. Furthermore this mechanism acts as a series compliance for the abduction/adduction degree of freedom, and protects the transmission elements and motors from shock loads associated with rapid touchdown of a foot. The implementation of this degree of freedom includes an additional angular sensing element to measure the deflection of the transmission both to provide accurate measurements of foot position to the system as well as to provide a measurement of foot force.

A single body degree of freedom (Fig. 2) is located between body segments, and allows the robot to modify its posture. This actuator enables steering adjustments of pitch during climbing, and allows the possibility of transitions between horizontal walking and vertical climbing. As only small adjustments of body pitch are required from stride to stride, the transmission is relatively simple, consisting of a single worm gear attached to the actuator.

Each actuator on the robot uses a worm stage as its primary gearing. This use of worm gears directly attached to motor shafts makes all joints non-backdrivable and allows the robot to maintain joint positions without requiring work by the motors themselves. This becomes extremely useful in the case of a climbing robot as the ability to maintain ground reaction forces and grip a surface, while not requiring motor activity, allows to robot to be deployed in a surveillance or network task, in which the robot effectively "perches" for long periods of time without consuming actuator power.

B. Electrical Design

RiSE Version 3 contains all of the necessary components for fully autonomous operation. Currently, communication with an operator laptop is achieved through a wireless 802.11 link. All computation of joint commands and actions, however, are performed on-board the robot.

The core of the electronics suite is a CPU carrier PCB that hosts a compact form factor PC, mini-PCI wireless card (802.11b/g), IDE compact flash module (on which the commercial real-time operating system, QNX, is installed), as well as breakout connections for standard PC I/O, such as a keyboard and VGA. The backbone of the CPU carrier is an FPGA-based PCI interface that connects the PC to hardware timers, as well as four channels of CAN-bus (Controller Area Network) running at 1 MHz for all onboard communication. The CAN-bus connects the CPU to nine brushless motor drives (Advanced Motion Controls DZRALTE-012L080), each capable of driving a motor at 55V, 6A continuously.

System power is provided from a single 2Ah 50.4V LiPol battery pack that is capable of sourcing 50 Amps continuously, 100 A peak. The average runtime observed for our climbing platform, on a single battery, has been approximately 30 minutes.

C. Climbing Gait and Behavior

While many different gaits, each conferring a distinct style of locomotion, can be used to achieve legged mobility, we highlight one specific gait chosen to produce fast, yet stable, locomotion for pole climbing.

Our chosen gait, taking advantage of the fore-aft differentiation between RiSE's front and rear legs, keeps some subset of legs in contact with the cylindrical surface at all times (in order to assure a good grip and maintain stability), while recirculating the legs as rapidly as possible to maximize speed.

The duty factor of a gait is the percentage of stride phase that a single leg spends in stance. Based upon the timing by which individual legs recirculate, allowable ranges of duty factor may be found to produce stable locomotion. In general, higher duty factors produce more stable locomotion, by keeping more legs in contact with a surface at all times. A crawl gait, one that recirculates all legs individually—minimum duty factor of 75% with a quadrupedal robot—produces the most stable locomotion possible. A quadrupedal trot or bound, however, being "virtual bipedal" gaits, may reduce duty factors as low as 50%, at the cost of fewer legs maintaining contact with the substrate. With both a specified stance stroke length as well as a maximum leg velocity in recirculation, a lower duty factor gait produces faster locomotion in two ways: the leg moves faster by covering the stance stroke in less phase, and the greater percentage of a stride dedicated to flight allows the stride rate to be increased more before hitting any motor speed limits.

The RiSE robot, with symmetric front and rear legs, is designed for a high-speed bound gait. In early bounding experiments, the robot experienced pitch back from the pole when using such a gait, during the phase in which both front legs recirculated. A crawl gait, however, does not recirculate the front legs together, yet travels much slower and lacks the lateral stability of the bound. Our early experiments with crawl gaits resulted in more stable locomotion, but with severe yawing, due to lack of symmetry.

We have chosen to use a gait halfway between a crawl and a bound, a form of *proto-bound*. This gait moves the back legs together in a simultaneous, symmetric thrust upward, as the bound gait does, yet recirculates front legs individually in order to maintain front leg contact with the pole, as a crawl would. The end-result gait—half bound, half crawl—produces locomotion that is faster and more symmetric than a crawl, yet is more stable than a bound by not allowing the robot to pitch back.

Fig. 6 presents a visualization of the gait timing. While the gait uses a rather large duty factor of 80%, it does so with stability in mind, and the robot can still rapidly recirculate its legs, due to the kinematically programmed fast-in-flight motion of the crank mechanism.

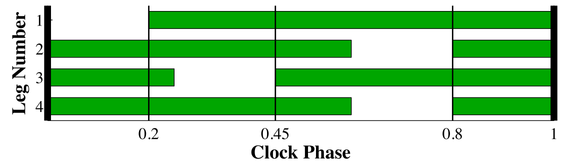


Fig. 6: The relative timing of stance (shaded) and recirculation for the climbing. The front legs (1 and 3) recirculate individually, with back legs moving together. At high speed, the robot repeats this gait at 1.75 Hz, once every 0.57 seconds.

The geometry of the gait motion is designed to sharply penetrate a wood surface, so that the robot will maintain traction during climbing. The non-backdriveable nature of the robot's actuators means that any opposing ground reaction forces are transmitted against the mechanism itself, and not into the motor, thus reducing excessive work or heat generation by the robot's motors.

III. Experiments and Results

A. Experiment Procedure

Our prototype of RiSE V3 has few sensors other than joint proprioception (magnetic encoders), thus precluding the use of sensor-based feedback such as the force-sensitive controllers we have utilized for previous versions of RiSE [17], [8]. The pole climbing behavior follows a fixed joint trajectory using a PD controller. Tuning such a trajectory and controller involved manual experimentation and study of logged robot data.

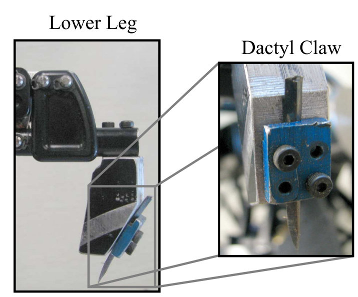


Fig. 7: Claw used for climbing, and foot mounting apparatus.. Claws, refitted post-mortem needles, are used to penetrate the wood surface.

For climbing a wooden telephone pole, the robot uses sharp claws that penetrate the wood.[2] The claws currently used for the robot are engineered from post-mortem surgical needles, and are sufficiently hardened and sharp for the task at hand. Front claws, with the fore legs wrapping around the pole, are angled to align with the expected ground reactions forces, angled inward and slightly downward. Hind claws angle down to dig straight into the wood when generating

[2]We thank Mark Cutkosky and Alan Asbeck for design ideas and early example prototypes of claws for this machine.

thrust upward. The tip of each claw has a triangular cross-section, and on-going research is studying their effectiveness versus conical tips.

For tuning the behavior, the first priority is establishing a plausible gait geometry; legs must clear the wall during recirculation, attach to the wall firmly but without significant reactive force in attachment, generate upward thrust consistently during stance, and detach without slowing the robot. Climbing failures occurred when, for example, a single leg would attach or detach too abruptly, with the resulting internal body forces causing a different leg to accidentally detach. Trajectories with overly slow velocity during attachment incurred limited penetration of a dactyl into the wood, resulting in poor traction force capability. Furthermore, PD tracking gains used through the gait required gain scheduling based upon expected actuator load, stance legs requiring significantly higher gains to achieve sufficient tracking. These improvements to the gait were engineered from simple observation of the robot during hands-on testing.

We iteratively tested the climbing behavior, studying the effect of gait parameters such as gait geometry, duty factors, and overall stride rate, upon the speed and success of the resulting locomotion. Certain tuning issues were discovered only by studying logged robot data. Gain tuning was greatly enhanced by eliminating oscillation in joint commands, while studying motor currents was useful to prevent potential overheating. For example, a deadband was implemented on the abduction/adduction motor during stance to prevent unnecessary current draw. A leg in stance that is gripping a pole generally encounters some PD tracking error. With leg compliance in series with a non-backdrivable actuator, however, a constant current command is unnecessary, thus the deadband helps to prevent motors from potentially overheating. Throughout robot experiments, no motors were burnt out.

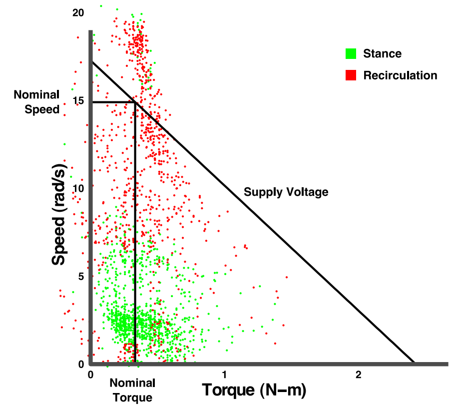
B. *Results*

The RiSE Version 3 robot, with its carefully designed mechanism and tuned behavior has repeatedly exhibited reliable, high-speed climbing of a wooden telephone pole. Fig. 8 shows multiple frames from a video of RiSE climbing a wooden telephone pole at an average speed of 21 cm/s.

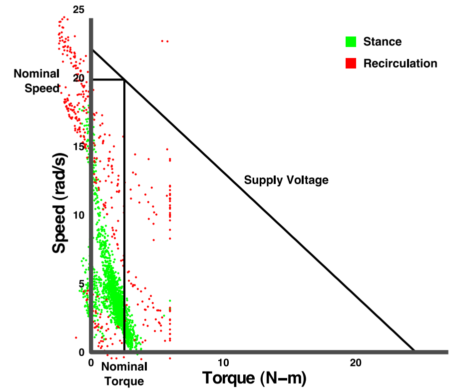
Fig. 9 compares speed-torque measurements for two versions of the RiSE robot, each from a single motor used to thrust the body upward. With the significant mechanical redesign, as well as introduction of energy-dense motors, the current version of the robot is sufficiently powerful to climb at high speed, and is not currently near its theoretical limit. One item to note in Fig. 9b is the large amount of negative work being performed. This data is from an early climbing behavior with PD gains that caused some ringing to occur during recirculation. As such, a leg overshoots and must brake occasionally, thus generating work.

A comparison of robot speeds on similar surfaces is shown in Table I. The RiSE V3 robot, using a chiefly open-loop behavior travels approximately an order of magnitude faster on a similar surface. The fact that RiSE V2 greatly increased speed using a feedback behavior suggests that future behavior improvements, incorporating task-level feedback, will be useful to achieve even faster speeds with the V3 platform.

Using this climbing behavior, RiSE V3 has climbed 5 meter distances up a telephone pole with repeated success, the robot producing a seemingly-stable limit cycle behavior that maintains pitch, roll, and yaw. Pitch-back is prevented as the robot always keeps at least one front leg attached at all times. The production of fairly symmetric lateral forces, and the use of stiffening wing actuators, passively maintains both yaw and roll while climbing. This passive stabilization, programmed into both the gait and the robot mechanism, allows the robot to climb meters of distance over geometri-



(a) RiSE Version 2, Leg 1 motor



(b) RiSE Version 3, Leg 1 crank motor

Fig. 9: Comparison of speed-torque plots for two versions of RiSE. Green data indicates stance, red recirculation. Version 2 of the robot [8] is severely speed limited, particularly during recirculation. RiSE Version 3 operates within allowable range of the motor.

TABLE I: Comparison of climbing speed. †: behavior utilizes task-level feedback.

Date	Version	Surface	Speed
March 2005	V1.5	Tree trunk	1 cm / s
April 2006	V2	Tree trunk†	5 cm / s
May 2008	V3	Telephone pole	21 cm / s

$t = 0.00$ $t = 0.33$ $t = 0.67$ $t = 1.00$ $t = 1.33$ $t = 1.67$ $t = 2.00$ $t = 2.33$

Fig. 8: A time-lapse of RiSE climbing. The robot covers half a meter of distance in 2.33 seconds, averaging above 21 cm/s.

cally uniform (cylindrical) but texturally highly variable hard wood grain surfaces without behavioral feedback.

IV. Conclusions and Future Work

We describe a series of mechanical improvements that are critical for development of a high performance behavior. Various elements—mechanical leg linkage and transmission designs, powerful motors, and a gait-based climbing behavior—demonstrate rapid climbing with a robotic prototype.

RiSE Version 3 is not yet near its energetic limits, thus we expect future studies into the use of bound gaits to produce far faster locomotion speeds. Such a gait will require studies into claw-surface interactions, in order to determine methods of claw attachment and detachment that are reliable and that reduce pitchback and slipping. Furthermore, the incorporation of sensor-based feedback will help the robot recover from locomotion errors such as a slipping foot or the robot pitching back. We also expect to add the ability to negotiate non-uniform cylindrical structures, such as tree trunks and branches. Finally, we are pursuing the development of automated transitions between level ground locomotion and vertical climbing as necessary.

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