

DETC2010-28153

LOCOMOTION STRATEGIES AND MOBILITY CHARACTERIZATION OF A SPHERICAL MULTI-LEGGED ROBOT

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ABSTRACT

Mobile robotics has seen a wide variety of mechanisms and strategies for motion in diverse terrain. Some robots employ rolling, some use legs for walking, some can hop, and some are capable of multiple of these modes. In this paper, we present the latest Robotic All-Terrain Surveyor (RATS) prototype as a unique design that can emulate a variety of locomotion modes by virtue of its geometric design and type of actuation. The novel robot has a spherical body the size of a soccer ball with 12 legs symmetrically distributed around its surface. Each leg is a single-DOF pneumatic linear actuator, oriented normal to the spherical body. Thorough investigation of this prototype's mobility and actuation behavior has demonstrated the feasibility of tipping, hopping, and prolonged rolling locomotion by altering the actuation patterns of its legs. Here we summarize the experimental results of this characterization and present an understanding of the system's performance limitations in an effort to draw insight for controlling its movements. We also discuss the effectiveness of RATS mobility strategies for varied terrains in light of initial testing on flat surfaces.

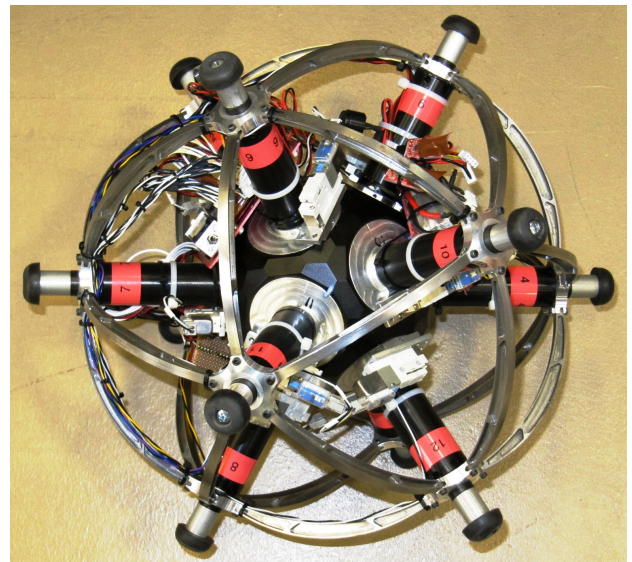


FIGURE 1. RATS IS A 12-LEGGED PNEUMATIC ROBOT DESIGNED FOR MULTI-MODAL LOCOMOTION.

INTRODUCTION

Planetary exploration and locomotion has historically been the domain of wheeled robots. Such platforms may be stable and reliable, but there are serious drawbacks when these robots

must maneuver through rough, uneven terrain with obstacles. As a result, there has been strong interest in recent years to develop robots that combine other forms of mobility to better handle diverse terrain.

The *Robotic All-Terrain Surveyor* (RATS) is a new approach

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to the hopping robot concept. It is a spherical robot designed for multiple modes of locomotion using its 12 single-DOF pneumatic piston legs. The robot is powered by a high-pressure tank at its center and its piston legs are evenly spaced and oriented radially, normal to the surface of the sphere.

RATS is unique in its diverse modes of locomotion resulting from these simple actuators. The robot has demonstrated ability to hop for obstacle avoidance and execute discrete tipping/walking. Simulation results indicate high-speed rolling/running is possible using more rapid, closed-loop sequencing of leg actuations. Its round shape makes rolling more efficient, and the symmetry inherent in the RATS design means there is no “right-side-up.” It has no need for self-righting mechanisms or procedures, because the robot is stable and equally capable of motion regardless of its initial orientation.

To understand the advantages of the RATS mobility system, this paper first reviews other examples of robot mobility with similarities to individual traits of RATS. We then present a description of the novel design of the RATS mechanism and analyze its mobility characteristics. The physical behavior of the system has been explored through a series of trials and experiments. The results of this testing illuminate the strengths and deficiencies of the prototype design and provide insight for the development of control strategies for mobility. We also present some initial locomotion testing performed on flat terrain and discuss the effectiveness and appropriate application of the various RATS locomotion modes based on these results.

RELATED WORK

Different terrains call for different locomotion techniques. In flat terrain, wheeled locomotion is the most efficient method. Once the terrain becomes discontinuous, such as traveling through boulder fields or in craters, the ability to interact with the ground at discrete locations becomes valuable. The following sections describe some alternative approaches to rolling or hopping that have similarities with the RATS concept. We also include a brief summary of previous iterations of RATS prototype development.

Spherical Rolling Robots

Instead of using wheels, spherical robots employ their entire body exterior as a rolling surface. In the past, they have been propelled by shifting the center of mass [1] or by manipulating the angular momentum of internal flywheels [2]. Such robots significantly increase their maneuverability over that of wheeled platforms while potentially reducing the footprint of the robot to allow navigation in tighter spaces. Spherical symmetry also enables effective locomotion without regard for orientation. Unfortunately, they still face the same challenge of obstacle avoidance that impedes wheeled robots in rough terrains.

Single-Leg Hopping Robots

A large variety of single-legged hopping robots have been developed to employ locomotion other than rolling. Hopping can be an efficient mode of locomotion in terrain with obstacles and in microgravity environments where rolling traction is difficult to maintain. The actuation mechanisms involved in these robots varies, as does the nature of the motion they can achieve. Some achieve dynamically stabilized, continuous hopping, actuated using a high-force electric solenoid [3], or a double-acting air cylinder [4]. Other robots use discrete hops, requiring a pause between each hop to reset their propulsion mechanism. Energy conversion techniques for discrete hopping range from a combustion-driven piston [5] to releasing energy stored elastically in a metal coil spring [6] or in a fiberglass leaf spring [7], which must be retracted after each hop. A common theme in these robots is the importance of body orientation for directional control and efficiency of motion. Consequently, posture control during flight and self-righting mechanisms/procedures after landing are crucial for sustained locomotion in hoppers.

Combined Mobility Robots

A few robots have been developed to use multi-modal locomotion. Some are wheeled robots with discrete hopping ability to jump over obstacles in otherwise flat terrain [8] [9]. The Jollbot uses a spherical cage to roll, but can execute hops through the sudden release of the energy stored by elastically deforming its cage [10]. The IMPASS robot uses rimless wheels with linearly extending spokes to handle discontinuous terrain with a combined wheel and leg approach [11]. These examples of combined mobility illustrate an improvement in rough terrain locomotion without sacrificing efficiency on smooth surfaces. They also achieve such capability with relatively simple combinations of mechanisms.

Relationship to RATS

The 12-legged pneumatic RATS prototype incorporates features from spherical, legged, and hopping robots. It combines the external linearly extending leg of hopping mechanisms with the rolling behavior used by spherical robots and the sequencing of leg actuations like a legged robot. Its round shape is beneficial for high speed rolling on flat terrain and down inclines. Its discrete hopping ability allows for obstacle avoidance. Controlled, precision positioning or navigation is possible using its tipping or walking mode. The elegance of the RATS design lies in its ability to achieve varied locomotion through the use of 12 identical actuators that are simple and robust. The symmetry arising from the geometric arrangement of its legs also eliminates the need for pose control or a self-righting mechanism, providing omni-orientational mobility.

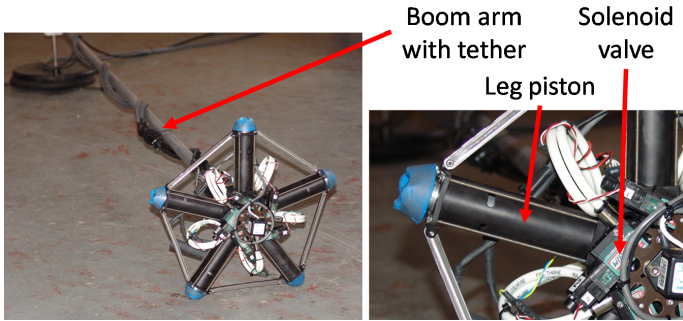


FIGURE 2. 5-LEGGED PLANAR *RATS* PROTOTYPE WITH PNEUMATIC LEGS.

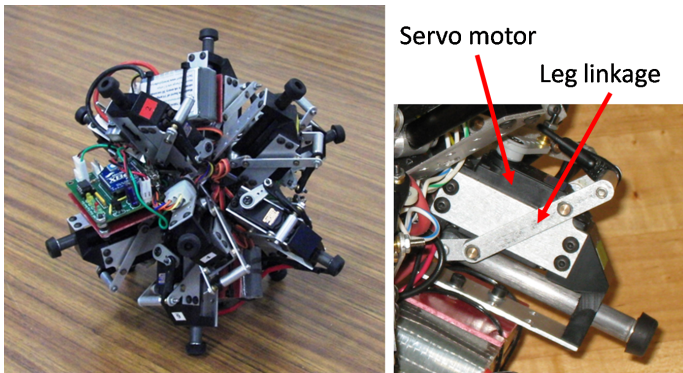


FIGURE 3. 12-LEGGED ELECTRIC *RATS* PROTOTYPE WITH SERVO-ACTUATED LEGS.

Previous Work in the RATS Project

The current embodiment of RATS is the continuation of four years of previous research and development. Two prototype robots have come before the 12-legged pneumatic prototype being discussed in this paper.

5-Legged Pneumatic Prototype The first mechanical prototype was a 5-legged planar robot with 1-DOF pneumatic piston legs (Fig. 2) [12]. The legs were spring-returned, single-acting air cylinders, arranged to form a wheel that could spin freely on the end of a pivoting boom arm. The boom arm restricted the robot to motion within a circular pseudo-plane. Each leg cylinder was controlled by a solenoid valve and by opening valves sequentially, the robot controller could induce rotation of the leg wheel to roll in a circle. This prototype served to validate the pneumatic leg piston design and also provided the groundwork for sensing and control strategies for the RATS system.

12-Legged Electric Servo Prototype The second RATS prototype was developed to explore the full spherical geometry to be employed in the 12-legged prototype while remov-

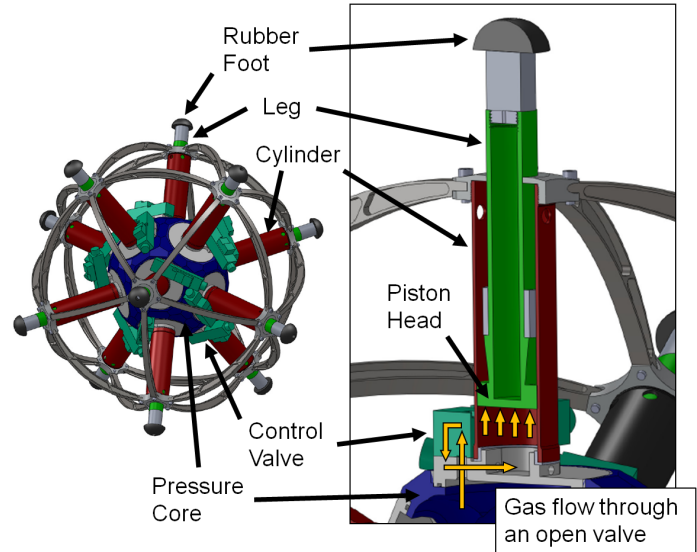


FIGURE 4. CAD DRAWING OF CURRENT 12-LEGGED PNEUMATIC *RATS* PROTOTYPE. CUTAWY SHOWS LEG PISTON DESIGN AND PATH OF GAS FLOW FROM THE PRESSURE CORE INTO THE CYLINDER.

ing some of the complexity associated with pneumatic leg actuation and control. This prototype had 12 radial legs (Fig. 3), each actuated by a servo motor via a five-bar linkage. Due to the relatively slow actuation of the servo-driven legs, this robot to discrete, quasi-static tipping actions for locomotion. The planning strategies developed for path-following using sequences of these tipping actions were also employed in the latest version of RATS.

12-LEGGED PNEUMATIC PROTOTYPE DESIGN

Mechanical Design

The latest RATS prototype possesses physical attributes used in both of the preceding prototypes. Like the 5-legged planar prototype, its legs are custom-fabricated pneumatic pistons - single-acting air cylinders with spring return to provide rapid linear actuation. Its body and leg arrangement reflects the geometry introduced in the servo-actuated prototype. It has 12 legs pointing radially outward, each centered on a face of the dodecahedron-shaped core. The resulting arrangement places the legs at the vertices of an icosahedron (the dual polyhedron of a dodecahedron) with equal angular spacing of 63.44 degrees between adjacent legs. A Platonic solid was chosen as the basis for the core structure to ensure symmetry [13]. Using 12 legs (dodecahedron core) provides better spatial coverage than 6 legs (cubic core) without the excessive complexity of controlling 20 legs (icosahedron core). Each leg cylinder is supported by a network of curved steel beams that span between neighboring legs,

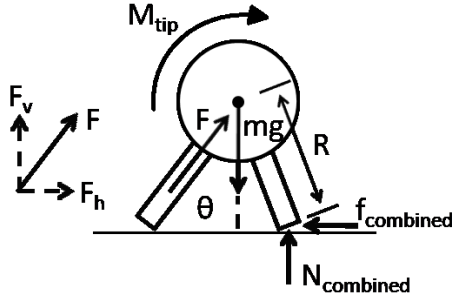


FIGURE 5. FREE BODY DIAGRAM OF RATS TIPPING.

creating a rounded icosahedron structure approximately 30 cm in diameter. When retracted, the leg ends protrude 3 cm from the exterior of the spherical support structure so that only 3 legs contact the ground when the robot rests on a flat surface.

Each leg cylinder is seated against the central core, which is a high-pressure aluminum tank with an internal volume of approximately 0.84 L. The core is pressurized from an off-board nitrogen gas (N_2) tank through a detachable hose. The robot has a mass of 3.446 kg when fully charged. A 3-way solenoid control valve is positioned at the base of each leg to allow gas to flow directly from the pressure core into the leg cylinder upon actuation (inset in Fig. 4) and exhaust gas from the cylinder to the atmosphere when deactivated. The valves are rated for a maximum pressure of 1 MPa and a response time of 13 ms or less. The leg has a 2.54 cm diameter aluminum piston head with polished radial face to minimize friction against the aluminum cylinder bore. The leg has a maximum linear stroke of 6.3 cm and terminates with a moderate-hardness rubber foot to provide traction and absorb some shock from impacts with the ground. A custom-wound spring retracts the leg when inactivated, expelling exhaust gas from the cylinder.

Control Architecture

The RATS prototype is controlled by sending actuation signals to the control valves on specific legs. The sequence in which legs are fired, the timing of the actuation, and the duration of actuation signals are what determines the nature of the robot's locomotion. The robot is configured with a tetherless control system for complete freedom of motion. It is outfitted with Lithium-polymer batteries for on-board electrical power. An on-board microcontroller provides low-level management of the solenoid valves, including control of valve timing to millisecond precision. The prototype is able to communicate with an off-board computer by radio. The off-board computer executes the high-level control logic and transmits firing commands to the on-board microcontroller consisting of which valve to actuate, how long to apply power, and how much time to wait before the next command is executed. The sensing capabilities of the current

robot configuration are limited to a 3-axis MEMS accelerometer rigidly mounted on the robot core. The sensor output is digitized with an ADC included in the microcontroller package and transmitted off-board for processing.

MOBILITY AND ACTUATION CHARACTERIZATION

The effects of fabrication details and interactions between actuator components are very difficult to predict. It is therefore important to study how the prototype behaves in response to many factors including the number of legs fired, the duration of the leg actuation, and the pressure in the core. This section of the paper addresses the behavioral trends observed during initial testing of the prototype and investigates characteristics of the system for the purpose of achieving controlled mobility.

Basic Mobility Behavior

The arrangement of legs and their actuation mechanism significantly affect the locomotive behavior of RATS. The pneumatic valve actuation scheme means the only method for controlling leg firing strength is to alter the duration for which the valve is held open. Longer valve firing times allow piston pressures to build up and provide longer duration for the application of the thrust force, imparting more kinetic energy to the system.

From a rest position on a flat surface, firing a single leg generates a thrust force F through the robot center at an angle $\theta = 37.38$ degrees from the surface normal (Fig. 5). This results in a vertical thrust component F_v tending to make the robot leave the ground.

$$F_v = F \cos \theta \quad (1)$$

Since the thrust force passes through the robot center, the horizontal thrust component F_h must couple with the combined friction reaction $f_{combined}$ at the other two stance feet a distance $R \cos \theta$ away to produce a tipping moment M_{tip} .

$$M_{tip} = f_{combined} R \cos \theta \quad (2)$$

The friction reaction is equal to the horizontal component of the thrust force up to a maximum value f_{max} related to the combined normal contact force on the ground at the stance feet $N_{combined}$ and the friction coefficient μ .

$$f_{combined} = \min \left\{ \begin{array}{l} F_h = F \sin \theta \\ f_{max} = \mu N_{combined} \end{array} \right\} \quad (3)$$

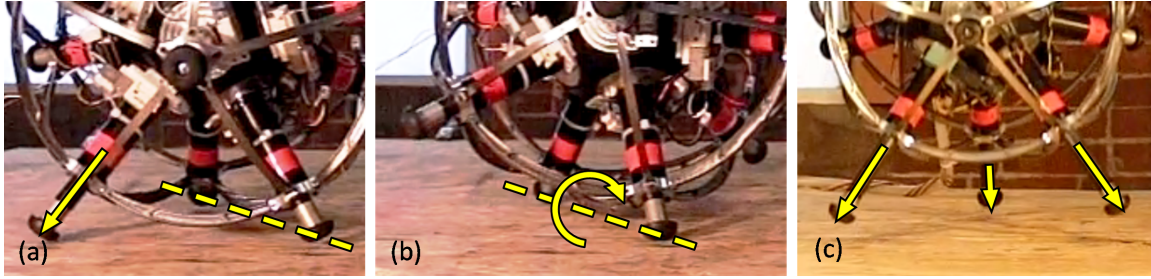


FIGURE 6. (a) SHORT DURATION FIRING OF A SINGLE LEG TO CAUSE (b) TIPPING ABOUT THE OTHER TWO STANCE LEGS. (c) FIRING THREE LEGS FOR A VERTICAL HOP.

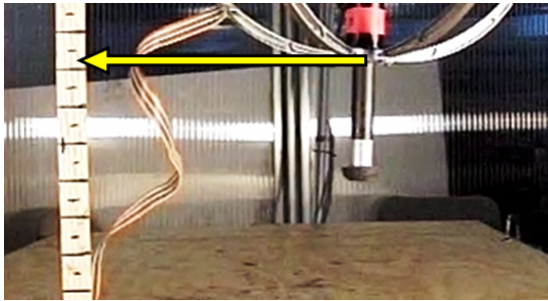


FIGURE 7. HOP HEIGHT MEASUREMENT TECHNIQUE: A HIGH SPEED VIDEO CAMERA CAPTURES THE APEX OF THE HOP TO MEASURE ROBOT POSITION AGAINST A RULER.

If a short valve time is used, F_v is insufficient to lift the robot and ground friction remains strong enough to produce a tipping moment. In this case, the robot simply tips over the two stance feet. (Fig. 6a,b). For longer valve times, F_v grows strong enough to lift the two stance feet off the ground. F_h briefly produces a rolling moment before the stance legs lose contact, and then continues to accelerate the robot forward. The result is a forward hop with induced tumbling. Firing three legs simultaneously from rest produces a vertical hop, as the horizontal thrust components from all three legs cancel each other out (Fig 6c). Any imbalance in leg strength during the launch phase results in rotation once the robot is airborne.

This basic behavior underscores the importance of characterizing the pneumatic leg actuators to understand the factors that determine leg strength. Deterministic tipping behavior requires individual leg firings that are strong enough to successfully tip but not so strong as to cause additional stochastic tumbling. Controlling the differences in leg strength when simultaneously firing multiple legs is also useful for controlling the direction, height, and induced rotation of a hop.

Actuator Strength Factors

Effects of Valve Time on Leg Strength Altering the valve opening time is the only available method to control the

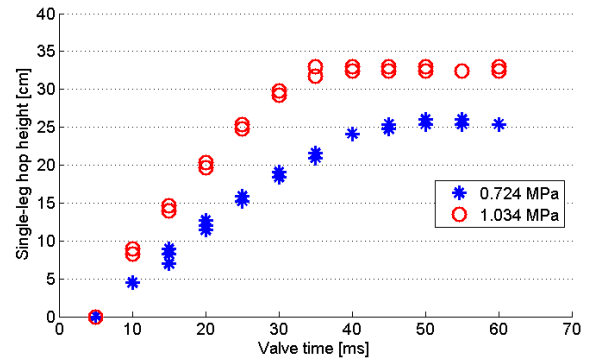


FIGURE 8. HOP HEIGHTS RESULTING FROM VARIED VALVE OPENING DURATIONS AT 2 CORE PRESSURES. SIGNAL TIMES BELOW 5 MS ARE INSUFFICIENT TO OPEN THE CONTROL VALVE. HOLDING THE VALVE OPEN AFTER THE LEG LOOSES GROUND CONTACT DOES NOT INCREASE HOPPING HEIGHT, RESULTING IN MAXIMUM HEIGHT PLATEAUS.

strength of a leg firing after the pressure core has been charged. In order to observe the empirical effects of varied valve firing times on the pushing strength of the leg, a single-leg vertical hopping experiment was devised. A launching platform was fashioned to allow RATS to balance on a single leg without obstructing the vertical hopping motion. Individual hops were recorded using a high speed digital camera, filming at a frame rate of 600 fps. A ruler marked in half-inch increments was positioned next to the robot to measure the robot's height in the video frame containing the hop apex (Fig. 7).

The tests were performed by initially charging the core with N_2 gas to a regulated level. An actuation signal was then sent to the robot for a specified duration. Valve times varying from 5 to 65 ms in 5 ms increments were tested, with each test using the same leg (Leg 8) for hopping to avoid inconsistencies between legs. Each duration of valve signal was tested 3 times. Data are plotted in Fig. 8 from two trials of this test using core charges of 0.724 MPa (105 psi) and 1.034 MPa (150 psi).

The robot exhibited nearly linear increase in hop height over

a large range of valve times for both core pressure conditions. For valve firing times 5 ms and below, the robot did not perceptibly leave the ground, which illustrates the inherent actuation delay resulting from solenoid valves. Current must be supplied to the solenoid coil for approximately 5 ms before the magnetic field in the coil saturates enough to trigger the air-pilot stage and shift the main valve poppet. At valve times above a distinct threshold (45 ms for 0.724 MPa core charge and 35 ms for 1.034 MPa), the hop height held constant at a maximum (26 cm for 0.724 MPa core charge and 33 cm for 1.034 MPa). It is proposed that this plateau exists because the robot's leg hits its maximum-extension dead-stop and its foot loses contact with the ground as the robot continues airborne. With no ground contact, RATS is unable to convert additional valve time into applied force. As expected, higher supply pressure led to a faster rate of leg extension. This caused the robot to lose ground contact (reach the hop height plateau) at smaller valve times and resulted in higher maximum hop heights.

Effects of Core Pressure on Leg Strength The pressure of the gas entering the control valve also directly affects leg strength. Higher supply pressure means higher pressures inside the cylinder, and consequently higher piston forces. Since the prototype was not designed with an on-board pressure regulator between the source tank and the control valves, the supply pressure to the valve intake is always the same as the pressure of the core tank. This pressure drops over time as gas is expended by leg firings and the leg strength of each subsequent firing consequently drops as well. This effect was measured by hopping repeatedly using a 40 ms firing time after a single 0.689 MPa (100 psi) charge of the core. The robot could not lift itself off the ground more than a few centimeters after 75 successive firings, as shown in Fig. 9. As a consequence, leg firing times must be increased as the pressure drops in order to maintain the same hopping energy.

Strength Variation Between Legs

While testing the system, it was observed that each of the legs on the RATS prototype provides a different thrusting force upon actuation. In order to produce consistent actuation performance from all legs, it was important to quantify this variation. Two different actuation tests were used to survey the relative strengths of all 12 legs.

Tipping Threshold Variation Tipping behavior is very sensitive to the strength of the firing leg, as a certain minimum amount of imparted kinetic energy is needed to carry the robot past the halfway point of its tipping motion. For a given short duration of valve actuation signal, a strong leg might impart sufficient energy to execute a complete tip, coming to rest on a set

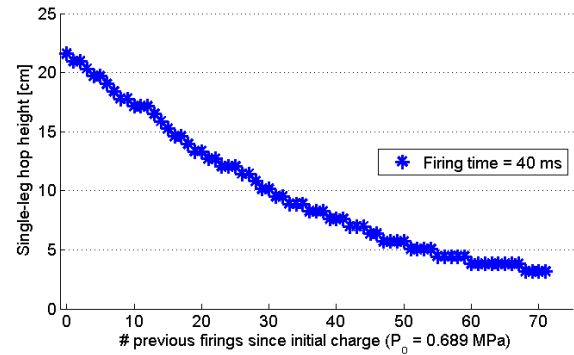


FIGURE 9. OBSERVED DROP IN HOPPING HEIGHT (LEG STRENGTH) AS SUPPLY GAS IS DEPLETED BY REPEATED LEG FIRINGS.

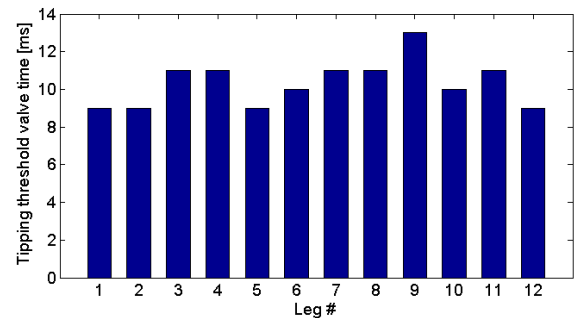


FIGURE 10. VALVE OPENING TIMES REQUIRED TO ACHIEVE CONSISTENT TIPPING BEHAVIOR FOR EACH LEG AT 0.689 MPa CORE PRESSURE. VALUES REPRESENT THRESHOLD FOR $\geq 90\%$ TIPPING SUCCESS RATE.

of 3 legs different from its initial set. A weaker leg might fail to completely tip the robot over for the same signal duration.

A set of experiments was carried out to identify the threshold valve time for each leg to make the robot execute one full tip with a core pressure of 0.689 MPa (100 psi). The threshold valve time was designated as the duration which produced a successful tip on at least 9 of 10 attempts and is plotted for each leg in Fig. 10. Tipping valve times for most of the legs were found to lie between 9 and 11 ms, while Leg 9 was distinctly weaker and required a 13 ms actuation time.

Single-Leg Hop Height Variation Another set of experiments investigated the hop heights achieved by each leg when fired at a single valve time of 40 ms. Stronger legs would be expected to hop higher (impart more launch energy) for the same valve time and core pressure. Using the same high speed camera technique for measuring the height of a single-leg hop as described before, each of the 12 legs was tested 3 times with a

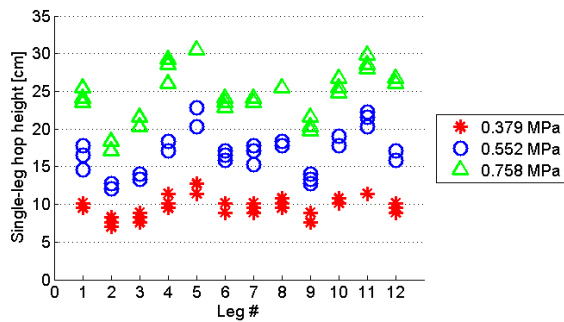


FIGURE 11. SINGLE-LEG VERTICAL HOP HEIGHTS FOR 12 LEGS AT 3 CORE PRESSURES. CERTAIN LEGS WERE CONSISTENTLY STRONGER OR WEAKER THAN OTHER LEGS REGARDLESS OF PRESSURE.

0.379 MPa (55 psi) core pressure. The series of tests was carried out twice more for 0.552 MPa (80 psi) and 0.758 MPa (110 psi) core pressures. The results are plotted in Fig. 11.

The data show clear trends in both the effect of pressure on leg strength and the relative strength of each leg. As expected, higher pressures resulted in higher hops for all legs. Legs 4, 5, and 11 were stronger relative to the other legs regardless of the supply pressure. Similarly, Legs 2, 3, and 9 were consistently weaker than the other legs at all pressures. These differences between legs seemed more pronounced at higher supply pressures.

The lack of uniformity in leg strength observed in the previous two characterizations may be attributed to several factors. Since all of the leg pistons were custom machined, there are bound to be non-uniformities in the fabrication of the individual leg pistons. Differences in friction between the piston and cylinder or variations in stiffness of the hand-wound return springs might cause the variation in effective thrust force. It is also possible that each solenoid valve has a slightly different response time (on the order of 0.5 ms in variation) such that some legs receive longer exposure to the supply pressure upon actuation.

Effects of Characterization on Control

The findings from these characterization tests have important ramifications for the development of locomotion controllers. Actuation response time must be accounted for in control design, introducing inefficiencies and error due to the need to act early. The intent of the robot's symmetrical geometry was to permit control strategies that are indifferent to which particular legs happen to be on the ground. Instead, the pneumatic piston mechanisms exhibit non-uniform strength. To further complicate matters, the limited on-board gas supply means leg strength drops as the number of previous actuations increase. Fortunately, the nearly linear relationship between actuation signal duration and imparted thrust energy makes it possible to effectively balance leg strengths and compensate for strength decay by adjust-

ing valve opening times. This is especially crucial for strength-sensitive tipping and hopping maneuvers.

IMPLEMENTATION OF LOCOMOTION STRATEGIES AND DISCUSSION

Tipping

Tipping as a form of locomotion was implemented on the untethered RATS prototype. The tipping valve time profile of each leg (described in the previous section) made it possible to perform sequences of successful tips on the flat concrete floor of our lab space. From an initial core charge of 100 psi, RATS could reliably execute at least 35 tipping actions (traveling a straight-line distance of 4 m) before the drop in supply pressure resulted in a failure to tip. This endurance could be extended to 166 tips and 17.3 m traveled by gradually increasing the valve times to compensate for pressure drop.

The robustness of tipping locomotion was increased by low frequency detection of the robot's orientation. Using the 3-axis accelerometer to track the orientation of gravity in the robot's reference frame allowed the controller to detect failed or unexpected tips. The immediate impact of this feedback is that RATS is able to identify which of its 12 legs are on the ground and which would result in tipping motion if fired. Failed tip detection also makes it possible to adjust valve times to compensate for unexpected ground surface conditions or detect path obstructions.

The quasi-static nature of this motion allows tipping success with minimal state feedback and makes tipping the most deterministic of the locomotion modes. Tipping is therefore appropriate for navigation along a specific path or for precise positioning of the robot. The caveat is that tipping, by nature, is a discrete form of locomotion that imposes unique constraints on how the robot moves. Since RATS can only tip over one of three edges from its current stance, it is constrained to motion in three discrete directions, 120 degrees apart. Additionally, the robot can only achieve positions in discrete locations of the plane. This presents problems when trying to follow a path, because the curve will most likely not coincide with the discrete locations RATS can reach. It is also not likely that the steering direction needed to follow the curve at any given time will exactly correspond with the three discrete directions in which RATS can move.

Thus the navigation problem becomes one of finding the best approximation to the desired path by points that the robot is capable of achieving. Figure 12 shows snapshots of the prototype following a straight line path (the black stripe on the floor) by executing the best approximation tipping sequence given the initial orientation and position of the robot. The resulting RATS motion is a zig-zag path. Attempting to follow a curved path results in a trade-off between minimizing the path-following error and minimizing the number of tips to conserve energy. Significant

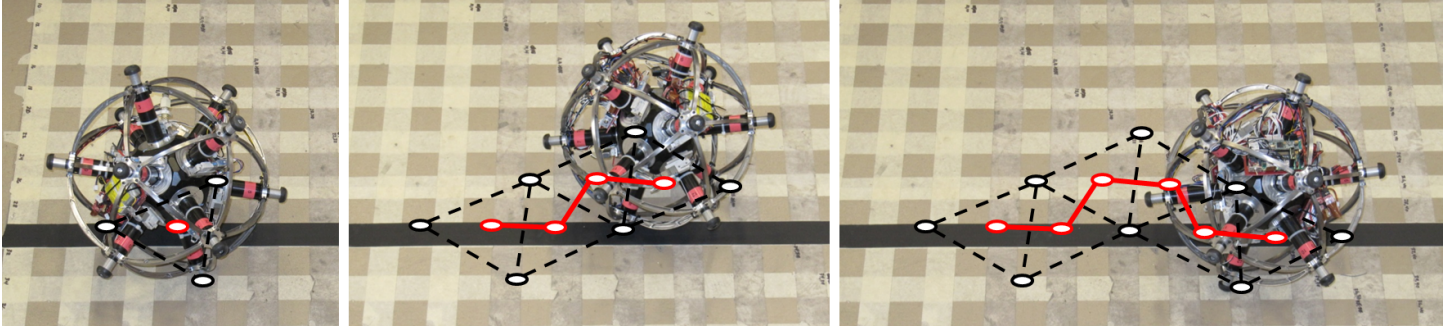


FIGURE 12. SNAPSHOTS OF RATS EXECUTING A TIPPING SEQUENCE TO FOLLOW STRAIGHT LINE (BLACK STRIPE ON GROUND).

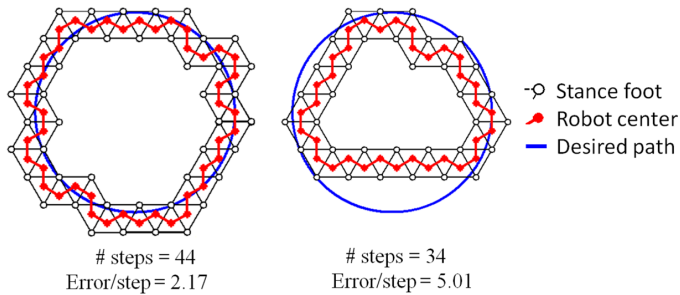


FIGURE 13. APPROXIMATIONS TO A CIRCULAR PATH BY RATS TIPPING SHOWS TRADE-OFF BETWEEN PATH-FOLLOWING ACCURACY AND EXPENDED GAS (NUMBER OF TIPS).

quantities of gas can be conserved if the robot is permitted to cut across the inside of the curve and stray further from the desired path (Fig. 13).

Rolling

In some ways, rolling may be seen as an extension of tipping. Indeed, our first attempts to implement high speed rolling behavior comprised executing the straight line tipping leg sequence in an open-loop manner with shortened pauses between firings. While this technique was successful as a short distance demonstration, the stochastic nature of dynamic rolling with only 12 possible points of contact with the ground quickly became apparent. The rolling and tumbling motions of RATS are very difficult to predict, even on flat, level terrain.

Since RATS does not attempt to control its orientation or maintain any specific body pose as it moves, a more successful rolling controller should be a reactive system that makes actuation decisions in response to the robot state (orientation, rolling rate, elevation) resulting from stochastic motion. We developed such a controller to run on a simulation of RATS implemented in *Open Dynamics Engine* (ODE), an open source rigid body physics engine. With access to state information provided by

the simulation (obtaining this state through sensing is another difficult challenge), the rolling controller successfully produced straight line rolling motion on flat terrain (Fig. 14).

Figure 15 illustrates the decision process executed in the controller calculations. For every control loop, the controller predicted when each leg would hit the ground if fired at that instant in time. A certain desirable impact angle $\theta_{\text{impact}} = \phi$ was defined as the angle formed between the ground surface normal and the projection of the leg onto the sagittal plane (the vertical plane containing the desired rolling direction and gravity). A leg was fired at the time when the leg was predicted to have the desired impact angle when it hit the ground in the future. The result of this control strategy was stable straight line rolling in a commanded direction at speeds ranging from 2 to 7 m/s.

This successful rolling in simulation was markedly different from the simple accelerated tipping we implemented on the prototype. Once the simulated robot picked up rolling speed, the zig-zag pattern characteristic to tipping was no longer apparent and the robot moved smoothly in a straight line. We also observed that leg sequence was no longer critical. Instead, the lateral alternation of leg thrusts needed to maintain straight forward motion followed naturally from the use of leg positions projected onto the sagittal plane.

The reactive nature of this controller is expected to make rolling much more robust to terrain irregularities. The robot should naturally adjust its leg firing patterns to compensate for behavior resulting from unexpected interactions with the terrain. The largest obstacle to implementation of this locomotion method on the RATS prototype is the need for accurate high frequency pose estimation, which is not available from the current accelerometer configuration. Additional sensing modalities and filtering techniques are needed to enable truly reactive rolling control.

Hopping

We are currently formulating and testing hopping strategies for locomotion as an extension of rolling, but so far we have only studied in-place hopping. We have demonstrated that the current

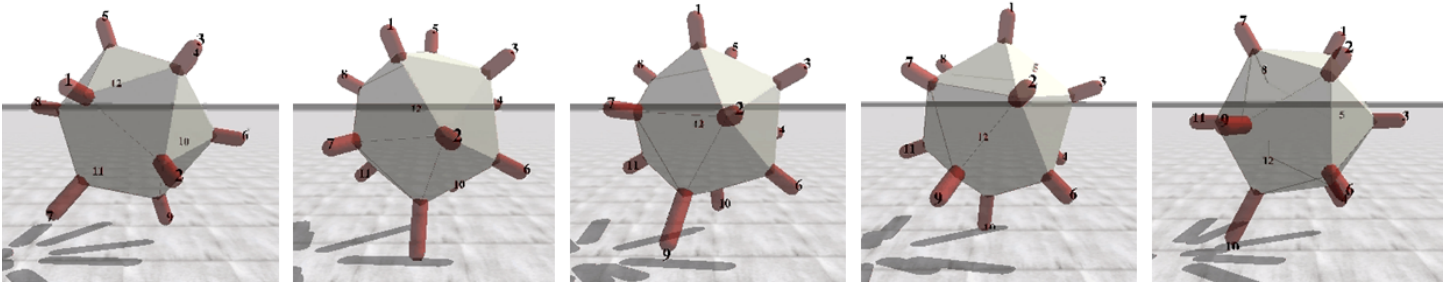


FIGURE 14. SNAPSHOT SEQUENCE OF ROLLING RATS BEHAVIOR IN *ODE* SIMULATION.

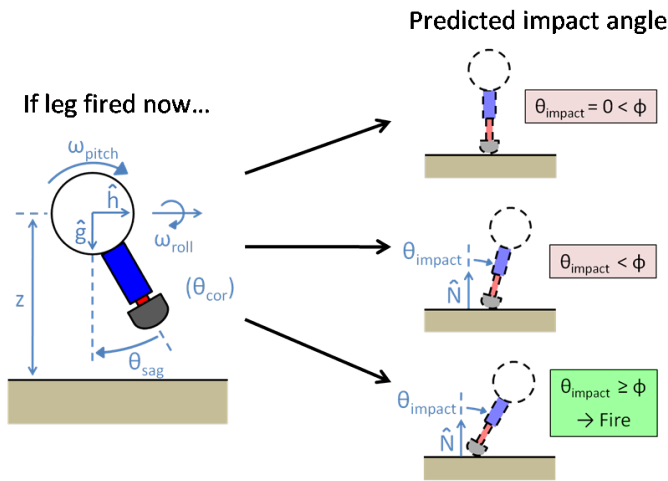


FIGURE 15. CONTROL LOGIC EMPLOYED BY ROLLING CONTROLLER (PROJECTION OF LEGS ONTO THE SAGITTAL PLANE IS SHOWN). THE ANGLE AT WHICH A LEG WOULD IMPACT THE GROUND IF FIRED NOW IS CALCULATED USING THE CURRENT ROBOT STATE. LEG IS FIRED ONLY IF ITS IMPACT ANGLE IS PREDICTED GREATER THAN THE OPTIMAL ANGLE ϕ .

configuration of RATS is capable of vertical hopping to heights of 33 cm - higher than its own diameter. Thus RATS should be capable of scaling obstacles nearly its own height using the same actuation mechanisms as are used for forward locomotion. The leg strength profiling described earlier is useful here for controlling the height and distance achieved in hopping. Different combinations of number of legs fired and relative firing strengths between legs should permit directional hopping behavior with broader scope than the tri-directional limitations of tipping.

Repeated hops from rest, as employed by many of the purely hopping robots surveyed above, may be an efficient mobility strategy and one that is successful with very limited feedback. It is certainly feasible with the existing prototype system. But RATS should also be capable of combining hopping with its

rolling behavior by firing a leg earlier in the rolling cycle (using a smaller or negative desired impact angle ϕ) or more highly energizing the fired legs to generate increased vertical acceleration from the leg thrust. This would permit the robot to cover greater horizontal distances (and clear more obstacles) with each bound. Such a combined rolling-hop scheme was developed and tested by Lüders on the 5-legged planar prototype [12]. More work is needed to develop leg firing strategies for directional hopping maneuvers and leaping from a rolling start with the 12-legged prototype, but the system shows much potential for the use of hopping as an effective locomotion technique.

CONCLUSIONS AND FUTURE WORK

The RATS system was designed to be capable of multiple locomotion techniques while limiting control complexity through the use of a simple actuation mechanism and symmetric leg arrangement. The system characterizations presented in this paper established techniques for actuator control and provided insight for the implementation of mobility strategies on the prototype. The ability to modify leg firing strength by changing valve opening duration has proven crucial to differentiate between locomotive behaviors, all using a single mechanism. Low energy actuation results in tipping, the proper sequencing of moderate energy actuations produces rolling/running, and high energy firing causes hopping. We also learned that reliable actuator performance requires compensation for the variations in strength between individual legs and the depletion of gas pressure over time. Harnessing 12 of these actuators in a spherically symmetric arrangement permits locomotion regardless of the robot's orientation when it comes to rest.

Our testing has shown that tipping is the most deterministic of the RATS locomotive options which makes it a viable option for minimal-feedback locomotion in flat terrain. We used the prototype to demonstrate path following as a suitable application of this mode. The reactive rolling controller developed and implemented in simulation is a faster option on flat terrain and is expected to be more robust in uneven terrain. Hopping and bounding may be a better solution for travel in discontin-

uous and obstacle-filled terrain. Mission objectives and terrain properties will dictate which locomotion mode is most effective or efficient for the particular application. Regardless of the terrain, the duration, timing, and coordination of leg actuations are the only control features needed to produce these behaviors.

It must be noted that the current design implementation is less than optimal when considering each mode of locomotion separately. The tipping mode is less effective because the line of action for all legs passes through the robot's center, requiring ground contact friction at the stance legs to establish the necessary moment couple. Vertical hopping is also less efficient because the horizontal components of thrust from each leg are used to cancel the others. Both of these deficiencies would benefit from legs that are oriented more normal to the ground, but such a design would be effective only for certain orientations of the robot. High-speed rolling, however, benefits from spherical symmetry and radially aligned legs. When considering energy conversion, the nature of pneumatic solenoid valve actuation is better suited for hopping, which favors brief high-force impulses, than for tipping, which benefits from longer duration low-force thrust to maintain ground contact. The design compromises in the current version of RATS represent a solution that facilitates three modes of locomotion and omni-orientational mobility using a single form of actuation.

Directions for future research must be driven by the objectives of RATS applications and missions. Considerations such as speed, efficiency, endurance, and terrain types will prompt investigations into improved efficiencies of locomotion and shifts through the mechanism design space. Currently, the distance traveled from a single gas charge is not yet conducive to application of RATS in the field. In addition to weight reduction measures, a multi-stage gas storage system with a high pressure tank and a low pressure accumulator or completely different propellant options could improve the endurance of the system. Changes to the piston design to arrive at a higher efficiency mechanism for energy exchange could enable higher jumping. A solid external shell into which the legs retract would improve rolling behavior. These and many other changes might enhance mobility potential, but controls and real-time sensing must improve as well. Development of a rolling controller demonstrated that using simplified actuation and reactive controls places higher importance on sensing to determine robot posture and position while moving. It is therefore important to understand what minimal sensing modalities are sufficient for robust motion and strive for open-loop locomotive techniques where possible. Regardless of these changes, the appeal of the RATS concept is that it is equipped to be adaptable to the mobility requirements of its environment, providing a higher degree of accessibility for diverse terrains.

ACKNOWLEDGMENT

The authors would like to thank Minas Tanielian of Boeing for his guidance and support. We would also like to thank R. Allan Lüders, Mike Rizk, James Teza, Stuart Heys, and Benjamin Koopman for their efforts in the design and engineering of RATS.

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