Teaching Robot Design: Locomotion Beyond Differential Drive

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Abstract: In this paper, we present a novel design challenge for a mobile robotics course, focusing on locomotive methodologies and mechanism design. This exercise requires that the students design a robot for locomotion over complex and challenging terrain. This exercise demonstrates the difficulties associated with nontrivial terrain and provides the students with an excellent experiential learning opportunity that significantly enhances their robot deign capabilities by expanding their experience beyond simple differential drive systems.

Introduction

Mobile robotics is a rapidly expanding field of research and education, but traditional mobile robot systems have a distinct lack of mobility and flexibility over uneven terrain. In general terms, mobile robots are the synthesis of mechanisms, electronics and computers. Most mobile robotics experiments and competitions (such as the Trinity College Fire-Fighting Robot Competition[1] or the Intelligent Ground Vehicle Competition[2]) focus on the sensor packages, computation, algorithms and mechanisms that are placed *on* the mobility platform to achieve whatever task is at hand. It is a rare challenge in which the basic locomotive methodology is not differential-drive, a tank-tread system or car-like steering (although competitions exist that require more complex mobility… e.g., the NIST USAR events[3]). Unfortunately, these typical locomotion designs have significant difficulties with very rough terrain such as that found on the surface of Mars, inside a collapsed building or in almost any non-urban environment. In fact, even under direct teleoperation, most of these systems have significant difficulty with a step rise over 33% of their wheel diameter[4].

In this paper, we outline a terrain challenge course and experiment that provides students with experience in the morphological design process and locomotion synthesis for mobile robotics. This challenge, along with appropriate motivating examples and in-class discussions, is used as a means toward producing robotics engineers who think about the robot as a whole, including structurally and mechanically. The conclusions and experiences discussed are based on three years of experience using the proposed terrain challenge in an undergraduate mobile robot design course.

The significance of the proposed exercise can been seen by examining likely domains for current future mobile robot applications. For every vacuum cleaner and lawn-mowing robot, there are robots designed for urban search and rescue and military reconnaissance. For every mobile robot application in a factory, hospital or museum, there is a more challenging application in the desert, the Antarctic or even on the Moon. As the computational capabilities of robots expand, there will be a strong impetus to bring for mobile robots into these new domains. The exercise discussed in this paper is intended to enhance traditional robotics education by making the students aware of various designs for overcoming typical terrain difficulties and providing hands-on experience with the same. The result is a robotics engineer with enhanced knowledge, experience and insight into their craft.

The Course

The course in which the terrain challenge task is embedded is a non-traditional senior-level elective course in Systems Engineering at the United States Naval Academy (USNA). Mobile Robot Design is a three-credit course with one hour of lecture and four hours of laboratory exercise per week. This structure allows a great deal of experimentation, which in turn provides outstanding opportunities for a variety of highly demanding design challenges. These challenges focus on all aspects of the robot, including mechanism design, computation and algorithms, sensors and electronics, actuator selection, power supplies, etc. Each component is tied to all of the others so that the robot is seen as an integrated whole as opposed to a collection of disparate parts. The students are instructed in such a way as to demonstrate that robotics is a discipline in its own right, not merely a combination of mechanical, electrical and computer engineering. Additional details regarding this course and the philosophy of the robotics program in Systems Engineering at USNA has been published separately[5].

The Terrain Challenge

The terrain challenge task occurs as the third primary project in the Mobile Robot Design course. At this point, students have studied basic drivetrains and vehicle kinematics, competed in a robotic hill climbing competition, and carried out a challenge involving dead reckoning using shaft encoders[6]. The terrain challenge builds on this knowledge and experience and enhances it, requiring application of the learning from the hill climbing and dead reckoning labs, but also demonstrating how those designs and methods fail when faced with nontrivial terrain. Thus, the exercise offers insight into the applicability of standard methods and forces the students to go beyond these to develop new solutions.

The terrain challenge is a two week exercise (comprising eight hours of lab time) using standard LEGO Mindstorms construction kits[7] for the physical component and Dave Baum's NotQuiteC[8] for programming. The standard LEGO kits are enhanced with optional sensors including shaft encoders. The RCX 2.0 firmware is used. The challenge as presented is tuned to this kit's capabilities, but simple modifications can be made to enhance the experience for any reconfigurable kit. The students are expected to build a wheeled or tracked vehicle; legged locomotion is covered later in the class.

The terrain challenge includes five distinct components, each easily assembled and tuned to the capabilities of any basic robot kit to be used. Each component has an identifiable design challenge associated with it. The components are: high-friction turn, uneven hill climb, canyon, uneven hill descent, and low-cohesion soil with obstacles. The robot must be autonomous.

High-Friction Turn: The first stage of the terrain challenge consists of executing a dead reckoning traversal from a marked starting location to a high-friction pad on which a 90^{o} turn must be executed.

Locomotion Objective: Dead reckoning, achieve turning without skid steering

Setup: Mouse pads, traction side up, attached to a set of three-ring binders. Number of binders depends on kit (the largest anticipated vehicle should be less than 2/3 of the total obstacle size).

Typical solutions: Steering (using an Ackerman-style drivetrain) or multi-point turns with differential drive. Difficulties are encountered with skid steering in both structural integrity and dead reckoning.

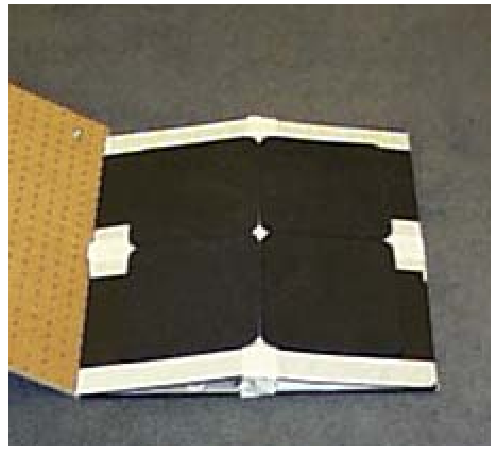


Figure 1: High-friction turn setup

Uneven Hill Climb: The second stage of the terrain challenge involves a traversal of a hill that includes snags and small irregularities.

Locomotion Objective: Traction, power and stability (including heading control).

Setup: 2’x4’ pegboard, inclined on a table edge, studded with ¼” bolts at various heights (depending on size of available wheels). Slope varies by material of both board and available tires.

Typical solutions: Systems must have driven rear wheels and a forward center of mass for traditional locomotion. The terrain irregularities require either a very stable frame or some form of compliance, so that the vehicle can maintain traction. Novel solutions involve grappling hooks and other methods by which the system can temporarily couple to the terrain. Feedback for heading control typically relies on a damped pendulum with an attached shaft encoder.

Figure 2: Uneven hill ascent setup

Canyon: After reaching the top of the hill, the vehicle must traverse a small canyon.

Locomotion Objective: Achieve motion without continuous wheel support.

Setup: Three-ring binders placed an appropriate distance apart. The width of the canyon should be directly related to the largest available wheel.

Typical solutions: Tracked vehicles or systems with long frames and a variety of contact points. Novel solutions involve a moving center of mass.

Figure 3: Canyon setup

Uneven Hill Descent: After traversing the canyon, the vehicle has a small area on which to execute any desired maneuvers before moving down a hill with an uneven surface.

Locomotion Objective: Controlled descent, vehicle stability.

Setup: Surface identical to the upward slope with same or greater angle, coated with material to provide an irregular surface. The tested system used a sprayable insulation foam (Great Stuff™ from DOW) laid out in a staggered terrace configuration.

Typical solutions: Successful vehicles typically possess some form of passive compliance in the frame, and most require that the vehicle traverse the hill downward in the opposite direction to that in which they ascended the previous hill (for stability purposes), and at much lower speeds. An active undercarriage is also frequently helpful.

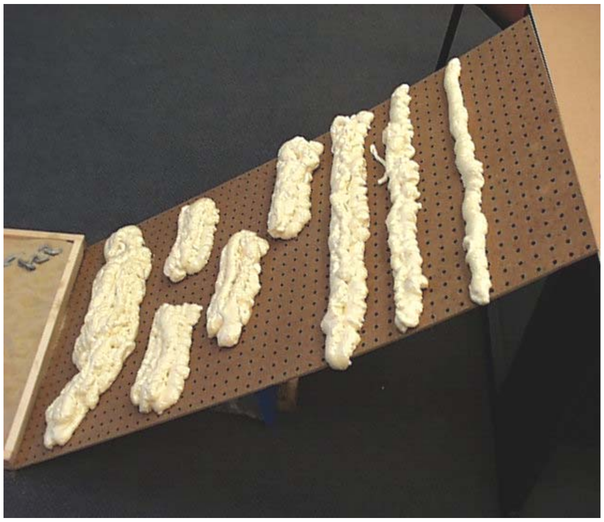


Figure 4: Uneven hill descent setup

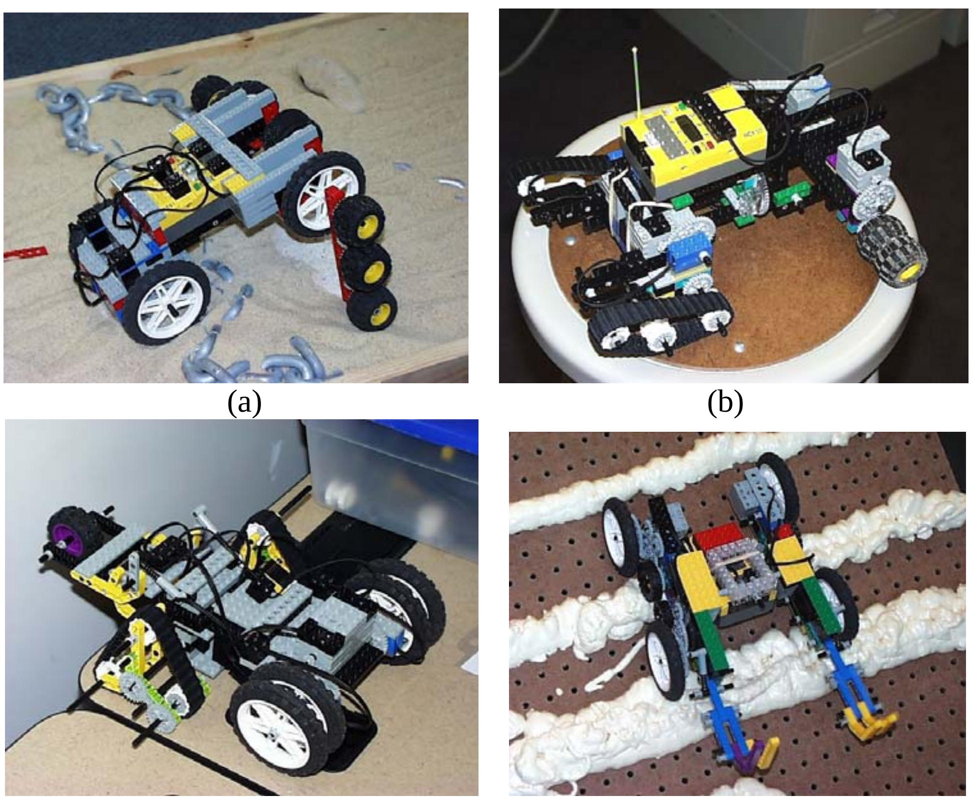
Low cohesion soil with obstacles: After reaching the bottom of the slope, vehicles must traverse a sand pit filled with a variety of obstacles.

Locomotion Objective: Traction control and regulation in loose soil with a variety of snags and obstacles.

Setup: A low-walled box (made from 1"x2" board for walls and a 2'x4'piece of pressed board for the floor) filled with sand, rocks and a large chain (sized to appropriately challenge the available kit)

Typical solutions: Vehicles must have sufficiently small ground pressure to avoid sinkage, maintain appropriate pace to avoid spinouts, and climb small obstacles without digging in. Students must also be careful to avoid too much "bulldozing" from the frame or the wheels, which can cause a significant drag on the system. Successful systems often include passive compliance (which aids in maintaining even weight distribution) and/or an active undercarriage as well as large ground contact area.

Figure 5: Sand obstacle setup



(a) (b) (c) (d)

Figure 6: Example student projects

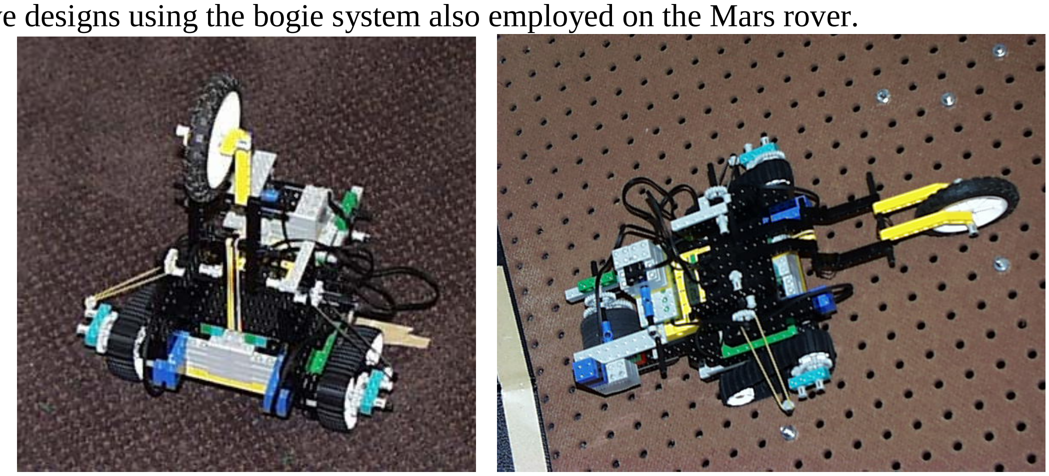
Successful Strategies

Many different vehicle designs can traverse the terrain challenge as posed, although it proves quite difficult for some. In Figure 6, we see several different designs that show fundamentally sound design strategies. In Figure 6.a, we see a system based on the PackBot by iRobot corporation. The flexibility in the system comes from the two flippers, each of which has active wheels but a passive connection to the body of the vehicle (with some stiction). This design “walks” over tough obstacles passively. The actual Packbot design has actuated flippers, but the limitations on available parts made this impractical. In the end, the students’ design was very functional even without the added actuation, which is desirable from a standpoint of cost, weight and control.

The robot in Figure 6.b is a large-footprint design that uses tracks and multiple wheels, geared to the same speed, to achieve locomotion. The frame contains a center-line passive joint to allow the wheels to ride up over obstacles. This coupled suspension is essential for good traction; a modern independent suspension is not well suited to this type of terrain[5].

Figure 6.c shows another method for achieving locomotion in the difficult terrain. The triangular track assemblies are completely passive with respect to the frame, but are still powered. Much like the vehicle in Figure 6.a, these wheels “roll” over large obstacles but provide reasonable traction over smooth terrain and in the sand. The back wheels provide driving power when climbing the hill, and the rolling triangular wheels aid in the turning challenge by reducing the amount of slip required.

Figure 6.d follows the principle of the Mars rover Soujorner, which relies on a pitch averaging system (a type of passive compliance) for part of its locomotive capability. This robot is bifurcated along the centerline, but the two halves are linked through a simple differential. This results in the following behavior: when one front wheel is pushed upward by an obstacle, the opposite wheel will push downward into the surface to achieve traction. If both wheels are pushed upward, the vehicle will simple angle up. The average pitch of the two halves is always zero with respect to the differential in the heart of the vehicle. This design proved very capable, as have designs using the bogie system also employed on the Mars rover.



(a) (b)

Figure 7: Multi-mode vehicle example

But designs need not be entirely based on fielded systems. In Figure 7, we see a multi-mode vehicle. The wheel that is elevated in Figure 7.a is lowered into contact with the ground (with some compliance) when necessary, as seen in Figure 7.b. This type of approach allows the vehicle to be quite agile over the high-friction surface but also offers good stability going downhill and through the sand.

There are many other designs that are quite successful for this challenge, but all of them obey basic principles of locomotive design. The system must maintain traction, preferably through compliance and various types of wheel-ground contact. The robot must also maintain stability through kinematic design and speed regulation, and provide sufficient ground contact to avoid sinkage in loose terrain. Finally, the system must be rugged enough (or possess enough articulation) such that a turn on high-friction ground can be achieved without breaking the frame (through internal shear).

Results

In three years of testing this project in the Mobile Robot Design course at USNA, very few groups have failed to meet the basic mechanical design challenge. The most common problems are lack of heading control on the slopes (resulting in the vehicle plunging to the ground off the edge) and lack of stability on the downward slope (resulting in the vehicle rolling over, frequently breaking apart[i]). Most groups of students go through three or more revisions of a basic design as various components of the challenge bring out faults and weaknesses in their developing system. Innovation is the hallmark of the exercise, and many interesting but ultimately futile mechanisms are proposed. The instructor must follow the groups' designs closely to avoid too much effort on a non-functional system. Typical class sizes are 15 – 21, with groups of three acting as a design team. Excusal from formal lab report writing seems to be a suitable reward for successful autonomous navigation of the entire challenge. Those unable to complete the challenge write a report detailing the failings of their vehicle and the potential remedies.

Conclusions

In this paper, we have presented a project designed to enhance traditional robotic curricula in the domain of locomotion and mechanism design. The testbed for the proposed project is simple, inexpensive to build and store, and offers a significant and adjustable challenge suitable for any reconfigurable mobile robot kit. Students find this project rewarding but work-intensive, so it is best used in a course where significant lab time can be devoted per week. In cases where the project is carried out over many weeks, students may lose interest or become frustrated with the slow progress. Intensive periods of work have shown great results in the Mobile Robot Design course at the United States Naval Academy. The developed design skills and the associated locomotion toolset enable these students to move on to develop real solutions and novel systems, including advances in locomotive methodologies for a variety of domains such as planetary exploration and search and rescue[9].

[i] Although in one notable instance, the vehicle was designed to allow a rollover, and the speed on the downhill slope was set to encourage such an event. The robot was able to drive on either side.

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