EXPLORING ALTERNATIVES TO WHEELED LOCOMOTION IN EDUCATIONAL ROBOT DESIGN

Bradley Bishop, Joel Esposito and Jenelle Piepmeier
Systems Engineering Department
U. S. Naval Academy

Background

The use of mobile robotics as a platform for engineering education is well-established. It is unfortunate that mobile robotics as a discipline is mostly overlooked in undergraduate programs. The goal of most of the available pedagogy on mobile robotics is to act as a platform for teaching teamwork, basic engineering principles, programming, etc.[1,2] The experiments which are the subject of this paper take place in a senior-level elective on mobile robot design. It is worth emphasizing that the course teaches mobile robotics from a design and experimentation point of view, as a discipline in its own right. While the pedagogical goals of the course certainly involve reinforcement of the basic ABET criteria for undergraduate education, we believe that the most significant goal is to actually teach the students about mobile robotics in such a way that they would be able to design and build real systems for use in the real world[3]. This is especially interesting for students at the United States Naval Academy due to the increased emphasis on unmanned and autonomous technologies in military settings. In addition to studying wheeled and tracked vehicle design and control[4,5], exercises in the subject mobile robotics course focus on the use of articulated serial links for locomotion, including a wormlike robot and a multi-leg walking robot.

The projects discussed in this paper have the following set of objectives.

1) To introduce and explore methods for locomotion other than wheels and tracks.

2) To demonstrate the methodology for both structural design and gait synthesis in articulation-based locomotion.

3) To demonstrate a methodology for extrapolating biological locomotion methods to robotic systems.

The metrics for success in these endeavors involve measurement of the performance of the students' designs as well as evaluation of the insight generated during the exercise. As such, all projects receive a performance grade separate from the report grade, wherein students may mitigate some of the poor performance of the system through careful exposition and discussion of the possible remedies for problems in the design.

Preparation

In order to prepare students to undertake articulation-based robot design, students are provided with a series of lectures on gait synthesis, basic leg design and biological locomotion. These discussions focus on the best practices of leg and locomotion design as motivated by a wide array of animals and insects as well as basic kinematics. This year, students were not introduced to limbless articulated motion prior to the exercises outlined below, but a wide array of limbed robots were evaluated in conjunction with the biomimetic studies.

Hardware

The most recent incarnation of the mobile robotics class uses the Bioloid kits from Robotis (~$849 USD per kit at the time of publication). These units have many significant advantages over servomotors and other reconfigurable kits. In the systems engineering robotics program at USNA we have experience with the Lynxmotion servo erector set[6], the ROBIX Rascal reconfigurable kit[7], LEGO systems[8], and component-based design (using a Basic Stamp[9] standard R/C servomotors and LEGO parts). The Bioloid kits are more expensive than these other options (with the possible exception of the Lynxmotion systems, which are purchased piecemeal as opposed to a kit). For this price, however, the kit includes eighteen (18) serially-controlled servomotors that can be software configured (including for continuous rotation) as well as a sensor head equipped with three-direction sensing of range (IR) and ambient light, as well as a sonic sensor. The kit also includes wheels and a wide variety of brackets and mounts.

Figure 1: Bioloid Kit (Comprehensive Version).

The design needs of non-rolling robots differ from the wheeled variety. Since articulated appendages and actuators must support the weight of the robot and possibly the power supply, frame rigidity and motor stall torque are of paramount importance. The motors are high-torque (229 oz-in stall) and moderate speed (0.196sec/60° no load). This is equivalent to the best R/C servos in the same size range. In addition, the hardware connections and components in the Bioloid Kits are strong and easy to reconfigure. Unlike the Lego kits, the mechanical connections use nuts and bolts providing equally strong resistance to tensile and compressive loads. Another advantage, versus the Robix kits, is that the links can be attached on both sides of the servo, via a C-shaped bracket. This symmetric mounting configuration eliminates the tendency of off-axis moments to cause the linkage to fail. Given the added capability of the kits, the assembly instructions and included video demonstrations are very clear and easy to follow. Wiring is a virtual non-issue, as the controller has four control-line connectors, and the motors may be connected to the unit or to each other in any order, so long as there is a connection chain tracing each motor to the controller. Each motor has an ID (which can be changed through software) and is immediately recognized by the controller when the software is executed.

Also, the large number of degrees of freedom of articulated robots requires a systematic interface for pose generation and programming. Here again the Bioloid kits excel. The programming of the Bioloid relies on two pieces of software: the motion editor and the behavior programmer. The motion editor is an easy-to-use pose storage system, under which the designer can manipulate the robot into a variety of poses and save a sequence for later execution. There are a few quirks with the system, but it tends to be a relatively easy way to store large numbers of coordinated joint motions for high-dimensional systems such as walking robots.

The behavior programmer is a relatively simple Basic-like programming language with some special constructs for interfacing to the Bioloid sensors and motors. With minimal instruction, students who are familiar with programming are able to generate moderately sophisticated code that interfaces with the poses and sequences stored using the motion editor. If desired, students may directly control the motors from the behavior program, although this tends to be effective only for very small robots or for systems that rely on rolling motion.

The Challenges

Two challenge assignments were used to emphasize the design concepts associated with locomotion without wheels. The first, intended to familiarize the students with the Bioloid kits as well as to encourage study of biological locomotion concepts, involved worm-like robots. The second challenge required the student groups to build and program a complete walking robot. Garnering design inspiration from other teams within the class was explicitly forbidden (especially for the contest-based challenge). This is achievable at USNA due to the honor concept, as students were required to indicate that their submitted design was theirs alone and fully conformed to the limitations on resources. Students who lied about their design's origin, and were caught, could face serious ramifications, up to and including expulsion from the Academy.

To encourage innovation, students were forced to carry out these design challenges with no recourse to diagrams, videos or discussions *of robots* on the web. Due to the proliferation of individual and course webpages at other universities – as well as the popularity of YouTube – the instructors felt this was a critical requirement. However, students were allowed to look at biological locomotion systems for inspiration, in the form of videos, kinematic analyses, etc.

The Worm Chariot Race

The first of the two challenges, and the less involved, focuses on the generation of a serial-chain mobile robot. The requirement was that each interior link of the robot be connected to exactly two joints (where a *link* is defined in the traditional robotics manner). The first and last links connect to exactly one joint. No active appendages of any sort were allowed, although the links themselves could be complex.

To ensure that the students focused their designs toward effective locomotion, the worm robots are required to pull behind them a 'chariot,' which contains the battery and processor. The robots were thus required to generate good traction and ground force, as opposed to simply generating forward motion. The exercise took place over one week, during which there were four hours of laboratory time.

Our prior experience suggested that the motivation of the students would increase significantly were the design cast as a competition. As such, the demonstration of the system was embedded in a race. Worms raced in pairs (single-elimination tournament) after an initial seeding round consisting of a straight-line dash. Once the race started, the worms were required to travel forward until they identified an obstacle in their path, after which they were to turn 90^{o} to the left and then repeat the process. The track followed after an obstacle was required to be within one foot of the obstacle, so that very long-range sensing was not possible. Worms that left their lane (defined somewhat loosely by the evaluators) were reset by hand into the proper area (if they were impinging on the other robot) or were allowed to continue off course. The evaluation track is shown below:

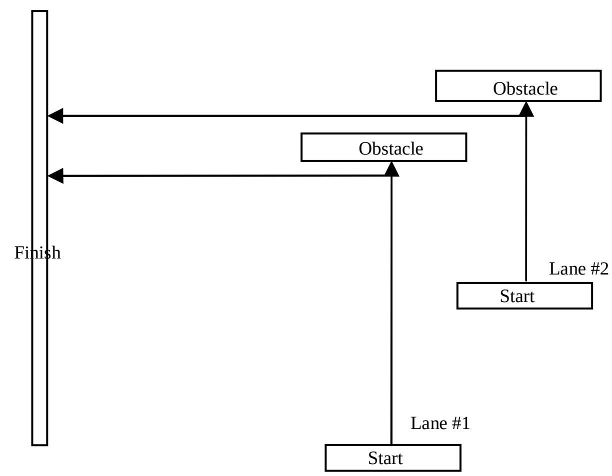

Figure 2: Test track for worm chariot race.

The students were given a performance grade (based on straight-line motion and accuracy of the sensing and 90-degree turns) as well as a report grade. The team that finished in first place after the single-elimination tournament was not required to write a lab report for the project, and received a grade based entirely on performance.

The Walking Robot

In this multi-week exercise, students were tasked with designing a 4+ limbed walking robot with locomotion and structure designed to optimize (or at least emphasize) one of the following concepts:

a. Speed (over level ground)
b. Power (load capacity)
c. Agility (obstacle clearance, foot placement ability (workspace))
d. Novel locomotion

Lecture material presented comparative anatomies, commenting on joint placement and limb lengths and the resulting effects on the speed and agility of the various animals. A variety of gaits were also reviewed and students were encouraged to seek inspiration from further study of biological locomotion.

Each leg of the system had to demonstrate at least 2DOF, and the system was required to be able to complete the following.

a. Walk forward and backward, turn left and turn right.
b. Move into a statically stable, zero-energy pose (for shutdown/startup).
c. Sense the environment and respond with the various gaits and the zero-energy state (sensor-action mapping was to be determined by students).

The robots were tested by evaluating:

a. Level-ground speed (both forward and backward);
b. Turn radius (left and right);
c. Turn rate (left and right);
d. Load carrying capacity (a plot of load vs. speed for straight-line motion, using batteries in LEGO saddlebags / cargo stays for loading);
e. Step-over height;
f. Foot placement area (full dimensions of ground area into which *each* foot can be placed when the unit is at standard body height); and
g. Stability issues.

In grading, it was imperative that all of the capabilities were demonstrated reliably, and that the students were able to explain the performance levels achieved for the metrics above, as well as how they might be improved. It was also essential that the students understood and explained the components of the design that led toward optimization of the selected locomotive capability. Finally, students were required to analyze the interaction of design elements as they impacted the various metrics, and discuss how the performance could be improved in a theoretical second generation.

Solutions

Worm Chariot Solutions

Students were apprehensive when told that they could not use templates from the Internet nor from the manual for the two challenges, but the results were more than satisfactory. Creativity and innovation levels were high, and the added requirement that students could not copy from one another provided impetus for critical thinking. Many students were convinced that the worm robots would all look and move identically, even under the restrictions on available materials and in-course copying. In the end, the breadth of solutions, and of capabilities, was quite satisfying for both the students and the instructors. It is clear that, with sufficient preparation and instruction, students can develop novel robot designs without recourse to similar designs online or even in the manual.

Designs varied in four significant ways: number of joints, joint configuration, link design and gait design. The number of joints varied from a two-joint “galloper”, which failed to turn, to a seven-joint worm; joint configurations typically consisted of at least three pitch joints, plus one or more yaw joints used for turning. Several teams experimented with one or more roll joints to little avail. Design of the links varied mostly in the ground contact surface. Some teams simply used traditional rectangular links, while others created non-articulated “feet” -- wide surfaces to increase balance and stability while the link was in contact with the ground. Several teams augmented links or feet with devices designed to increase traction on the carpet such as "cleats" made from exposed screws. Examples are shown in Figure 3.

The three primary modes of locomotion were: [plant front – contract - plant rear-extend] gaits (both vertical and horizontal planes), a novel crab-like [plant front and rear – move body – lift front and rear – move legs] gait, and sinusoidal locomotion methods (with the sinusoid traveling from the rear to the front in the vertical plane).

Walking Robot Solutions

Sample walking robots are shown in Figure 4-Figure 6. Note the variety of designs and objectives. Most common were 4- and 6-legged designs. Bipedal designs were forbidden due to difficulties with attaining static stability and the high likelihood of locomotive failure. Only one group entered a design with an odd number of legs (with the fifth leg used in turning). The most variation was seen across the 4-legged designs, such as link length, sensor mounting and foot design, and body-leg attachment points. The 6-legged designs varied significantly in their gait design but less so in terms of their mechanical configuration. Building a 6-legged walker requires using most of the parts in the kit, limiting some of the possible design permutations. No students submitted designs with more than six legs.

Gait generation proved to be complex and varied. Most common for 6-legged designs was a tripod gait, in which at least three legs stay in contact with the ground at all times. Again the 4-legged robots exhibited more variation, including an alligator gait, a tripod gait and a gait which was not statically stable. This last gait relied on a forward center of gravity to cause the robot to fall forward in a controlled manner when, for example, the right front and left rear legs were lifted simultaneously. The robot required a qualitatively different gait to locomote backward.

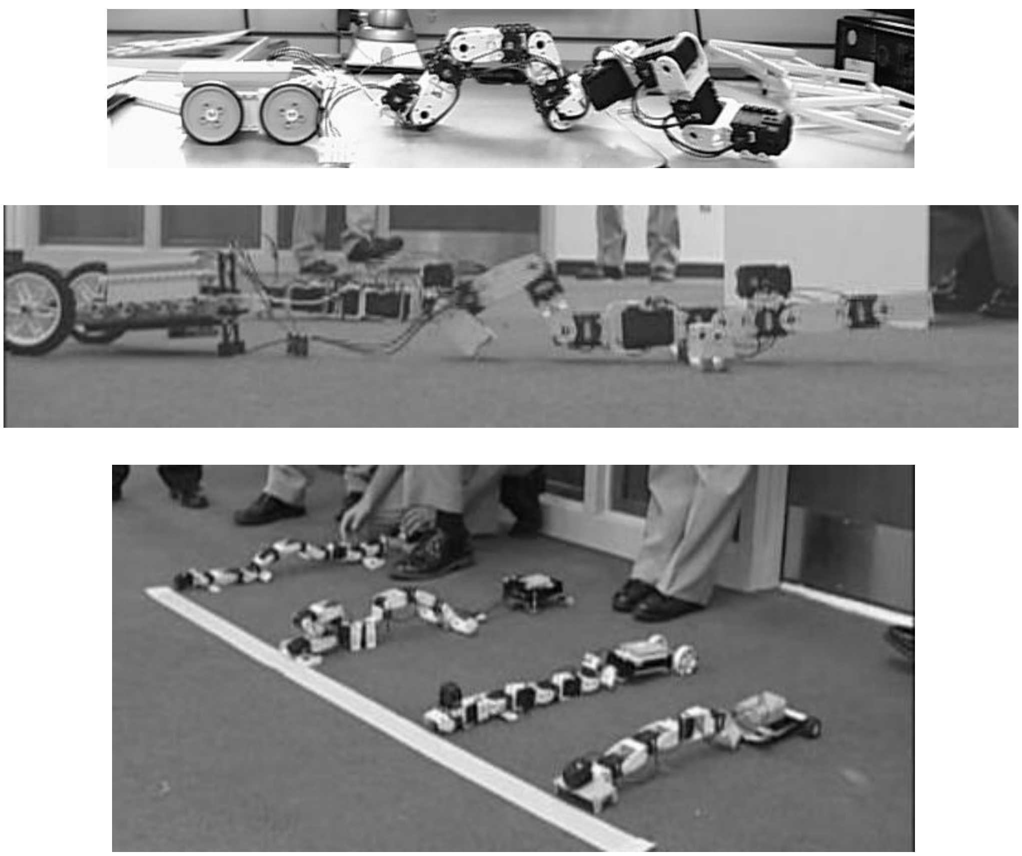

Figure 3: Sample worm chariots.

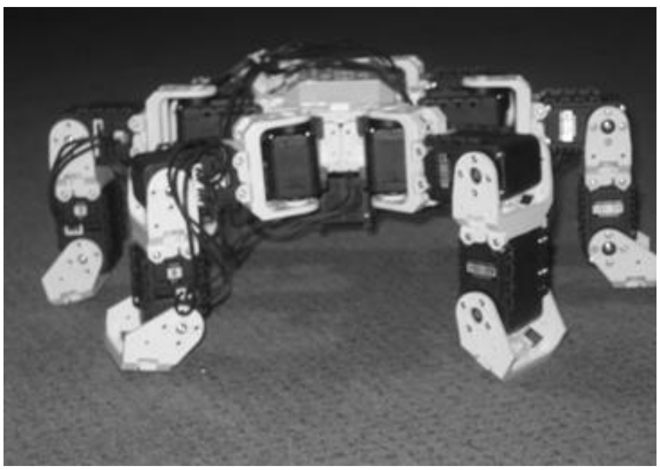

Figure 4: Six-legged walking robot. Designed for stability and speed.

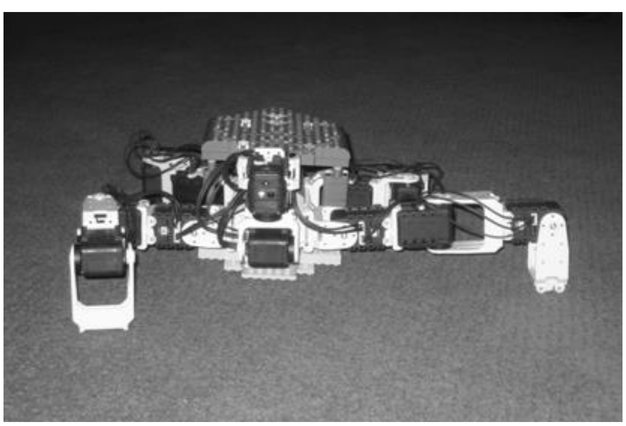

Figure 5: Turtle-like robot, designed for power.

Figure 6: Ape-like robot, designed to perform knuckle-walking and allow a bipedal stance.

Assessment

While it is misleading and inappropriate to list all of the values of the metrics for the walking robots (as each design focused on different objectives), the outcome was very good. The grades for the exercise can bee seen in Table 1 (there were 16 performance grades and only 10 report grades available for analysis).

Poor report grades mostly stemmed from lack of detail in communicating gait patters and joint configuration. A second issue was lack of rigor in testing (e.g. single trial or failure to quantify performance).

Common causes for poor performance across both projects are identified below.

- Poor traction: the feet tend to backward slip against the carpet during the power stroke of the gait. Without good traction the net forward motion per gait cycle is limited.
- Difficulty turning: In both exercises turning proved to be more difficult that forward motion.
- Gait inefficiencies: Students tended to increase speed by simply increasing the frequency at which the gait was executed. However, many gaits lacked efficiency, such as not fully extending

Grade \ Metric	Worm Performance (of 16)	Worm Report (of 10)	Walker Performance (of 16)	Walker Report (of 10)
A	7	5	11	9
B	6	5	5	1
C	2	0	0	0
D	1	0	0	0
F	0	0	0	0

Table 1: Grades Distribution.

the raised leg(s) during the foot placement phase. Slippage from poor traction also was a contributor here.

- Poor joint coordination: During the power stroke phase of the gait, the robot must alter all the joint angles so as to shift its center of gravity forward while maintaining all feet in contact with thePoor joint coordination: During the power stroke phase of the gait, the robot must alter all the joint angles so as to shift its center of gravity forward while maintaining all feet in contact with theground. Doing this correctly is equivalent to velocity control of a parallel kinematic chained mechanism and was beyond the scope of the course. Still, students found a series of intermediate poses that seemed to work.
- Time management: Students falsely assumed that the majority of the work was in the mechanical design and underestimated the amount of time required for gait design and programming

The important lesson to learn from the grade distribution is twofold. It is clear from the grades as well as student response that a number of lessons were learned from the worm robot and carried forward to the walking system. Primary among these was the need for significant time devoted to generation of gaits and the importance of traction. Many students indicated that they had assumed gait generation would be straightforward for the worm robots, but were unpleasantly surprised. It is also clear that the students gained familiarity with the kits and were able to better utilize them for the walking robot.

Although it is tempting to point to these results as a clear indication of student learning, there are other factors involved, including available time, weight of the exercise in the course, and instructional support for the objectives. The walking robot was designed and fielded over the course of three weeks, while the worm chariot was completed in just one. The relative weighting of these exercises in the course was in proportion to the length of time as well, so students who did poorly on the worm exercise may well have placed more emphasis on the walking robot.

Student feedback on the projects was excellent, although no numerical assessment of these learning tools was carried out this semester. Comments in the formal reports and on course critiques indicated an overall positive response to the projects, with a few notable concerns.

Primary among the complaints was that the test track for the worm chariot race was not shown to the students in advance. It has been suggested that this should be changed next semester, but we are currently leaning toward showing a sample track that is not identical to the actual course. The reasoning for this is that we want to emphasize design for objectives, not design for a specific course. The required actions of the worm robot should allow it to crawl through any course with one-foot lanes and left-only turns. If provided with the actual course, students will learn how to configure their system (aim it on the starting line) so that it optimizes the run, rather than adjusting the code as we would like. We saw exactly this behavior in an earlier challenge in the class (a dead reckoning course). However, providing the sample course allows for adjustment of sensing parameters and tuning of the turning gait as well as clearly indicating the need for very straight motion.

Other than this complaint, students were mostly concerned with the hardware and its associated learning curve. Complaints about the robustness of the equipment were minimal, as were complaints about the software.

Conclusions

The exercises were quite successful in terms of the objectives outlined in the Introduction. Students were able to use biological motivation to design and implement articulation-based locomotion concepts for both limbed and limbless locomotion. The classroom discussions clearly provided sufficiently rich background information for students to carry out even novel designs (such as the worm-like robot) with little external guidance and no 'pattern matching' of robot designs seen online.

In the future, some minor changes will be implemented based on the results from this year:

1) A formalized metric for worm performance (linearity and turning) will be provided to the students. Grades in this iteration were based on a qualitative and comparative analysis of speed, linearity and accuracy of the turn.

2) A model test course will be provided for the worm chariots. The final race course will have more than one turn.

3) Walking robots will engage in competitions in several events, much like gymnastics, with individual awards and an overall winner. Students will take notes on the winning robots to use in analysis of their own devices.

Bibliography

1. URL: http://www.trincoll.edu/events/robot/, "Trinity College Fire Fighting Home Robot Contest," accessed 12 Jan 2006.

2. URL: http://www.igvc.org/deploy/, "The Annual Intelligent Ground Vehicle Competition," accessed 12 Jan 2006.

3. Dudek, G., and Jenkin, M., *Computational Principles of Mobile Robotics*, Cambridge University Press, Cambridge, MA, 1999.

4. Bishop, B. E. and Wick, C. E., "Educational Control Studies of a Differentially Driven Mobile Robot," *Proceedings of the 2003 Southwest Symposium on Systems Theory*, March 2003, pp. 308 - 312.

5. Bishop, B. E., "Teaching Robot Design: Locomotion Beyond Differential Drive," *Proceedings of the 2005 ASEE Annual Conference, CD-ROM, June 2005.*

6. URL: http://www.lynxmotion.com/Category.aspx?CategoryID=73, "Servo Erector Set," accessed 18 Jan 2008.

7. URL: http://www.robix.com/default.html, "Robix Rascal Home Page," accessed 18 Jan 2008.

8. URL: http://mindstorms.lego.com/,"LEGO.com MINDSTORMS NXT Home," accessed 18 Jan 2008.

9. URL: http://www.parallax.com/Default.aspx?tabid=295, "About the BASIC Stamp microprocessor," accessed 18 Jan 2008.

Biographical Information

Bradley E. Bishop is a Professor in the Systems Engineering Department at the U.S. Naval Academy. He received his BS degree in Honors Electrical Engineering from Michigan State University in 1991, and his MS and PhD degrees from the University of Illinois at Urbana-Champaign in 1994 and 1997, respectively. His research interests include cooperative robotics, robot locomotion and autonomous vehicles, with an emphasis on ground-based, surface and multi-mode systems.

Joel M. Esposito is an Associate Professor in the Systems Engineering Department at the U.S. Naval Academy. He received the BS degree from Rutgers University and the PhD from the University of Pennsylvania in 2002. His interests are in the areas of Robotics, Control Systems and Autonomous Vehicles.

Jenelle Armstrong Piepmeier is an Associate Professor in the Systems Engineering Department at the U. S. Naval Academy. She received the BS degree from LeTourneau University and the PhD from the Georgia Institute of Technology in 1999. Her interests are in the area of vision-based control of robotic systems.