Testing of the FE Walking Robot

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I. Abstract

This paper documents the method and result of testing the FE walking robot during spring 2006. Improvements in code and launch technique throughout the semester are discussed. At its peak performance, the robot achieved 18 steps on two occasions. The author predicts that with continued optimization and testing, the FE walking robot can surpass this record.

II. Introduction

The early Fe team envisioned creating an energy efficient robot that was able to achieve reliable long distance walking by using passive dynamic principles. In spring 2005, the Fe team designed and constructed a bipedal walker with a telescoping leg [1] [2]. The final prototype at the end of the semester was able to walk a few steps; however, the prototype was unable to achieve this with every attempt and was not considered reliable. During fall 2005, the electrical sub team added additional sensors and re-wrote the code more efficiently. The mechanical sub team attempted to improve the robots reliability by adding a mechanical locking mechanism that aimed to regulate step size [3].

The design, machining, and implementation of the locking mechanism took longer than expected. As a result, the team was unable to test or evaluate the effectiveness of the mechanism during the fall semester. Throughout the spring semester, the team tested more frequently and documented the testing trials to increase the robot's reliability and maximum number of steps. Most of the testing sessions were video taped, which allowed the team to watch the robots dynamics in slow motion and to gain a better understanding of the system. The robots settings were also recorded, to document conditions for the robot at a given time, for improved repeatability and organization. This paper focuses on the testing and iteration step in the design process, and it documents the evolution and results of testing during the spring semester.

III. Methodology

A. Testing Schedule

For the first few weeks of the semester, two or three people tested the robot once a week. At the end of February, testing frequency was increased to 5 days a week, as an on-campus student project show case approached. A few weeks after the show case, the team refocused testing efforts, and created one primary testing group. The primary testing group had three people, which tested three days a week, in pairs. The idea behind this primary testing group was to focus the knowledge of how the robot behaves with a fewer number of people. However, all members of the FE team were included in testing, by contributing an additional one or two days of testing per week. One of the three primary testers would also be present during these additional testing sessions to facilitate communication among all testers.

B. Video Footage

Testing and filming simultaneously was easiest when three testers were present. One tester was responsible for launching the robot, another for catching the robot when it fell, and the last for filming and panning the camera as the robot walked. However, it was often difficult to coordinate the teams schedules, and usually only two people were able to test. Typically, the person launching the robot became the video recorder after the robot was launched. After recording video for a certain number of runs, the testers would watch some of the videos in slow motion to observe what was happening and then discuss what could be tweaked or tried next.

C. Documentation

Video taping was extremely helpful for observing and understanding system dynamics. However, the footage itself only records how the robot is performing, and it cannot not help increase reliability without careful documentation of current settings. The testing team kept a testing log to accompany the video footage taken during testing. On these testing sheet, basic information was recorded, including tester names, testing date, and start time on the tape. Additionally, the potentiometer readings for the length of the middle leg and the locking angle were recorded, as well as special conditions and launch technique used as described in Section III-E. Lastly, the log included comment areas for both observations, stating the number of steps or how the robot fails, and reactions, including hypotheses explaining robot behavior or ideas of what to change for the next testing session.

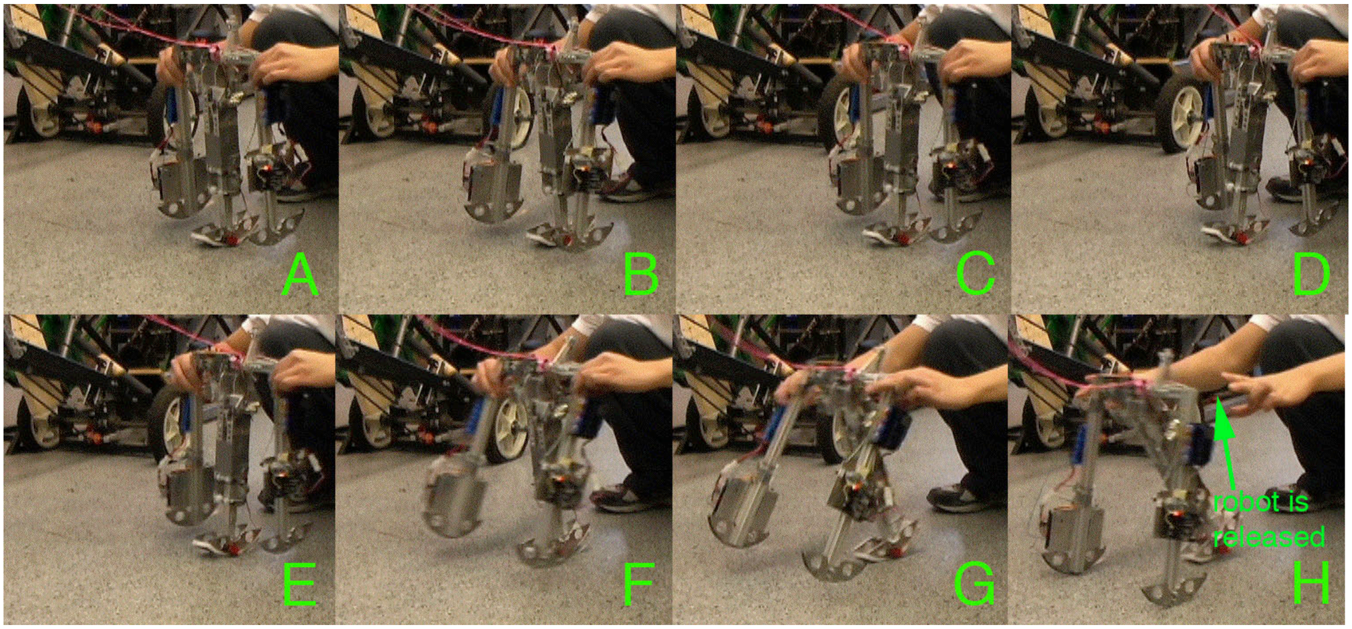

Fig. 1. Demonstration of Push Launch Technique

D. Code

The robots code was also changed as the semester progressed. Parts of the code were re-written to run more quickly and efficiently. Also, the trigger that controlled when the motor extended the middle leg was changed from a critical angle, determined by a hip potentiometer reading of how far the middle leg swung out, to the depression of the middle leg limit switch. This caused the middle leg to extend once in contact with the ground, agreeing with how the robot actually performed. This performance is described in more detail in Section IV-A. Also, a switch was added that consistently extended the middle leg to the longest position before the launch. Additionally, the primary testing group learned how the code functioned, with the intent to optimize the system for reliability by changing the code, including variables such as motor power, motor ramping speed, or time delays.

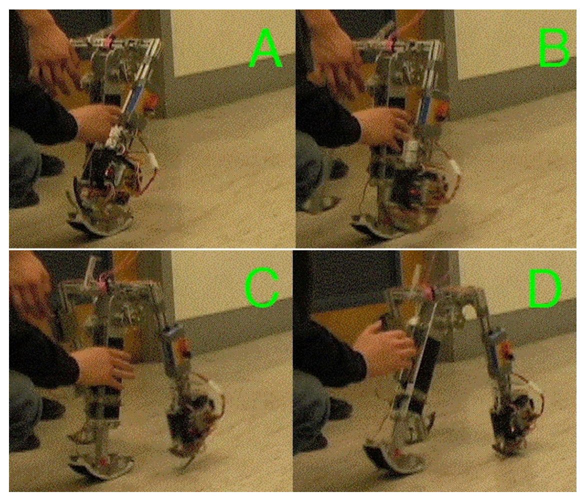

Fig. 2. Demonstration of Drop Launch Technique

E. Launch Technique

As testing increased, the testing team attempted to eliminate as many variables in the system as possible. One major factor that hindered repeatability was the inconsistency of the launch. A repeatable launch is essential because the system will not behave the same way in every trial run without a consistent set of initial conditions.

The first launch technique, called the "push technique," was not effective. The person launching the robot would rest the robots inner leg on the ground at a medium leg length (Figure 1a), and swing the outer legs forward and backwards (Figure 1b-e) before releasing them forward with a wrist flick (Figure 1f-h). Of course, with every launch the push technique added a different amount of momentum to the system, released the robot from a different height, and caused a different angle between the inner and outer legs. Additionally, the exact length of the middle leg was not recorded, and the push technique varied slightly among testers. The robot only achieved 3 or 4 steps with this technique.

The next method of launch developed was the "drop technique." Instead of adding momentum to the system by swinging the outer legs, the tester would drop the outer legs from a certain height behind the middle leg (Figure 2a-b), and release the robot as the outer legs swung through (Figure 2c). However, the amount the robot was tilted forward or the height the outer legs were dropped from were not measured. The middle leg was set on the ground with a medium leg length as in the push technique. This technique was also ineffective, and only yielded a few steps. A variation of the drop technique that used the front locking mechanism to fix the angle between the two legs was also used, although the forward angle of tilt or the height of outer legs were still not measured. Using the drop technique with the front locking mechanism, the robot reached 6 steps during a few trials and set a new record of 8 steps.

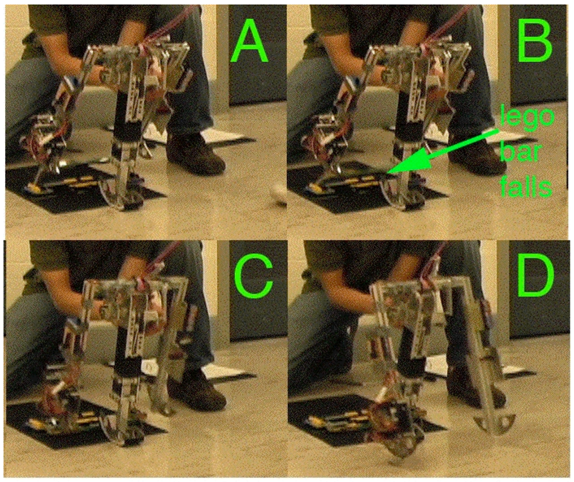

Fig. 3. Demonstration of Lego Launch Technique

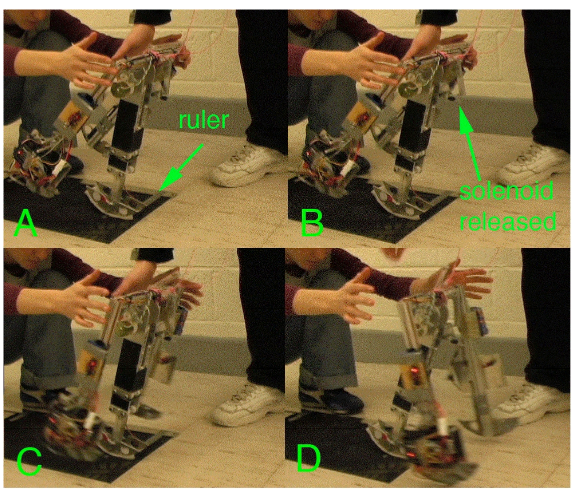

Fig. 4. Demonstration of Launch Technique with One Laser Pointer

Next, the testing team attempted to standardize the height the outer legs were released from by building a Lego launcher. As before, the robot was positioned with the outer legs behind the inner leg, which was set to a medium leg length. The robot was positioned such that it was near the equilibrium position between falling forward and falling backwards, and the Lego stand barely supported the weight of the robots outer legs (Figure 3a). In this technique, the angle between the inner and outer legs was fixed by using the locking mechanism. The robot was released from rest when the tester pushed the solenoid, releasing the arm that held the inner leg locked. Releasing the lock caused the outer legs to swing freely, and since the Lego stand was barely supporting the outer legs, the portion of the Lego stand in contact with the outer legs would rotate toward the ground (Figure 3b). The robot was then free to take its first step (Figure 3c-d). This technique showed improvement toward the goal of reducing the number of variables in the launch; however, it was difficult to use because of the necessary balance in the set up. Not only did the robot need to be balanced forward and backwards, but it also needed to be balanced left and right for both legs to rest on the Lego stand. The latter was difficult because of the unequal side to side weight distribution of the robot. The exact position or angle needed to use the Lego launcher was not optimized because of the difficulty of use. The robot only obtained 3-4 steps using this technique.

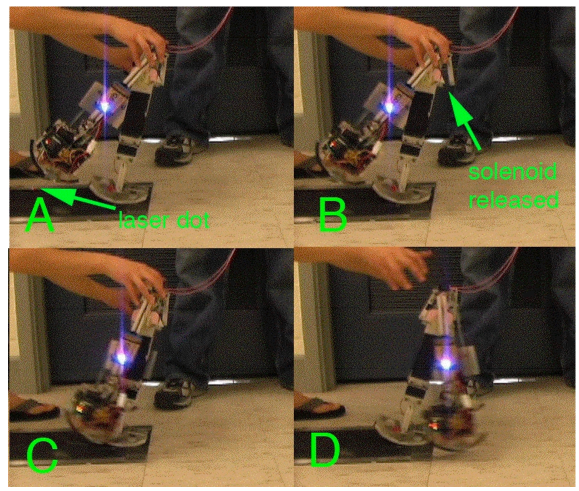

Fig. 5. Demonstration of Launch Technique with Two Laser Pointers

The next launch technique developed used a laser pointer. The laser pointer was attached to the inside of one of the outer legs with a switch. The outer legs were again in front of the middle leg, set to a medium leg length, and the angle between the inner and outer legs was also fixed by the front locking mechanism. The robot was placed on a mat that had a ruler attached to the side, and the laser indicated the angle of forward tilt, which is easily recorded and repeated (Figure 4a). The robot is tilted forward such that the center of gravity of the robot is in front of the point where the middle foot contacts the ground, and therefore, the robot must be held at rest by the tester. The tester releases the robot by pushing the solenoid (Figure 4b), releasing the front lock, as in the Lego launching technique. The robot is again free to move freely for its first step (Figure 4c-e). This design was quickly adapted to include a second laser pointer on one of the outer feet and second ruler on the launching mat, to ensure that the robot was balanced left and right (Figure 5) This launch technique also included various attempts to record and make the initial inner leg length constant. The final method of achieving this was with the addition of a switch that caused the motor to extend the middle leg fully and slowly. This technique has proven

Fig. 6. Expected Walk Cycle

fairly successful this semester, and the robot achieved 18 steps, its record, using it. This technique also has the advantage that it is easy to modify and record the launch angle as needed. It is a great improvement from the push technique used at the beginning of the year.

F. Other Considerations

1) Safety: It is possible to get injured while testing, especially by getting one's fingers caught in the telescoping leg during extension or retraction. Therefore, tester safety must be considered. All members of the FE team were alerted of this danger, and other measures were taken, such as filing sharp corners and covering holes in the middle leg. Additionally, to prevent damage to the robot if it fell during testing, a cord was attached to the top of the frame. This allowed the tester to walk beside the robot more easily and to catch it before falling.

2) Environment: The FE walking robot is a small-scale project which does not significantly affect the environment. The robot's largest environmental impact is material use, which is minimal due to the robot's small size.

3) Standards: In fabricating new parts for the robot during testing, the FE team was aware of different unit systems. For example, the aluminum extrusion frame requires metric connectors, while most of the student machined parts use English units.

4) Aesthetics: The robot's appearance was also considered to be important, since the robot was presented at two poster sessions and continually video taped. The FE team increased its efforts this semester to replace temporary solutions, such as duct tape, zip ties, and hot glue, with more permanent solutions, including screws and angle brackets.

IV. TESTING RESULTS AND DISCUSSION

A. Push Technique

The push technique was used through the middle of February. The push launch typically yielded 3-4 steps, with a maximum of 6, where each step is counted when the inner or outer legs contact the ground. The robot was not consistent during this phase of testing, though the testing team began to learn exactly what was happening when the robot walked.

The testing team observed and attempted to understand two common behaviors. First, the robot was not performing the walk cycle as originally expected. As described in the FE design reports from last year [1] [2], the middle leg has three distinct lengths: short, where the middle leg is able to avoid scuffing because it is shorter than the outer legs; medium, where the outer legs are able to avoid scuffing because the middle leg is slightly longer than the outer legs; and long, where the middle leg extends to a length to push the robot off balance. The description of the walk cycle is summarized in the stages below:

- push off: The outer legs are in front of the middle leg, and the middle leg extends from medium to long (Figure 6, 1-2)
- retraction: Immediately after push off, the middle leg retracts from long to short, so that the middle leg is able to swing through without scuffing (Figure 6, 3-4)
- extension: After the middle leg has swung past a certain angle, the middle leg extends to medium, then the middle foot hits the ground (Figure 6, 5-6)
- outer swing: The middle foot is in the medium position, the outer legs swing through, and the cycle repeats (Figure 6, 7-9)

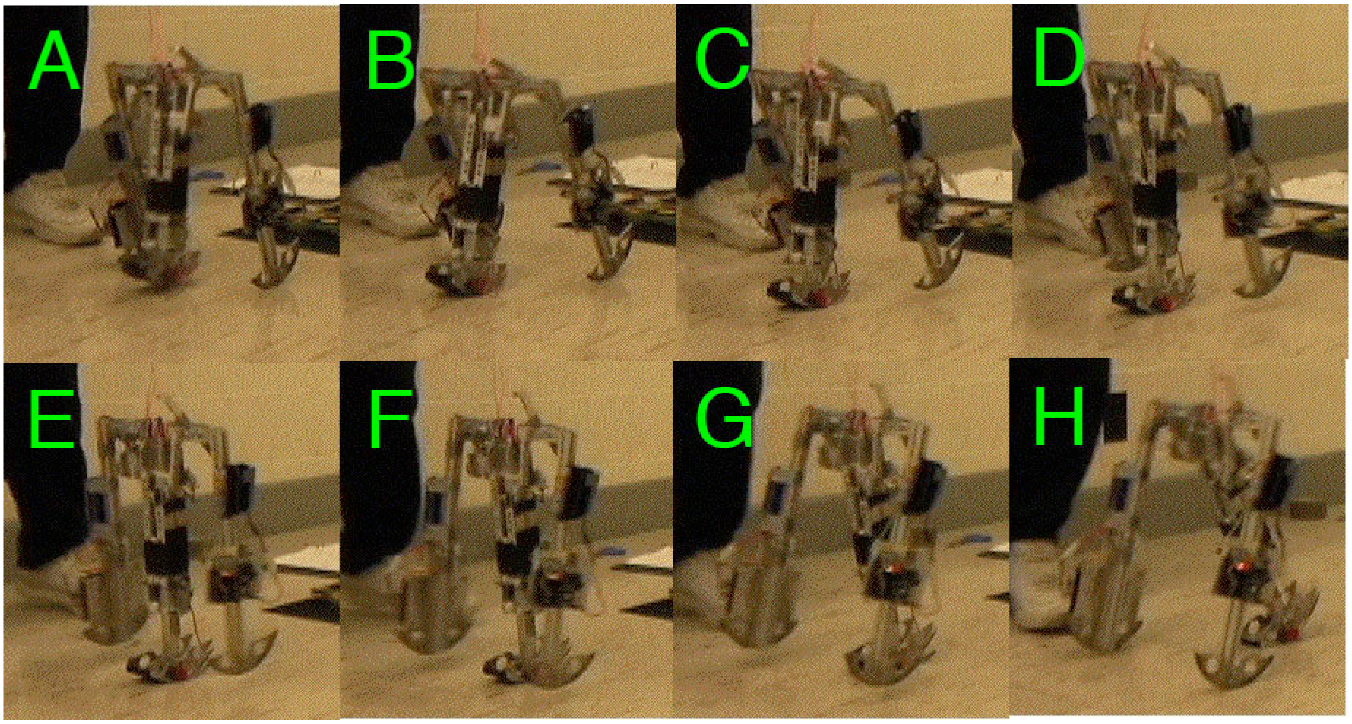

Fig. 7. Walk Cycle as Performed

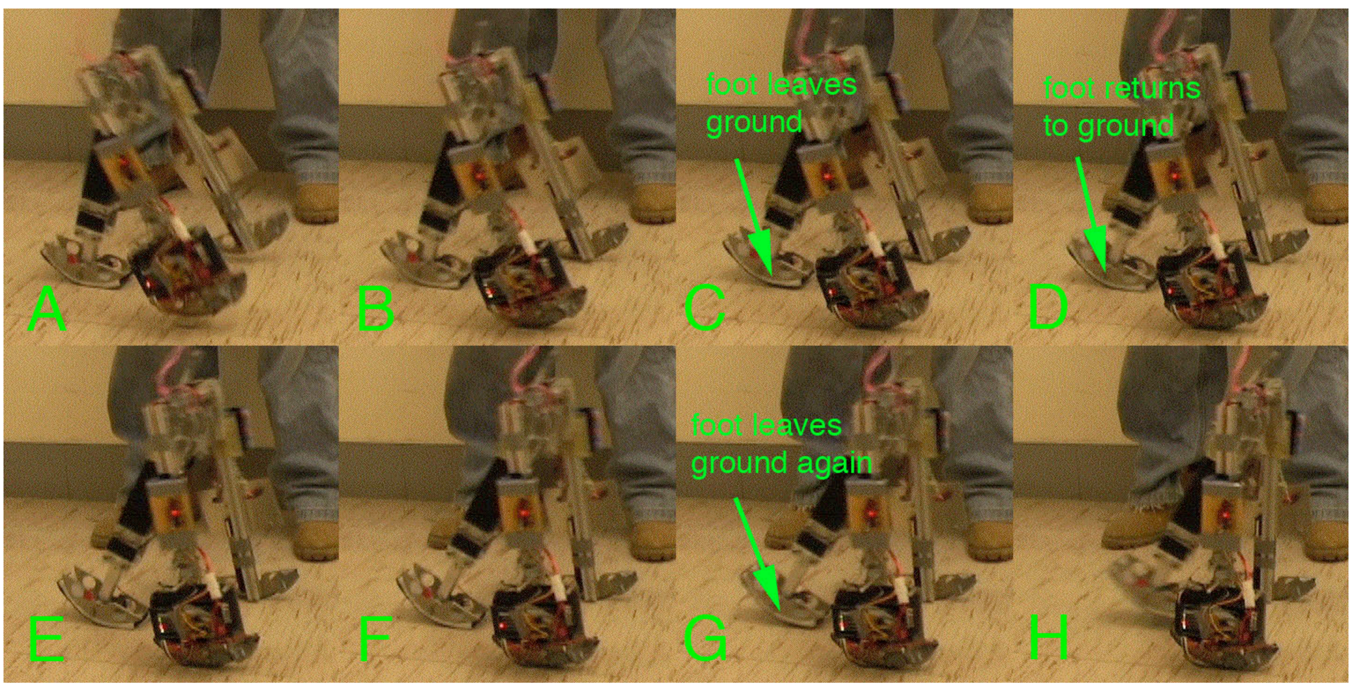

Fig. 8. Double Push Observation

However, after watching the early video footage, the testing team observed that the leg extension was occurring after the middle leg made contact with the ground, instead of in two distinct stages as described above. In Figure 7, the middle leg contacts the ground at b, and extends at c through e, before the outer legs swing through at f through h.

The combination of these two stages was most likely the result of time delay in the hip potentiometer reading and motor ramp up function, as well of the continuous motion of the middle leg swing. The testing team spent two weeks tweaking the robot and trying different launch techniques to make the robot walk as previously expected, while discussing whether the walk cycle as expected was actually the best. Since the robot had been walking a few steps with the modified walk cycle,

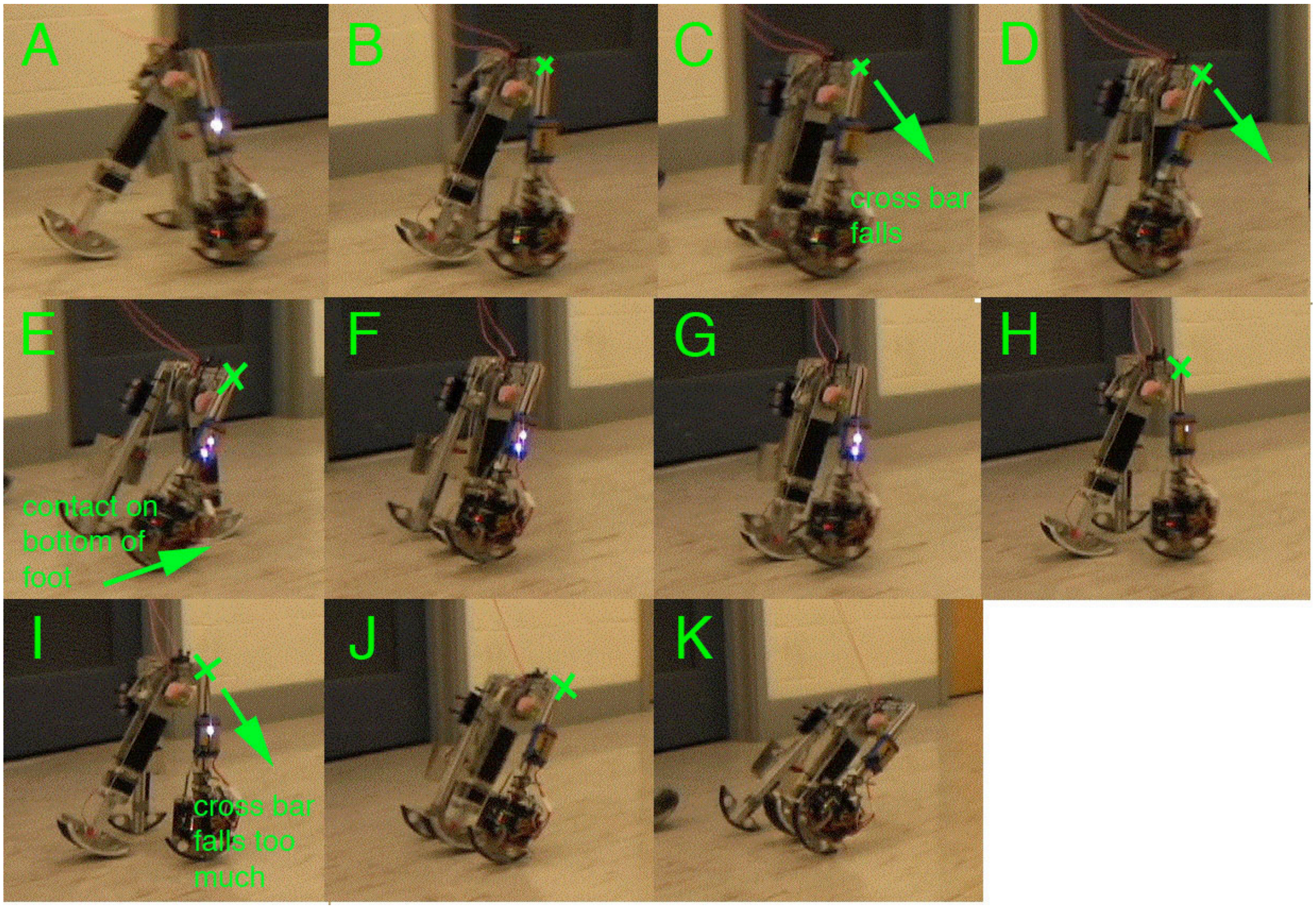

Fig. 9. Common Falling Mode

the testing team decided to maintain the walk cycle as the robot had been performing, and not how the robot was expected to perform. The testing team continued to tweak the mechanical variables and modify the code to optimize the robot using the new walk cycle.

Second, as the robot extended the inner leg from the middle to long position during the push phase of the walk cycle, the middle foot appeared to contact the ground twice, resulting in what appeared to be a double push off. The double push seems to be a result of a delay in the code. Theoretically, when the outer legs hit the ground and the limit switch is triggered at heel strike (Figure 6, 1), the middle leg extends from its middle position to long for the push off (Figure 6, 2), then immediately retracts to short for the middle leg to swing through (Figure 6, 3). However, in the case of the delayed push off, the outer legs hit the ground and the limit switch was triggered, but the inner leg did not immediately extend from medium to long. Instead, the inner leg began to lift off the ground (Figure 8c) as the robot rolled forward on the outer feet (Figure 8b-c). At some point after the inner leg started lifting off the ground, the inner leg extends to long for the push off (Figure 8d-f), then retracts to short for the swing through (Figure 8g-h). This means that the inner leg actually lifts off the ground at c and returns to it at d for push off, resulting in contact at two points. The double push was reduced by bending the arm of the limit switch toward the ground to trigger earlier, in order to compensate for the delay in code. This also appeared to help the consistency of the walk, because the robot was able to obtain four steps a few trials in a row.

B. Drop Technique and Lego Launcher

During the next phase of testing, we experimented with the drop technique. Although the robot was able to walk 6 and 8 steps with this technique, we were still unable to reach these distances reliably. We again realized the need for a consistent launch, and attempted using the Lego launcher to achieve this. The Lego launcher proved successful for a few trials of 5 steps. While experimenting with the Lego launcher, we eliminated the middle leg length as a variable in the launch by turning the cam such that the middle leg was set to the longest length possible. The main problem we identified while testing with the drop technique and Lego launcher was that the robot would fall forward before the middle leg was able to fully swing through to take another step (Figure 9). The robot appears to fall forward when the robot has too much momentum. As the outer legs roll forward from the bottom of the foot to the front of the foot, the cross bar connecting the two outer legs moves toward the ground (Figure 9b-e). This also brings the middle leg, which is in its retracted position, toward the ground, since the middle leg is attached to the cross bar. When the robot has too much momentum, the outer legs cause the cross bar to fall more quickly than the middle leg can passively swing through. Therefore, the middle foot hits the ground on the bottom of the foot instead of at the heel (Figure 9e), and the middle leg scuffs (Figure 9i-j) instead of swinging through to take another step. When the middle leg scuffs, the robot continues to roll forward and falls to the ground, unable to recover for the next step (Figure 9j-k). To remedy this problem, we experimented with the amount of potential energy given to the system, by varying the robots angle of forward tilt and the height the outer legs were released from.

C. Laser Launch

By the beginning of March, the laser pointer was installed, and the testing team started to experiment with varying angles of forward tilt by varying the position the laser points to. With the laser pointing approximately 12 from the front of the mat, the robot was able to obtain between 4 and 6 steps fairly consistently over approximately two weeks of testing. During this time the robot achieved a new record of 9 steps. The middle leg continued to scuff as described above by Figure 9, and system momentum, observable as the rate that the outer legs fell, appeared to be dependent on how quickly the motor pushes the robot off balance during leg extension. To account for this, motor power was decreased, which slightly improved consistency.

By mid-March, we added the second laser pointer, which helped the robots lateral balance during launch. With the laser pointing approximately 16 from the front of the mat, the robot achieved a maximum of 12 steps, with a larger percentage of trials at 5 steps. Additionally, a switch was added that caused the motor to slowly extend the middle leg to the maximum length. This eliminated the variability in previous approximations of the maximum length extension. This motor extend switch seemed to drastically improve the robots walk. During one testing session of 16 consecutive trials, the robot achieved both 16 and 17 steps once, between 9 and 15 steps 9 times, and less than 9 steps only 5 times. This testing session made it obvious that our robot was not perfectly balanced laterally. With the trials of more steps, it was clearer to see that the robot veered toward the right. In fact, on the 16 and 17 step trials, the robot did not fall over, but instead walked into the wall of the hallway where it was being tested. During the next testing session, the testing team altered the weight distribution by adding a weight at different locations. When adding a D battery on the left leg between the motor battery and speed controller, the robot walked between 10 and 14 steps 4 times, between 5 and 10 steps 10 times, and 4 or less steps 9 times. When the same battery was moved directly above the left foot, the robot reached a new maximum, 18 steps, during two different trials. It also walked between 6 and 10 steps 11 times, and less than 6 steps only once. This experiment in changing the weight distribution clearly demonstrates both the drastic effect of a small change on the robots walk and the importance of documenting all small changes for repeatability.

When analyzing the video footage from these two testing sessions, the testing team observed that the step size decreased as the number of steps increased. This change in step size was large enough such that we were able to hear the steps getting faster. The testing team discussed methods of detecting the acceleration so the robot could adjust itself before falling over. A counter and wireless data acquisition were going to be installed; however, the testing team ran out of time in the semester to experiment with them fully.

D. Current State

The testing team is entirely sure what happened during the next testing session, only 4 days after the 18 step trials. During a few of the trials, the micro-controller turned off after one or two steps, and the back lock was not firing consistently. The micro-controller battery was low; however, after charging, the robot reached 7 steps once, but more commonly 2 or 3. The extra battery as counter weight was removed, which appeared to help the robot walk about 4 steps. The only thing that was different between one day and the next was the addition of a small, light, wireless transmitter on the micro controller, which did not appear to be the problem. Additionally, both the front and back locking mechanisms stopped working reliably, even though nothing else appeared to change. Unable to return the robot to the state it had been in, the testing team began re-tweaking and re-optimizing the robot from where it was. As of the beginning of May, this is the current state of the robot.

V. Conclusions

Prior to this semester of testing, the robot had only achieved 4 steps; however, by the end of the semester, multiple distance records were set, with a final record of 18 steps. Additionally, the robot achieved the goal of increased reliability, with a higher percentage of successful runs beyond 4 steps. The robots progress was accelerated because we documented and taped each testing session, allowing the testing team to observe and record the system dynamics more closely. The author attributes the robots successes this spring to an increasingly consistent launch technique and improvements in code. With continued optimization of mechanical and electrical variables, specifically in launch and code, the author anticipates that the current FE walking robot, with passive hip swing and telescoping-leg, is capable of reaching and surpassing its 18 step record.

VI. Appendix

A. Video Links

1. Testing during February-March 7, 6 step maximum $www.cornellfe.org/movies/fe\_success.mov$
2. Testing during March 9-May, 18 step maximum $www.cornellfe.org/movies/fe\_successes2.mov$

References

[1] Ren, JP, et al. *Mechanical Design of a 2-Dimensional Powered Bipedal Walker with Telescoping Leg*. Cornell University; Ithaca, NY: Apr 2005.

[2] Cheng, Chris. *Mechanical Design of a 2-Dimensional Powered Bipedal Walker with Telescoping Leg*. Cornell University; Ithaca, NY: Nov 2005.

[3] Cheng, Chris, et al. *FE Walking Robot Mechanical Team Final Report*. Cornell University; Ithaca, NY: May 2006.

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