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DESIGN OPTIMIZATION OF A NOVEL TRIPEDAL LOCOMOTION ROBOT THROUGH SIMULATION AND EXPERIMENTS FOR A SINGLE STEP DYNAMIC GAIT

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ABSTRACT

This paper presents the concept and design of a unique three-legged walking robot, and results from the simulation and experiments of a single step tripedal gait. The STriDER (Self-excited Tripedal Dynamic Experimental Robot) incorporates aspects of passive dynamic walking into a stable tripedal platform and is capable of changing directions. To initiate a step, the legs are oriented to push the center of gravity outside of the stance polygon, and as the body of the robot falls forward, the swing leg naturally swings in between the two stance legs and catches the fall. Once all three legs are in contact with the ground, the robot regains its stability and the posture of the robot is then reset in preparation for the next step. The changing of the direction is done by a unique way of changing the sequence of which of the three legs is the swing leg.

To guide the design of the robot, a dynamic model was developed and a simulation of a single step tripedal gait was performed to allow for tuning of several design parameters, including the mass properties and link dimensions. By considering the two stance legs as a single effective link connected to the ground, the robot can be modeled as a planar four-link pendulum in the sagittal plane. Further development of the simulation also allowed for optimization of the design parameters to create an ideal gait for the robot. A self-excited method of actuation, which seeks to drive a stable system toward instability, was used to control the robot. This method of actuation was found to be robust across a wide range of design parameters and relatively insensitive to controller gains. The design of the first prototype and result from the experiments are presented with a discussion of future work.

INTRODUCTION

STriDER (Self-excited Tripedal Dynamic Experimental Robot) is a novel three-legged walking machine [1-4] that exploits the concept of actuated passive dynamic locomotion to dynamically walk with high energy efficiency and minimal control. Unlike other passive dynamic walking machines, this unique tripedal locomotion robot is inherently stable with its tripod stance, can change directions, and is relatively easy to implement, making it practical to be used for real life applications.

The concept of passive dynamics has been around since the 1800s. The earliest walking machines were simple toys that could walk down declined surfaces using only gravity and the built in dynamics of the toy for locomotion. This concept was expanded upon by Tad McGeer in the 1980s, who developed the passive dynamic locomotion into a new philosophy in the control and design of bipedal walking machines [5, 6]. Passive dynamics utilizes the natural built in dynamics of the robot's body and limbs to create the most efficient walking and natural motion. His robots demonstrated how proper mechanical design of a robot can provide energy efficient locomotion without sophisticated control methods, the concept of which is affecting how actuated bipedal robots are being designed and controlled [7, 8]. The validity of the concept of passive dynamic locomotion is evident by the numerous examples of passive dynamic walkers that function with little actuation and no control [5-7, 9-13]. Although the concept of passive dynamics

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is well developed, the implementation of a practical robot that can walk in this fashion is a challenge. The tasks of getting all the design parameters that affect the dynamics and kinematics (dimensions, mass properties, etc.) to be just right for a stable gait cycle are difficult and usually rely on systematic changes of a physical model rather than parameters developed through analytical methods [8].

The task of walking dynamically in a stable limit cycle is challenging; but there are few, if any, dynamically walking robots that can stop, turn, or perform motions that statically stable, multi-limb robots can perform. STriDER (Self-Excited Tripedal Dynamic Experimental Robot) shown in Figure 1, combines the dynamic walking characteristics of passive dynamic robots with the stability and versatility of statically stable robots.

In this paper, we present the results of our preliminary research on the STriDER platform, including the mathematical model of the dynamics for a single step, as well as a discussion of the simulation and parametric study for design that were performed. A brief overview of the mechanical design of the proof of concept prototype will be presented as well as feasibility experiments that were run to determine the validity of the concept and reinforce the results of the parametric study for an optimized design.

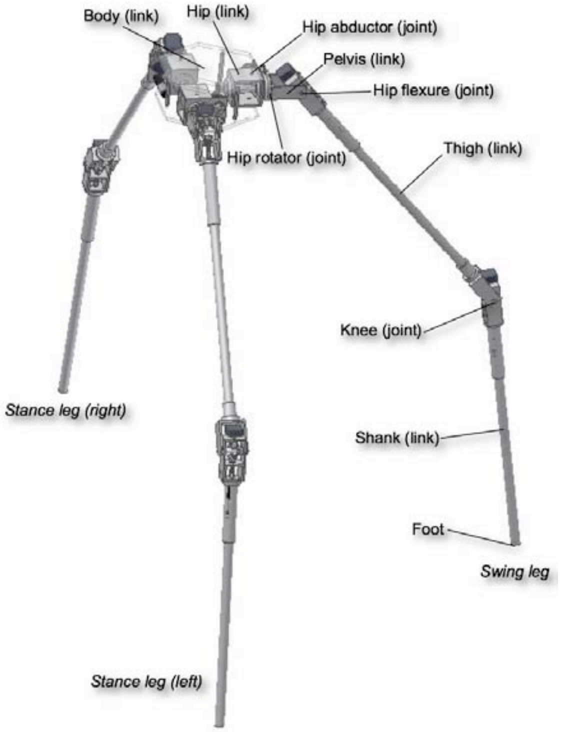
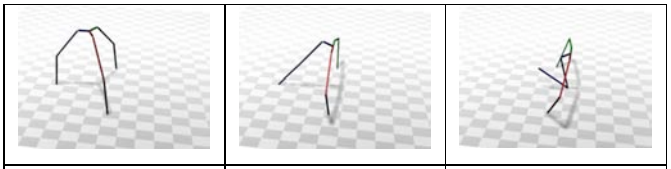


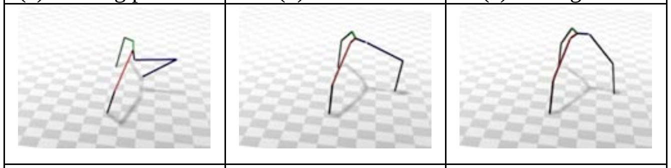
Figure 1. STriDER: Self-excited Tripedal Dynamic Experimental Robot

SELF-EXCITED TRIPEDAL DYNAMIC EXPERIMENTAL ROBOT (STriDER)

Unlike other passive dynamic walking machines, or actuated versions of them, the STriDER has a kinematic structure which makes it inherently stable and allows it to change its directions. The scope of this research is to develop the dynamic model of the STriDER taking a single-step to allow for a parametric study for the optimal design, and to fabricate a prototype for experiments. The development of a tripedal gait for the robot will provide insight into the dynamics of legged locomotion in general. Figure 2 illustrates the motion strategy for a single step of the unique tripedal gait of STriDER (patent pending). From its starting position, using the abductor joints, the robot shifts its center of gravity by aligning the two pelvis links (and thus the axes of the rotator joints) of the stance legs [4]. Then, the body of the robot falls over in a direction perpendicular to the line connecting the feet of the two stance legs. The swing leg (the middle leg) naturally swings between the two stance legs and catches the fall, regaining the stability of the robot. Once all three legs are in contact with the ground, the robot resets to its initial position by actuating its joints, storing potential energy for its next step.



(a) Starting position (b) CG shift (c) Falling over



(d) Leg swing... (e) ...catching fall (f) Reset posture

Figure 2. Single step tripedal gait (patent pending)

The walking path, shown in Figure 3, illustrates how the STriDER walks straight and how it can change directions. The changing of the direction is done by a unique way of changing the sequence of which of the three legs is the swing leg (patent pending). By altering the stride width and the direction of the swing, a variety of different paths can be formed.

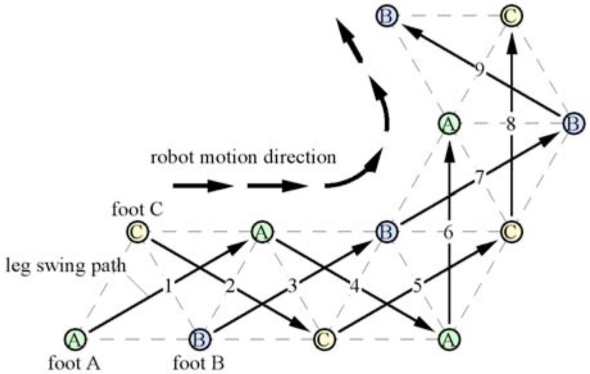


Figure 3. Walking path for the tripedal gait

An important feature of this unique tripedal gait is the natural swinging motion of the swing leg, which is made possible by the flipping of the body about the aligned hip rotator joints connecting the two stance legs. With the right mechanical design parameters (mass properties and dimension of links), this motion can be repeated with minimal control and power consumption. The flipping of the body prevents the three legs from tangling up as the robot takes its step.

DYNAMIC SIMULATION AND OPTIMIZATION OF PARAMETERS FOR DESIGN

Modeling of the System

While the addition of a third leg might seem to make the system more complicated, the dynamics that govern the motions of STriDER as it takes a step closely resembles that of a 2 dimensional passively dynamic walking robot. The stance triangle, formed between the two foot contact points of the stance legs and the center of the hip, acts as a single link with an equivalent mass and moment of inertia of the two legs combined. Thus when viewed in the sagittal plane, STriDER can be modeled as an inverted four-link pendulum with one free degree of freedom at the interface between the stance triangle ‘foot’ and the ground and the other three joints actuated (or passive). The model can be described by its link lengths, l_i, its masses, m_i, and its center of gravity location, c_i, measured from the joint between link *i* and *i-1* (the ground is considered in this case to be link 0). Figure 4 illustrates the model used. The mass properties of the links will be determined from physical parts fabricated for the scaled prototype, and the moment of inertia values and the location of the center of gravity will be calculated from the CAD models.

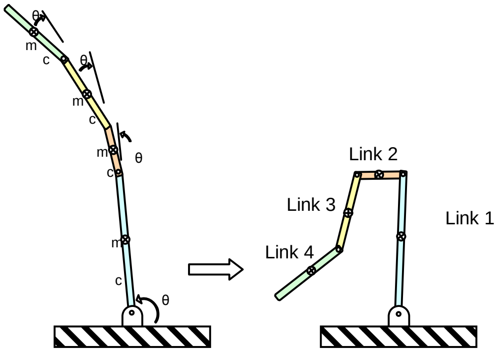


Figure 4. Multilink pendulum model for STriDER

Assuming no slipping at the ground foot contact points for both stance legs, the dynamic model is developed using the Lagrangian formulation given by equation 1,

$$M(q)\ddot{q} + C(\dot{q},q)\dot{q} + G(q) = Q^* \qquad (1)$$

where *M* is the inertia matrix, *C* is the centripetal and Coriolis effects, and *G* is the gravitation effects. Q^* is the generalized force which represents the inputs and other losses, such as damping, in the system. The solution for an initial condition problem with the three supporting legs in contact with the ground was solved using MATLAB.

Motion Generation for a Single Step Dynamic Gait

A variety of motion generation schemes were investigated to generate a smooth and energy efficient motion during a single step. One approach was to use motors to store potential energy in torsional springs at the joints, which could then be released. The release of the potential energy would thereby input a torque on certain links and would then allow the built in dynamics of the system to generate the motion. The amount of energy stored could be adjusted to get the desired trajectory based on the dynamics of the system. Although not a completely passive dynamic robot, the energy consumption would be far less than a statically stable robot that uses joint position control since the actual motion would be generated by the built in dynamics. Ultimately, this approach was abandoned for its complex mechanical design but will be investigated in the future as an alternative actuation method.

Another approach was to have the robot shift its center of gravity such that the robot would begin to fall forward. The swing leg would then be actuated so that its shank would be forced down and out until the swing legged straightened (similar to the motion used to build up speed on a swing). A torque in the opposite direction would be applied at the knee to get the swing leg in a position to contact the ground. This approach was abandoned because as the body of the robot flipped between the two stance legs, the overall length of the swing leg, combined with the length of the body, was too large and the swing leg was prone to scuffing the ground.

A more direct approach to generating the desired motion was to manually dictate the motion of each link; setting the joints to be either passive or active. It should be noted that the words *active* and *passive* will be used to describe the joints on STriDER. This is a bit misleading, as all the joints (both *active* and *passive* joints) will be actively controlled by a DC motor using a proportional differential (PD) controller for the prototype presented in this paper. The *passive* joints will be driven to match the motion profile of a completely passive link as it is derived in the MATLAB simulations. In this sense, the motors are not physically driving the links and thus theoretically, less energy is inputted into the system. This implementation is done for robustness against external disturbances to prevent it from collapsing, and to guarantee the robot will remain standing at the end of the step as the foot hits the ground

Self-Excited Control Model

Inspired by the work of Ono et al. [14], a successful approach to motion generation was found using the concept of self-excited actuation. Self-excited actuation is based on self-excited vibration, a phenomenon commonly referred to as flutter, which results when a stable system is excited at one of its natural modes and driven to an unstable state. The inverted pendulum model of the swing leg has two natural modes, one where the links of the swing leg move in phase with one another and a second where the two move out of phase. The desired motion is for the thigh to swing forward as the shank swings backward, so the second mode generated the necessary motion. An illustration of Ono's self-excited model is presented in Figure 5.

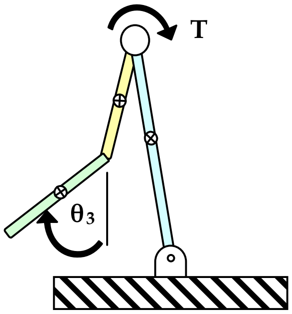


Figure 5. Self-excited model developed by Ono et al. [14]

Mathematically, self-excitation occurs when the stiffness matrix of a system becomes asymmetric. By generating a torque at the hip with negative feedback to the shank angle (measured from the vertical rather than relative to the previous link), the stiffness matrix becomes asymmetric and the motion of the shank is delayed approximately 90 degrees from the thigh motion. The torque at the hip is represented by equation 2.

$$T = -k\theta_3 \tag{2}$$

The value of *k* can be determined by linearly approximating the equations of motion of the system and determining for what values of *k* and at what frequency the eigenvalues of the system go unstable. Although mathematically possible to calculate, the values for friction were unknown and according to [14], can greatly affect the values of *k*. Therefore, a trial and error method was employed to determine the value of *k.* A wide range of *k* values was tried to determine if the torque at the hip rotator joints were sufficient to generate the desired motion. The larger the value of *k* was, the more likely the motor torques were to saturate. A *k* value of 5 Nm/rad produced the desired motion for the model and prevented the motor torques from instantly saturating upon initiating a step.

The self-excited method of control was used in the optimization for its simplicity and robustness of the controller to create feasible gaits over a wide range of link parameters and controller gains. Although Ono's model was a three link bipedal walker it is still applicable for use in the planer model of the four-link STriDER robot by altering the starting configuration of the robot such that the pelvis and thigh of the swing leg were collinear, effectively creating a three-link robot. The relative angle between these two links was then maintained by controlling the hip flexure joint of the swing leg with a PD controller until the swing foot impacted the ground. Once back in a stable tripod position, the joints could then be actuated to reconfigure the body to prepare for the next step. An illustration of the step phase is shown in Figure 6.

Figure 6. Simplification to the four link STriDER model that allowed for the application of the self-excited controller

One thing that was observed was that the PD controller used to keep the hip and pelvis links inline with one another always caused the thigh to lag behind the motion of the pelvis. This turned out to be beneficial in some cases because it allowed the swing leg to bend at the hip flexure joint, increasing the foot clearance throughout the step.

Optimization Based on Self-Excited Control Model

A goal of this research was to gain some insight into how the design parameters, such as link lengths and mass distributions, affected the robot's gait and how the parameters could be changed to create an optimal single step. In order to optimize the full model in Figure 4, as many as twelve parameters could be optimized. The mass, link length, moment of inertia, and mass distribution (the location of center of mass) of links 2 through 4 could be changed to get the desired motion. The properties for link 1, which is stance triangle when viewed in the sagittal plane, are determined by the properties of the thigh and shank links.

An investigation into the contributions of these parameters to the gait of STriDER was performed to reduce the number of parameters. Changing the mass at the hip had little effect on the motion of either the stance or swing leg. The angular rotation of the stance legs relative to the ground is a function of the height of the robot. Since a larger mass would produce a greater force at the end of the step, one of the design goals was to minimize the mass of the hip. Also, a design that was relatively symmetric would have a center of mass located roughly in the middle of the link. These two simplifications reduced the number of parameters by two. The parameters of the thigh were then investigated and revealed that the hip flexure joint motor torque was more likely to saturate at higher masses or longer link lengths. It was decided to keep the mass of the thigh at a minimum and to keep the link length of the thigh as a design variable. This decision was made based on the desired functionality of the robot; height was desired over a heavier robot. Since no additional mass would be added to the thigh, the location of the center of mass of this link became a constant and would be dictated by the design of the linkages and components of the leg. Once again, this reduced the number of parameters by two. The investigation revealed that changing the mass of the shank had the greatest impact on the general motion of the swing leg. To further reduce the number of parameters, the mass of the link was kept constant. The value of the mass was determined by a trial and error approach that produced reasonable gaits over a wide range of link lengths without exceeding motor and controller specifications. Setting the mass and mass distribution of the links constants also meant that the moment of inertia of each of the links could be held constant once the design of STriDER was finalized. In total, these assumptions reduced the number of parameters to be optimized to three: (1) the length of the thigh, (2) the length of the shank and (3) the location of center of mass of the shank.

Developing a Cost Function

To develop the cost function to quantify how "good" a step was, different criteria were added based on two premises: (1) will the resulting motion result in damage to the robot and (2) will the resulting motion make it difficult or impossible to take the next step. Five penalties were created to quantify the resulting motion of the step. First, the horizontal and vertical velocities of the foot of the swing leg were evaluated. In an ideal case, the horizontal and vertical velocities of the foot would be zero at the end of the step. A high horizontal velocity could potentially lead to the foot slipping when it impacts the ground. A high vertical velocity could cause damage to the links and joints due to the impact of the foot with the ground. Next, the ratio between the stride width to the overall height of the robot is evaluated. If this ratio is too small, the robot will be unstable upon completion of a step. If the ratio is too large, the torque produced by the motors may be insufficient to allow the robot to recover from its step, or in another case, require the robot to drag the swing leg along the ground to regain its posture. Another criterion was that the height of the robot's center of gravity at the beginning of the step should be equal to the center of gravity at the end of the step. The reasoning behind this is that if the center of gravity is lower at the end of the swing, insufficient energy was put into the system during the motion and thus additional energy would have to put into the system to get the robot into a position to take the next step. Conversely, if the center of gravity is higher than the beginning of the step, too much energy was put into the system. Finally, the difference between the actual step length and ideal step length was evaluated. For taking a straight step over a level surface, the three feet of the STriDER make up an equilateral triangle. Any deviation from the ideal might lead to a configuration at the end of the step that would make it difficult or impossible for the robot to reconfigure for the next step. A summary of the criteria and the goals are shown in Table 1.

Table 1. Cost function criteria

Criteria	Goal
Stance width / height ratio	The ratio is a constant based on the geometry, deviations from this ratio are accessed a penalty
Magnitude of foot velocities at end of the step	The ideal case would be a zero velocity impact at the foot
Vertical CG location at the end of the step	Change in CG height between the beginning and the end is ideally zero
Difference between ideal and actual stride length	The difference between actual and ideal stride length should be zero

Each of these criteria was assigned a penalty based on its potential to cause an undesireable step or to cause harm to the robot. The limits of the design space were determined by the desired dimensions of the robot. To see over small obstacles, the robot was desired to be at least 1.0m tall. Torque limitations of miniature DC motors were also taken into consideration when choosing the maximum link lengths and masses. A computer program was developed to calculate a cost function with all combinations of design parameters within the desired design space. The method used in the optimization was crude, but the underlying principals are justified; the worse a design was, the higher the design's associated cost.

The optimization yielded a set of parameters that produced a feasible gait for STriDER. The PD controller did a sufficient job in maintaining the joint angle between the pelvis and thigh of the swing leg. Phase lag was still present but was beneficial in allowing the swing leg to bend more, increasing foot clearance as the swing leg passed between the two stance legs. With the optimized parameter values shown in Table 2, the simulation showed that STriDER can achieve a stride length of 0.539m and a maximum step speed of 0.735 m/s. The resulting motion from the dynamic simulation can be seen in Figure 7.

Table 2. Parameters for the STriDER

Link$_i$ Parameter	1	2	3	4
l_1, Length (m)	1.87*	0.187	0.50	1.3
c_i, CG Location (m)	0.898	0.0935	0.1	0.42
m_i, Mass (kg)	2.05	5	0.75	1.30

* L1 ≠ (L3+L4) because the stance legs form a triangle to increase the stance width

From a mechanical point of view, the simulation revealed that the maximum rotational speed of the joints never exceeds 60 RPM but has a high acceleration at the start of the step. Therefore, the DC motors for the joints were chosen with the appropriate motor specifications and gearing to satisfy the acceleration and torque requirements.

Parametric Study of STriDER

With the design parameters for the prototype of STriDER set, a parametric study was performed to provide insight into how the variables affected the overall gait of the robot. This insight could be used as a tool in problem solving during testing, so that the parameters could be systematically changed to correct the robot's gait.

While keeping two of the three parameters constant (l_3, l_4, and c_4), the sensitivity to change of the third parameter was investigated. Although the three parameters are coupled together, using the optimum values for the constant parameters will demonstrate how changing one parameter deviates from the ideal step. The relationships between the parameters and foot clearance and foot velocity were examined. These two parameters were considered to be the most important, since foot clearance was a determining factor in whether or not STriDER could take a successful step and a high vertical velocity would impart large shock loads that could damage the robot.

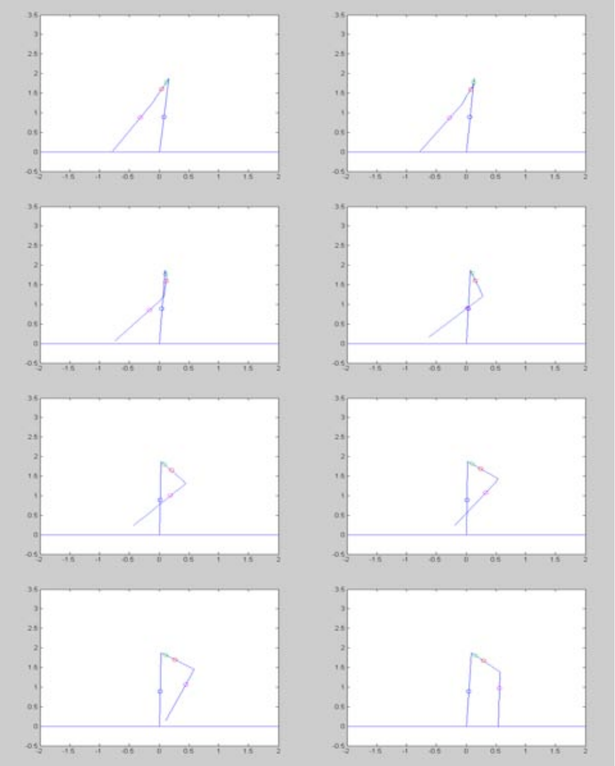


Figure 7. Animation of a single step for the STriDER with a time step of 0.1 seconds. Total step time is 0.73 seconds.

The first parameter that was investigated was l_3, the length of the thigh link. To investigate the effect of this parameter on the overall motion of the step, a number of simulations were run, varying l_3 through a range of 0.5 to 1.5m (the ranges used in the optimization) while keeping the parameters l_4 and c_4 constant at their optimal value. The effects of the parameters on foot clearance and the vertical velocity of the foot were investigated as shown in Figures 8 and 9, respectively.

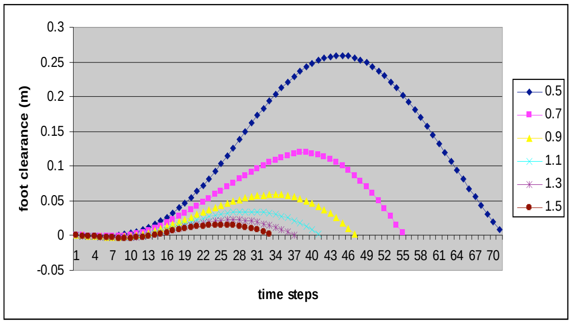


Figure 8. Foot clearance for different l_3 values

From Figure 8, it is observed that as the link length of l_3 increases, the maximum foot clearance decreases. Also, the peak of the foot clearance occurs earlier, which may lead to the foot impacting the ground prematurely, resulting in an unsuccessful step. Although the trend might show that a value smaller than the optimized value of 0.5m may be better, the values are outside the range of useful link lengths that would produce a robot that would be sufficiently tall. Figure 9 demonstrates that the vertical velocity of the foot at the point of impact with the ground increases as l_3 decreases within the range of 0.5 to 0.9 meters. From 0.9 to 1.5 meters, the trend is different as the vertical velocity decreases slightly as l_3 gets larger.

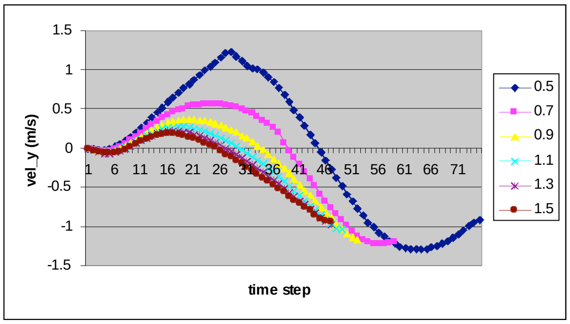


Figure 9. Vertical velocity of the foot at impact for different l_3 values

The next parameter that was investigated was l_4, the length of the shank link. For this simulation, l_3 and c_4 were kept constant at their optimal values as l_4 was varied through a range of 0.5 to 1.5m (the ranges used in the optimization). The effects of the shank length on the foot clearance and vertical velocity can be seen in Figures 10 and 11, respectively. For values less than 1.1m, the STriDER failed to take a successful step since the foot of the swing leg immediately impacted the ground. Over the range of 1.1 to 1.5 meters, the maximum foot clearance decreases as the length increases, while the timing of peak of the step remains fairly constant (see Figure 10). The velocities of the foot, shown in Figure 11, do not show an obvious trend. The profiles and final values of the velocity are similar, which shows that the velocity of the foot is relatively insensitive to changes in l_4.

The final parameter that was investigated was c_4, the location of the center of gravity for the shank, measured as the distance from the knee joint toward the foot. For this simulation, l_3 and l_4 were kept constant at their optimal values as c_4 was varied through a range of 0.0 to 0.75m (the ranges used in the optimization). The foot clearance and velocity trends can be seen in Figures 12 and 13. For values less than 0.15m, the STriDER failed to take a successful step since the foot of the swing leg immediately impacted the ground. The maximum foot clearance increases as c_4 increases (see Figure 12). Figure 13 reveals that there is a significant difference in the foot velocity as c_4 is varied. As c_4 increases so does the vertical velocity of the foot at the impact of the ground. Such an increase in the velocity can lead to the foot bouncing after it hits the ground and repeated shock loads seen at the components of the swing leg.

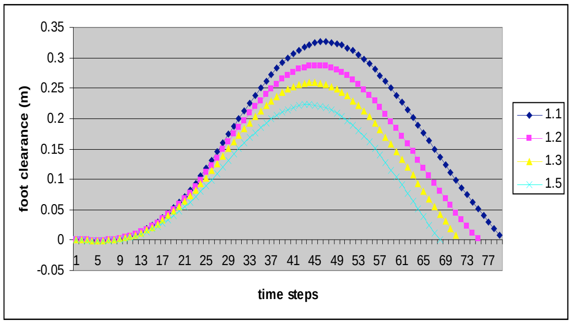


Figure 10. Foot clearance for different l_4 values

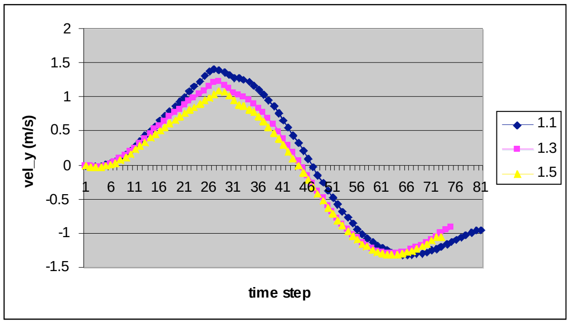


Figure 11. Vertical velocity of the foot for different l_3 values

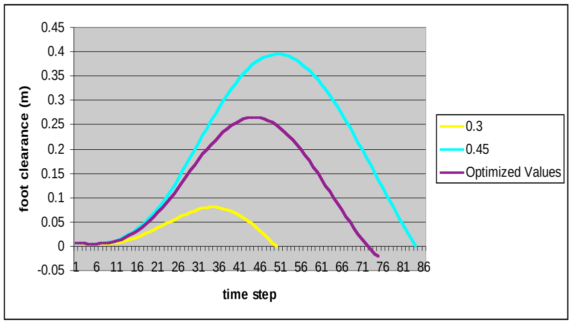


Figure 12. Foot clearance for different c_4 values

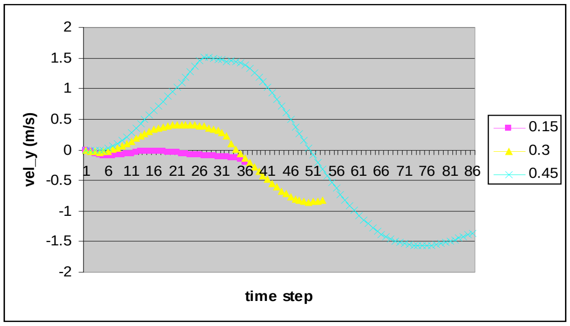


Figure 13. Vertical velocity of the foot for different c_4 values

The parametric study revealed that l_3 and c_4 had the greatest impact on the foot clearance and horizontal velocities of the foot. Variability in these two parameters could be achieved, but c_4 could be changed much easier by placing moveable weights on the shank. This flexibility would allow for easier adjustments during testing and as a guideline to check the assumptions of the parametric study.

EXPERIMENTAL RESULTS

Mechanical Design of the STriDER

One advantage of the STriDER over other walking robots based on passive dynamic walking in the sagittal plane is the ability to change its direction. In order to accomplish this, the motions of the hip joints are unique to the STriDER and design inspirations cannot be found in other walking machines. There are a total of three degrees of freedom at the hip for each leg (Figure 1). The first degree of freedom, the hip abductor joint, allows the hip links to pivot such that the axis of rotation of the hip rotator joints of the stance legs line up. The direction of travel of the STriDER is dictated by which pair of hip links is driven such that their hip rotator joints are inline. The second degree of freedom, the hip rotator joint, allows for continuous rotation of the body about the center line of the hip link. Lastly, the third degree of freedom, the hip flexure joint, allows for a pivoting motion similar to the knee joint. For the feasibility study experiment, several of the degrees of freedom were fixed to simplify the complexity of the system. The knee joints and hip abductor joints of the stance legs, as well as the hip abductor joint of the swing leg, were fixed. The joints of the stance legs were fixed to create a rigid stance plane. Hard stops were placed on the hip abductor joint of the swing leg in the event the PD controller was insufficient in maintaining the angle between the pelvis and thigh. A more complete prototype with full actuation of all joints is presented in [4]

The three legs of STriDER all had the same mechanical design. The hip rotator joint was designed so that a miniature DC motor with encoder feedback could drive the hip through continuous rotation (Figure 14). This required a slip ring to be run inline with the joint to the electrical components below the hip joint.

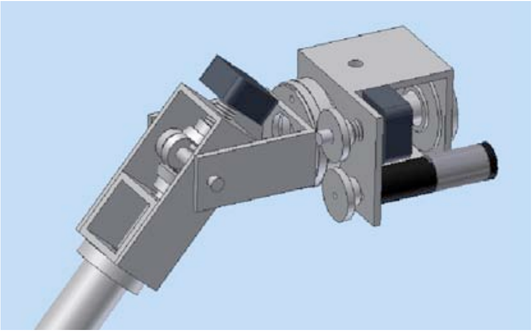


Figure 14. Hip flexure and hip rotator joint design

The hip flexure and knee joints shown in Figures 14 and 15 share a common design. Three bevel gears make up the gearset with the intermediate gear fixed to a shaft which is rigidly attached to the upper link. As the motor turns, the gear attached to the motor walks around the stationary intermediate gear pulling the lower link around the intermediate gear. The optical encoder for feedback is mounted to the lower structure opposite the motor and has a gear affixed to it which rotates along with the lower link in the opposite direction than the motor. The optical encoder and motor wires are run inside the tubular legs links to prevent them from getting tangled during motion.

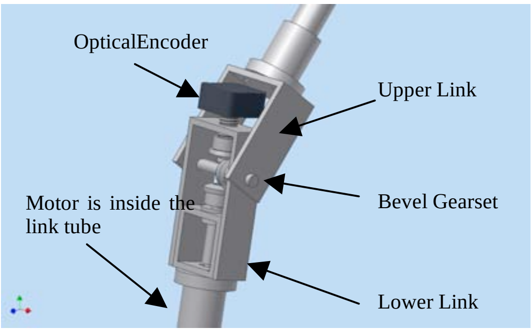


Figure 15. Hip flexure and knee joint design

Feasibility Experiments

The goal of testing was not to recreate the trajectories generated in the simulation, but rather to validate the optimization of the design parameters that produce a smooth gait for the STriDER. Several modifications were made to better emulate the conditions of the simulation and to safeguard the robot from damage during testing. In the simulation, the thigh of the swing leg is held inline with the pelvis link through the use of a PD controller at the hip flexure joint. During testing, however, there was a fear that the sudden acceleration of the body about the hip rotator joints would cause damage to the plastic gears, which had already sustained damage during the initial tests. Rather than using a PD controller to maintain the angle between the thigh and pelvis link, hard stops were put in place to limit the motion of the links to within ±5 degrees. This would still allow a similar motion as seen in the simulation, without endangering the robot. In order to more closely follow the actuation methods of the simulation, the knee joint of the swing leg was made completely passive by removing the set screw between the coupler shaft and motor output shaft. Once removed, there was no way of transmitting the torque from the motor to the knee and the shank rotated freely. The encoder, however, was still mounted to record the position of the shank. These simplifications meant that only the hip rotator joints of the stance legs were actuated, while the thigh and pelvis links are constrained and the knee joint made passive. This more closely resembles the simulation.

Rather than generating a torque at the hip rotator joints based on negative feedback from the shank, the stance legs' hip rotator joint trajectory followed the trajectories generated in the MATLAB simulation. A LabView program takes the angular positions generated by the MATLAB simulation and creates a plot of the motion profiles of the three actuatable joints.

Results

The program successfully controlled STriDER through a single step dynamic tripedal gait. The data from the encoders, however, did not closely resemble the trajectories generated by the simulation. Part of the reason behind the difference is in the data acquisition of information from the encoders. The sampling rate of the DAQ card and baud rate of the motor controller communication was insufficient to capture the rapid accelerations of the linkages and often time resulted in sporadic data with little or no data during these periods of high acceleration. Rather than defining the torque at the hip rotator joint as a negative feedback of the shank angle, the hip rotator joint was made to follow a trajectory. This method of trajectory following was different enough from the simulation to result in noticeable differences. Another interesting phenomena that was recorded was the effects of noise in the controller bus as problems arose when low current power wires ran parallel to the signal wires. This problem was addressed by better cable management.

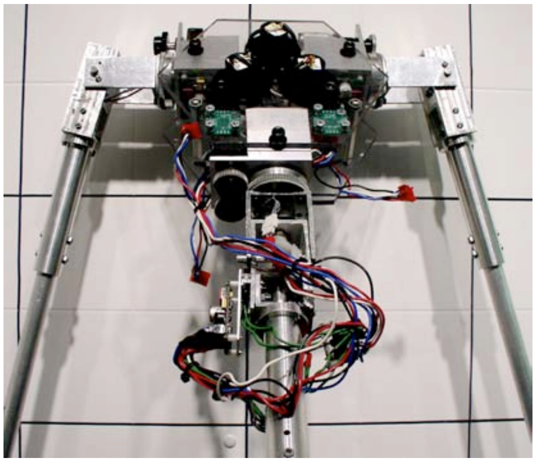


Figure 16. The body of STriDER with the two rotator joints of the stance legs aligned

From a physical standpoint, hours of repeated testing produced large shock loads on the mechanical components, which resulted in damage to the motors and gears. The bevel gears in the hip and knee joints were damaged and the result was slippage or binding. Backlash in the gears was also a problem which further added to the errors in the data. Other factors such as the manufacturing of the parts to the approximations of the coefficient of friction in each of the joints can explain some of the differences between the simulation and experiments. Testing also revealed that the success of a step was highly dependent upon initial conditions, most notably the angle of the stance leg to the floor. The successful step was not done by exactly matching the design parameters stated in the simulation but by systematically changing the location of the center of mass of the shank until the desired motion was achieved.

Despite the errors in data acquisition and mechanical problems, the STriDER did perform as expected and successfully took a step and supported the validity of the optimized parameters as a viable solution. The motions of the links through a step, shown in Figure 17, generally resembled those of the simulation (Figure 7).

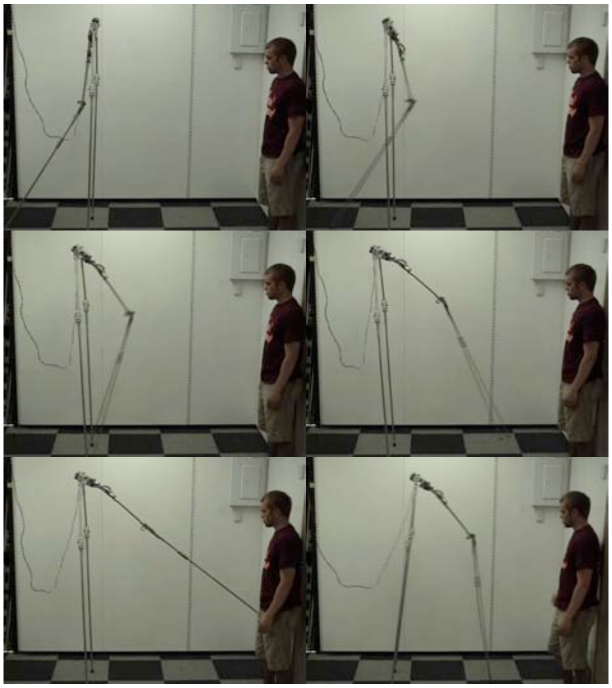


Figure 17. Feasibility experiment of the STriDER successfully taking a step

The STriDER did successfully take a step and could do so repeatedly once the LabView program was tuned. The goal of the research was not to match the trajectories of the joints to those of the simulation, but rather to validate the optimized parameters that were calculated in the simulation. The control of the motors in testing was different enough from the simulation to affect the dynamics of the system, which contributed to the largest disparities between the motions. Furthermore, the constraints placed on the hip flexure joint of the swing leg, while necessary to ensure the operation of the robot, were not present in the simulation creating more differences between the motions. Also, the simulation is based on parameters which are easy to specify but difficult to implement in a physical system. Motor friction and true physical properties such as mass, mass distribution, moment of inertia are difficult to measure. The success of a step is highly sensitive to the initial conditions and only after several trial and error approaches could a configuration be found that would consistently produce a step.

CONCLUSIONS

In this paper we have presented the concept and design of STriDER, a unique three-legged walking robot, and results from the simulation and experiments of a single step tripedal gait. To guide the design of the robot, a dynamic model was developed and a simulation of a single step tripedal gait was performed to allow for tuning of several design parameters, including the mass properties and link dimensions. By considering the two stance legs as a single effective link connected to the ground, the robot can be modeled as a planar four-link pendulum in the sagittal plane. Various motion generation schemes were considered, but ultimately a method of self-excited actuation was decided upon due to its flexibility across a wide range of design parameters and the relative simplicity of the controller. Using self-excited actuation, a smooth step was generated in simulation from which optimal design parameters of the STriDER were determined. Of all the design parameters that could be optimized, the link lengths of the thigh and shank as well as the center of gravity of the shank were evaluated. These parameters were shown to have the greatest affect on the motion of the robot.

Testing of the first prototype of STriDER revealed design problems that contributed to errors in data acquisition from the motor encoders. Worn down gears led to intermittent motion as gears engaged and disengaged, backlash between the gears in the flexure and knee joint, and additional friction in the system as gears bound. Finally, the method of actuation used in testing (trajectory following) was different enough from the simulation (negative feedback) to create discrepancies between simulation and test data.

Ultimately, the STriDER successfully completed a step and mimicked the motions predicted by simulation. Although the two motions cannot be compared directly, a visual comparison between the two provides supporting evidence that the parameters that resulted from the optimization are viable and that the novel tripedal locomotion strategy is possible. Without the simulation and optimization of the design parameters, implementing a design that successfully takes a dynamic step by trial and error only would have been very difficult.

RoMeLa (Robotics & Mechanisms Laboratory) at Virginia Tech will continue to develop STriDER as a novel locomotion platform and expand on the lessons learned from the single step prototype. The second prototype of STriDER which addresses the mechanical issues seen in the first prototype is presented in [4]. The inverse and forward displacement analysis of the pose when all three feet are on ground is presented in [3]. STriDER's capabilities to walking on uneven ground will be explored which will require the development of 3D dynamic models, unique path planning schemes, and studies on the interaction between STriDER and a variety of environments will be studied next. Work will also be done on incorporating sensors, such as rate gyros and force sensors, to be used for the new controller of the next generation STriDER.

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