Proposed Design of a Triped Robot

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ABSTRACT

Nature may be drawn upon as inspirations for robotic design. Biomimetics is the term used when the goal becomes replicating biological mechanisms. This method leverages the evolution of a life form over the course of many iterations. The concept of "better than bio" has emerged in order to combat functional fixedness that can occur from biomimetics. The goal of design being to take a biologically inspired base and then improve upon it with classical engineering methods.

This paper presents an analysis of the locomotion, energy consumption, and control of a tripedal robot. The aim is to gain insight into a perceived gap in evolution and apply results to robotics design. This is achieved through the construction of a SimMechanics model of an 11 degree of freedom 2S4P triped robot, the characteristics of which are similar to the biped developed by Raibert et. al [18].

Keywords
Triped, robotics, biomimetics

1. INTRODUCTION
The increasing demand for robots has been met with a supply of biologically inspired design solutions [14, 10, 2, 16]. In some applications, as in therapeutic robots, the replication of an animal is the goal [11]. Still, more open problems exist where biomimetics has been chosen as a solution [22]. One benefit of this choice is the ability to leverage the many iterations from evolution [17].

In particular, pedal locomotion offers a robust platform for navigating uncertain terrain [1]. Significant attention has already been turned towards autonomous navigation [7]. The combination of these two mechanisms enable applications of robotics currently in research and development [4].

Current [20] and past research has investigated various aspects of the design space involving robots with three appendages. In 1988, a three-legged robot was proposed for lunar base construction by McMurray and MacLaren [15, 9]. The report presented various gaits such as pivoting, crutch walk (akin to knuckle walking), and jumping. The kinematics were modeled as a four-bar mechanism where one leg was fused into one link. The four-bar exists on a plane that then pivots about a line due to gravity, thus moving the robot forward. One of the benefits of a three legged design offered in the paper is the ability to return to a statically stable position from having three points of contact with the ground.

Introduced in 1993 by Argaez [3] and later expanded upon [6] is a three-legged climbing robot. For this 2-D robot two legs affix to pegs while the third adjusts location. The stability characteristics of this geometry is analogous to a quadruped in 3-D space.

A three-legged robot was chosen in 2000 by Irie et al. [19] to study the use of genetic algorithms as a fast control scheme for locomotion. Using the minimum legs necessary for static stability resulted in a 25% mass conservation from typical quadrupeds. Another benefit cited is being axisymmetric. The gait consists of using pneumatics to lift the leg and swing forward. After the leg is grounded the center of gravity (CG) is adjusted. Both proportional and gravity control schemes were compared in the paper.

In 2005 a novel triped, called a rotopod, was developed by Lyons and Pamnany [13]. The novel design utilizes rotational energy to pivot the robot about a single foot. The gait demonstrates an ability to make sharp turns from one step. Another result from the study was demonstrating curve following.

Some tripods are produced through automated design or reconfigurable robots [21, 12]. In a study by D. Frutiger [8] an iterative design approach was used to develop various robot morphologies. During the course of the exploration the algorithm produced multiple tripod robots. The Titan series included an architecture where the legs were not axisymmetric. Meanwhile, the Titan07 is shown to exhibit two hopping gaits: a single leg forward and another with two.

The exploration of the under utilized design space of a tripedal configuration was the motivation behind this research. Insight into the benefits and disadvantages of such a design will aid in the advancement beyond previous biological specimens.

The objective of this paper is to present a working 3P2R kinematic model. Previous designs have simplified models [15] or utilize prismatic joints [19, 20]. A biped was used as an inspiration for the locomotion and morpohology [18]. SimMechanics was chosen as the program to develop the model.
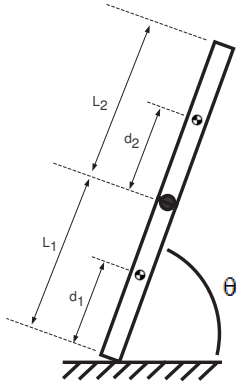
Figure 1: Leg Model

2. TRIPED MODEL

The robot consists of 6 links and 7 joints. When static, the robot resembles a three-sided pyramid. The links are modeled as rods with length L_i and CG located a distance d_i from the base. Contact with the ground is represented by a spherical joint without friction. The knees are a single rotary joint with an axis orthogonal to the associated leg. At the hip, each leg has two degrees-of-freedom.

3. SIMMECHANICS

The absence of a biological analogy means there is no known solution to design towards. This results in a need for flexibility and multiple iterations during design. SimMechanics was chosen for this task as it offers a suite of interchangeable robotic components. In addition, SimMechanics is able to visualize the results without any additional coding. For any modeling problems unique to the triped typical MatLab code may be embedded. Two models were utilized: one for investigating statics and another for dynamic motion.

In order to verify the results it is possible to attach sensors to the various components. A joint sensor can provide the quaternion and reaction forces. Body sensors can provide position, velocity, acceleration for both translation and rotation as well as the resulting rotation matrix. These are stored in a vector with time for post-processing and plotting.

It is also necessary to apply forces and initial conditions to the model. As with the sensors, there are actuators for both joints and bodies. For joints, torque can be applied to each degree of freedom individually. Spatial actuation is also possible but is not used here. For a body, torque and force can be applied to a designated coordinate system on the body frame.

3.1 Feet

The feet of the triped in contact with the ground are modeled as a point contact with the surface. The feet are considered spherical joints and have three rotational degrees of freedom. Friction between the robot and the ground is modeled as infinite and prevents any slipping. The joint is passive and no torque will be applied to it. This model is similar to the one presented by [15].
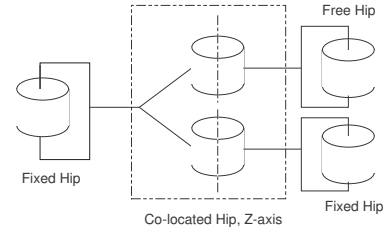

Figure 2: Hip Kinematic Model

Exclusion of a footpad and ankle to represent the foot reduces the complexity of the simulation. However, this also prevents the use of some techniques useful to control and locomotion. In humans, the foot can be used to push off of the ground and aid in the creation of forward momentum. The contact area for the foot with the ground is larger which aids in balance. Finally, torque can be applied at the ankle using the foot as a lever aiding in the control of the system.

However, the definition of a footpad for a robot is not so clear. In [19] the footpad is a disk connected to a passive joint. This is not constrained to just the triped though. In [2] the footpad is a square centered at the base of the ankle. The geometry of the foot has a significant impact on the gait of the robot. While discriminating between a biomimetic foot and one that is designed is within the intent of this investigation, it is not within the scope.

3.2 Legs

The leg consists of two links, the shin and the thigh, intersecting at a revolute joint, the knee. This is an active joint and each knee has a feedback control associated with it. For legs in contact with the ground the control law is given in (1). The axis of the knee is orthogonal to the plane on which the two links lie. These planes are then spaced 60(deg) from one another. The shins of all three legs are identical as are the thighs. Consequently, the leg is identical to that of the biped model found in [18].

$$\tau(t) = K_d(\dot{\theta}(t) - \dot{\theta}_{ref}) + K_p(\theta(t) - \theta_{ref}) \qquad (1)$$

$$\dot{\theta}_{ref} = \theta_{ref} = 0 \qquad (2)$$

3.3 Hip

The hip of the robot occurs at the point where the three legs converge. Due to the architecture of SimMechanics the hip is not modeled as a single joint. Instead, two rotary joints branch from one of the fixed legs to the free leg as well as the other fixed leg. Between the fixed legs the axis of rotation is that of the z-axis. This constrains the geometry such that it is mirrored about the plane bisecting the legs.

The axis of the free leg, however, is identical to that of the associated knee: orthogonal to the plane of the leg. This results in constraining the motion of the robot to be along the line of the projection of the free leg. There is a control algorithm for the free hip but none for the hip joints of the fixed legs. Mobility of the triped can be increased by controlling the free hip to rotate in the z-axis. However, it causes the center of gravity to move off a plane of symmetry making balance more difficult.
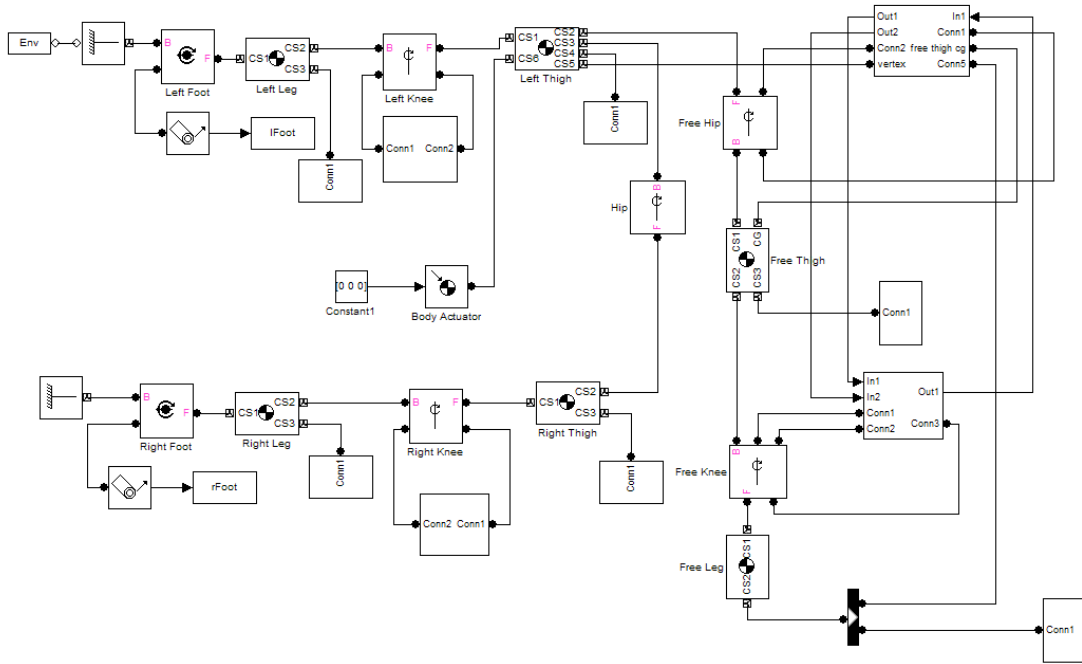
Figure 3: SimMechanics Code

4. INITIAL POSITION

In the nominal position the robot has each foot at the vertex of an equilateral triangle as seen in Figure 4. The hip is located at the center of the triangle projected in the z-axis. Determining the initial angle of the legs with the ground and the height is a simple application of trigonometry.

$$\theta = asin(h/(L_1 + L_2)) \tag{3}$$

5. DEGREES OF FREEDOM

There are two configurations of the robot to consider when calculating the degrees of freedom. When all feet are touching the ground the triped is purely a parallel mechanism. During the swing and double support phase the triped is a five-bar parallel linkage with a 2R arm at the apex. By calculating the degree of mobility and degree of parallelism [5] insight can be gained into the operation of the robot. These are presented in equation 4 and 5 respectively.

$$M = \sum_{i=1}^{n_{joint}} n_{dof_i} - d_{n_{loop}} = m - d_{n_{loop}} \tag{4}$$

$$P = \begin{array}{ll} \frac{n_{loop}}{M-1}, & \text{if } M \neq 1 \\ 1, & \text{if } M = 1 \text{ and } n_{loop} > 0 \\ 0, & \text{otherwise} \end{array} \tag{5}$$

Using the degree of mobility during the swing/support phase we can calculate the degree of redundancy found in equation 6. This can be used as a rough gauge of robustness to actuator failure.

$$\rho = M - E \tag{6}$$

When all legs of the triped are fixed to the ground the mobility of the robot is 6. This is advantageous for control as the number of joints requiring control are small compared to that of the whole system. When one leg is raised the mobility increases to 7 and the parallelism is at $\frac{1}{2}$. This complicates the control but the existence of redundancy, $\rho=3$, is an indication that the robot has a flexible envelope.

6. PARAMETERS

The basis for the size and mass of the robot was derived from the robot developed by Tzafestas [18]. The mass and location of the center of mass differ as required to accommodate the additional mass of the third leg.

- $L_1 = 0.332$m

- $L_2 = 0.302$m

- $m_1 = 3$kg

- $m_2 = 2$kg

- $d_1 = 0.1$m

- $d_2 = 0.1$m

The deviations from [18] are within the same order of magnitude. By using values similar to that of an actual robot it is possible to develop a sense of the requirements and performance of the theorized triped.

7. ORIENTATION

The two primary perspectives for robot orientation are that of a body local coordinate frame and a world coordinate frame. The body coordinate provides information in terms that are useful for the control algorithm. Meanwhile, the world local frame is useful for path planning.

7.1 Robot Local

The concept of forward and backward for the triped is a function of the stepping leg. A coordinate is created with one axis being the line between the two fixed feet. The other axis is perpendicular and intersects the foot of the free leg. The side on which the center of gravity begins will be considered backwards and the side on which the CG ends as forward.

7.2 World Local

If the direction of the robot is fixed to the world coordinate the concept of direction becomes less clear. The two configurations possible are when the direction faces a leg or when it faces away. For the former, the directions available are backwards, foward-left, and forward-right. Similarly, in the latter configuration the viable directions are forward, backward-left, and backward-right. As will be discussed in the following chapter, this prevents the robot from walking in a constant direction.

8. TRIPED WALKING

Triped locomotion consists of three phases: swing phase, contact/triple support, and double support phase. The first step taken to develop a successful control algorithm was to replicate the results of Tzafestas [18]. This requires the application of an assumed trajectory for each of the joints and proportional-derivative control.

9. PD KNEE CONTROL

For all of the subsequent control schemes the algorithm applied to the knees of the fixed legs remains the same. To prevent swaying off the line of forward motion the legs are locked. This also reduces the degrees of freedom of the system by two. In order to achieve this a simple proportional-derivative feedback control is applied.

The reference signal is zero for both the relative angle and the angular velocity. There is no control law for the hip joints of these legs. As the plane of the legs pivot the links rotate about their longitudinal axis. From this point on the focus of control will rest with the free leg in the swing/support phase.

10. PD ANGLE CONTROL

The initial properties of the triped were the same as in [18]. The same applies to the reference signals. The triped base was set to be the same width as the stride of the biped. This method was successful in that the robot had no difficulty in reaching the desired reference. A problem occurs due to the intent of the control to have the robot fall due to gravity at the end of the swing phase. For the triped, this doesn't occur because of the mass of the additional leg.

At the beginning of the swing phase the leg builds up forward momentum in order to reach the desired angle. At the end of the phase the leg is held fixed while the body rotates about the pivot of the back leg. For the triped, the pivot is the line between the two legs attached to the ground. This motion is opposed by the moment of the CG about the same pivot.

It becomes apparent that in order for the robot to fall forward some combination of forward momentum and translation of the CG is required. Without active control of the feet the only control over the CG comes from the reference signal to the swing leg. Therefore, to maximize the forward translation of the CG the leg must be parallel to the ground.

The other option, increasing forward momentum, can be achieved by increasing the gain on the proportional-derivative control. This option is not limited by geometry and could result in unrealistic levels of torque. Energy efficiency is a desired attribute for the robot so this avenue must be traveled cautiously. The robot was still unable to achieve forward motion during the double support phase. The reason for this can be found from looking at the moment balance of the robot.

This result suggest that an increase in the gain is necessary. The application of which causes forward motion during the double support phase. However, by increasing the gain overshoot is increased as well. This makes the system volatile and unable to reach the reference signal causing the robot to fall.

One step to mitigate this problem is to decrease the distance required for the swing leg to travel. This is achieved by decreasing the initial distance between feet. This has the additional benefit of reducing the initial angle of the fixed legs.

Controlling the stride length results in two effects: decrease in torque to reach the reference and a decrease in forward momentum. It is important to note that the maximum forward CG is independent from the stride length.

As the stride decreases the angular distance traveled decreases. This results in a lower torque requirement. At the same time, the portion of the swing able to produce forward momentum decreases by the same amount. Therefore, it is important to strike a balance between the two.

The momentum at the end of the swing can be counterproductive to forward motion. The vector of momentum is in the positive z-direction. This causes the robot to want to rotate backwards about the pivot. This may necessitate a compromise between the two parameters.

11. ALTERNATIVE CONTROL

Another option, not applied in [18], is to apply torque to the hip at the end of the swing phase. The direction of the torque would be reversed from previous application. This would place the momentum vector in the negative z-axis. It then becomes a matter of determining when is the appropriate time to initiate the opposing torque. Two options were considered to apply this mechanism. One was when the leg reached the peak angle and the second was when the CG translates a certain distance forward.
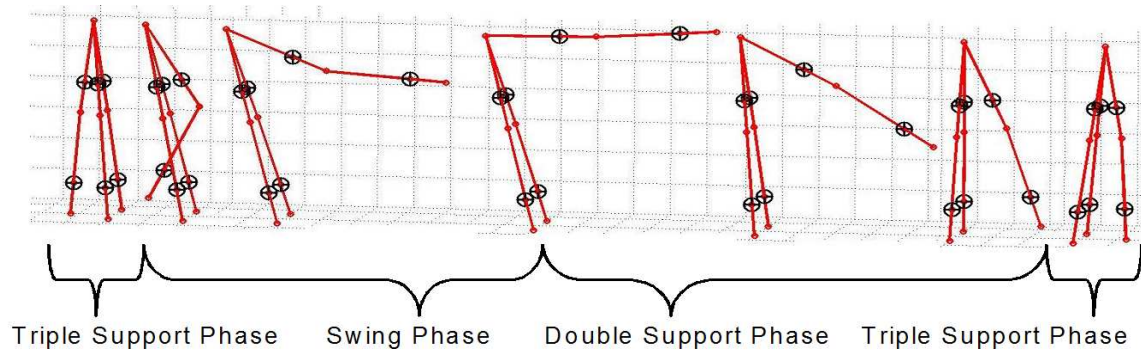
Figure 4: Triped Phases

11.1 Knee Control

For either of these the control algorithm applied to the free knee remains the same. Similar to that of the fixed legs, the reference input for the relative angle and angular velocity are zero. However, the torque applied to the hip of the free leg can make it difficult for the same control system to keep up. This artifact of the thigh motion can be leveraged as a benefit to the motion.

As the thigh rotates the angle between the thigh and the shin increases. This results in a larger torque applied to the knee by the feedback control. The thigh angular velocity decreases while at the same time the knee velocity is increasing. This results in a kick that contributes to the robots forward motion after the thigh has neared the end of its actuation. The result is an increase in the duration of applied forward momentum to the system.

The artifact also has the benefit of helping to avoid interference with the ground. It is not possible for the leg to remain straight for the initial swing as the foot would come in contact with the plane of the ground. The lag of the shin allows the foot to step over the surface. This phenomenon may have additional applications and challenges for terrain navigation.

11.2 Overshoot

Unique to the free leg is the occurrence of overshoot. Both the hip and the knee will oscillate about the final position set forth by the reference. This is undesirable as it contributes to momentum in the positive-z direction. This can cause the robot to rotate backwards and fall over. Still, even if the robot falls forward the additional angular displacement makes it difficult for the leg to reach the desired orientation by the time the foot contacts the ground.

As a result it is necessary to add an additional condition to the control algorithm for both the hip and the knee to prevent overshoot. The chosen solution was to simply increase the gain of the system in the presence of overshoot. This problem could also be mitigated by the inclusion of damping. Also, depending on the geometry requirements for the triped the angular velocity may be sufficiently small that the overshoot can be restrained without a gain increase.

11.3 Counter-Torque at the Peak Angle

The first point at which it is reasonable to apply counter-torque at the hip is when the leg is fully extended and the robot is assumed to be falling forward in the double support phase. This would minimize the torque required to maintain the reference angle of the free leg at the peak. It also offers more time for the control system to reach the final configuration. However, this result is not obtained and causes the robot to fall backwards.

During the swing phase there is a transition of the robot from falling backwards to that of falling forwards. This is a combination of the forward momentum from the swing of the free leg and the shift in the CG. The counter-torque is being applied near this transition point where the triped is, for the most part, balanced. Rotating the free leg down results in a negative-z momentum which presses the system down. In fact, if the robot is made to apply a positive torque at the hip any time the robot is falling the result is an oscillation about the balancing point. The configuration is unstable and undesirable. Therefore, it is necessary to wait to apply the counter-torque until sufficient forward momentum has been achieved but before the robot has fallen so far forward so as to prevent reaching the desired landing configuration.

11.4 Counter-Torque, Vertical Fixed Legs

A reasonable point at which to bound the counter-torque is when the fixed legs are vertical. In order for the triped to reach this point it must have already traveled half the distance of the step. Also, the CG must be forward of the pivot. These conditions guarantee that the triped has both sufficient forward momentum and moment balance. Any point between the beginning of the swing phase and vertical fixed legs could result in backwards motion. However, it may be necessary to utilize this space if in order to allow enough time for the foot to get into position.

This control scheme results in a successful triped step. At this point locomotion continues through the repetition of the three phases. If the same foot is chosen then the robot will travel backwards and return to the original position. Otherwise, the robot will step left or right from the previous orientation. To simulate this, the state at the end of the previous step is used as the initial conditions for the next step.
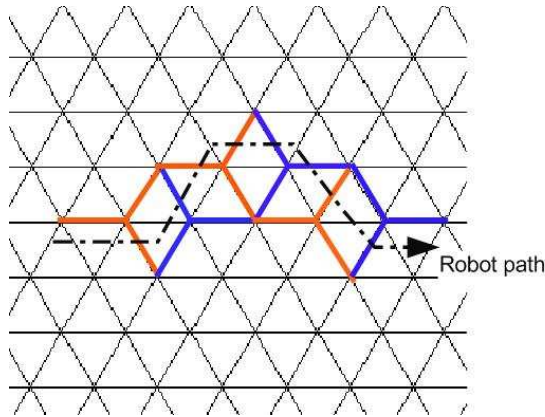
Figure 5: Triped path following

12. TRAJECTORY

Using this control scheme the robot is only capable of traveling on a triangular grid. In order to travel along a straight line the triped passes through a three step pattern. This consists of stepping with the right, left, and then left foot as seen in Figure 5.

Having only three discrete directions to travel from any given step is a significant drawback. However, this does not limit the robot from traveling in a general direction or turning around. Achieving such motions may be cumbersome and inefficient due to the extra steps involved.

13. CONCLUSIONS

It is clear that a niche exists for a triped robot. In the cases where stability takes a priority over agility the additional leg, compared to a biped, is beneficial. When static, the triped requires less energy consumption and computational power.

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15. REFERENCES

[1] Walking robotic test vehicle. *Control Systems Magazine, IEEE*, 6:22–23, Dec 1986.

[2] I. American Honda Motor Co. Asimo - technical information. Accessible online @: http://asimo.honda.com/downloads/pdf/asimo-technical-information.pdf.

[3] D. Argaez. An analytical and experimental study of the simultaneous control of motion and force of a climbing robot. Master's thesis, Massachusets Institute of Technology, 1993.

[4] H. Corp. Mechatronics center of excellence. Accessible Online @: http://www.govcomm.harris.com/about/capabilities/mechatronics.html.

[5] J. Cortés. Motion planning algorithms for general closed-chain mechanisms. Master's thesis, National Polytechnic Institute at Ecole, December 2003.

[6] S. F. D. Bevly and S. Dubowsky. Action module planning and its application to an experimental climbing robot. *Proceedings ICRA*, 2000.

[7] DARPA. Darpa grand challenge. Accessible Online @: http://www.darpa.mil/grandchallenge/index.asp.

[8] D. Frutiger. Iterative product engineering: Evolutionary robot design. Accessible Online @: http://www.puppetmasta.net/content/SP1/SP2002_report.html.

[9] G. M. J. Brazell, B. MacLaren and W. Williams. Mobile work platform for initial lunar base construction. *2nd Conference on Lunar Bases and Space Activities*, pages 633–635, 1992.

[10] L. W. Junzhi Yu. Design framework and 3-d motion control for biomimetic robot fish. *Intelligent Control, 2005*, pages 1435–1440, 2005.

[11] A. Lazinica. The hits of tokyo robot week. *IEEE Spectrum*, 2006.

[12] H. Lipson and J. Pollack. The golem project. Accessible Online @: http://www.demo.cs.brandeis.edu/golem/results.html.

[13] D. Lyons and K. Pamnany. Rotational legged locomotion. *Advanced Robotics ICAR Proceedings*, pages 223–228, July.

[14] R. P. M. Buehler and M. Raibert. Robots step outside. 2005.

[15] G. McMurray and B. MacLaren. Three legged walking mobile platform. Master's thesis, Georgia Institute of Technology, June 1988.

[16] NASA. Buck rogers, watch out! Accessible Online @: http://science.nasa.gov/headlines/y2001/ast01mar_1.htm, 2001.

[17] K. R.E. Tripedal knuckle-walking: A proposal for the evolution of human locomotion and handedness. *Journal of Theoretical Biology*, 213:333–358, 2001.

[18] C. T. S. Tzafestas, M. Raibert. Robust sliding-mode control applied to a 5-link biped robot. *Journal of Intelligent and Robotic Systems*, 15:67–133, 1996.

[19] T. H. T. Irie and K. Itoh. Study of three-legged-robot using genetic algorithms. *Transactions of JSCES*, 2000.

[20] A. Wagner. Three legged robot. Accessible Online @: http://sirius.ti.uni-mannheim.de:8080/proaut/content/e74/e160/e197/index_eng.html.

[21] M. Yim. Locomotion with a unit-modular reconfigurable robot. Master's thesis, Stanford University, December 1994.

[22] S. Yun-Jung Lee; Hirose. Three-legged walking for fault tolerant locomotion of a quadruped robot with demining mission. *IROS 2000 Proceedings*, 2:973–978, 2000.