Proceedings of the 39th ISR(International Symposium on Robotics), 15~17 October 2008

Gait Design for Three-Legged Robot

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Abstract

In this research, the locomotion of a three-legged robot has been studied. Since the three-legged creature does not exist in nature, the challenge of this research is to identify the possible gait for the symmetrical three-legged robot without mimicking the natural gait of an animal. The optimal gait should allow the robot to move forward with the best performance such as speed and stability. The evolutionary approach has been applied in order to achieve this goal. The dynamic simulation of the three-legged robot is constructed to allow the implementation of the evolutionary algorithm to be performed beyond the hardware and environment limitations of the actual robot prototype.

1. Introduction

Most of studies in legged robot are focused on mimicking the existing creatures such as biped [1], [2], quadruped [3], [4] or hexapod [5], [6]. These robot gaits are usually designed to imitate the gaits of their biological counterparts. Biped robot has the advantage of its agile movement but it is more difficult to maintain stability. However the quadruped robot is more stable but needs more actuators and power to operate, thus results in slower motion. The trade-off between them emerges an idea of a three-legged robot which minimizes the number of legs that always maintains static stability. The challenge of the three-legged robot is to design its walking gait which cannot be imitated from animals.

There are a number of researches for the three-legged robot. In those researches, three-legged robots have been constructed and their locomotion were implemented in several patterns [7], [8], [9]. Furthermore, the three-legged robot platforms are also used in the other research fields such as reconfigurable robot [10] and modular robot [11].

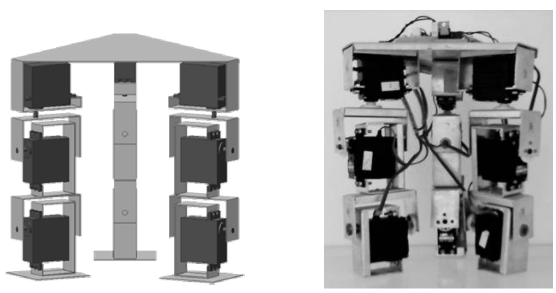
The main subject of legged robots study is the designing of their gaits. Several approaches have been studied in order to obtain gaits for different types of legged robots. The evolutionary algorithms are the ones which widely used for gait construction as shown in [1], [2], [4], [5], [12], [13]. The implementation of evolutionary approach needs the repeat operations which result in many problems. The hardware and the experimental environment could affect the performance of the evolutionary algorithm and require longer time to perform. To eliminate these problems, the computer-based simulation is used by many researchers [2], [12], [13]. The computer-based simulation enables the evolutionary algorithm to be performed faster and easier than real world implementation.

This research uses a genetic algorithm to design a walking gait for the proposed symmetrical three-legged robot. The research has begun with the construction of three-legged robot and the study of its locomotion on the actual robot hardware. Then the evolutionary algorithm was performed in the computer-based simulation.

2. The Robot

The prototype of three-legged robot has been designed as in Figure 1a. From the top view, the body of the robot is a symmetrical triangle. Its legs are connected to the body at each vertex of the triangle. Each leg contains 3 links, which are connected together by 3 revolute joints. Therefore the robot has 3 degrees of freedom (DOFs) in each leg. The top joint of each leg corresponds to the yaw motion while the other two joints of each leg correspond to the roll motion.

The actual robot was built according to the design. The body frames of robot are made of aluminum. The actuator of each joint is a servo motor with the limited range of motion between $-\pi/3$ and $\pi/3$ approximately. The robot is about 20cm high and weight about 1kg without battery (see Figure 1b).



(a) (b)

Figure 1. The design of the three-legged robot (a) and the actual three-legged robot (b).

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Table 1. The angle of each joint for each step in the manually designed gait.

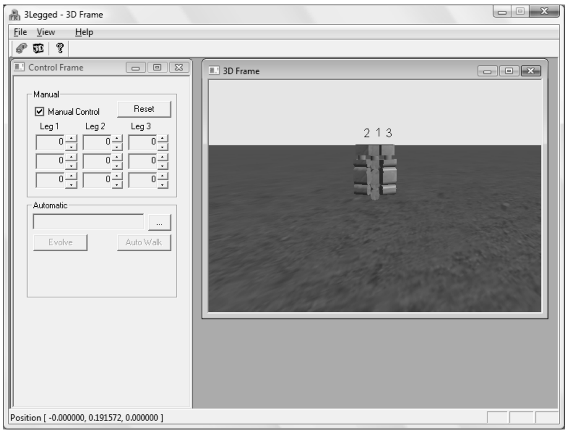
Joint	Angle of each step (radians)															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0.41	0.58	-0.39	-0.39	-0.39	-0.39	-0.39	0.00	0.59	0.59	0.59	0.59	0.59	0.59	0.59	0.00
2	-0.51	-1.04	0.53	0.53	0.53	0.53	0.53	0.00	-0.86	-0.86	-0.86	-0.86	-0.86	-1.04	-0.39	0.00
3	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	0.00
4	-0.42	-0.42	-0.42	-0.42	-0.42	0.39	-0.18	0.00	0.42	0.42	0.42	0.42	0.42	-0.39	0.18	0.00
5	0.51	0.51	0.51	0.80	1.04	-0.53	-0.07	0.00	-0.51	-0.51	-0.51	-0.80	-1.04	0.53	0.07	0.00
6	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	-1.04	0.00	1.04	1.04	1.04	1.04	1.04	1.04	1.04	0.00
7	-0.59	-0.59	-0.59	-0.59	-0.59	-0.59	-0.59	0.00	-0.41	-0.58	0.39	0.39	0.39	0.39	0.39	0.00
8	0.86	0.86	0.86	0.86	0.86	1.04	0.39	0.00	0.51	1.04	-0.53	-0.53	-0.53	-0.53	-0.53	0.00
9	1.04	1.04	1.04	1.04	1.04	1.04	1.04	0.00	-0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00

3. The Dynamic Simulation

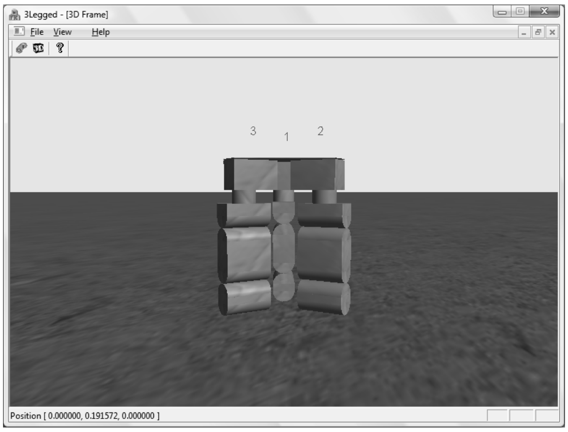
In order to avoid the limitations of real hardware in experiments. The dynamic simulation system is employed in this research. The simulation system is developed using Visual C++ with Microsoft Foundation Class (MFC).The Open Dynamics Engine (ODE) library is integrated into the program to provide a physic-based simulation. The ODE is a C/C++ API, which supports bodies, joints and collision detection with friction [14]. Although the graphic display library with OpenGL is bundled with the ODE. It is not integrated to the dynamic simulation here. The dynamic simulation has its own developed graphic display module with OpenGL (see Figure 2a).

The virtual robot has been modeled in the simulated environment. The model is simplified to represent the significant characteristics of the actual three-legged robot (see Figure 2b).

The model consists of 16 ODE’s bodies and 15 ODE’s joints. Six of fifteen joints are the ODE’s fixed joint type. The remaining are hinge joints, which are used to simulate the locomotion of servo motors. Each simulated joint is actuated by using the velocity control. The rotational velocity of each joint is controlled by the Proportional-Derivative (PD) controller as described in (1).



(a)



(b)

Figure 2. The dynamic simulation (a) and the virtual three-legged robot (b).

$$V = k_s\,(\theta_d - \theta) - k_d\,\mathring{\theta} \qquad (1)$$

where θ is the current joint angle, θ_d is the desired joint angle, k_s is the constant gain of proportional controller, and k_d is the constant gain of the derivative controller.

4. Implementation

To obtain an optimized gait for the three-legged robot. The gait is manually designed as the initial condition for the genetic algorithm. The initial gait consists of 16 steps which can be divided into 2 phases. These 2 phases are symmetrical to each other (see Table 1). The initial gain of P-controller and D-controller are configured to 10.0 and 0.8 respectively. The gains and the angles of each joint in each step are chosen to be parameters for the optimization. There are 2 objectives to be achieved for the optimization. The first is to maximize the speed of movement in the desired direction. This can be measured from the distance of the robot after it completes 16 steps of walking within the given time constant. The second is to minimize the total of side sway range while the robot is moving.

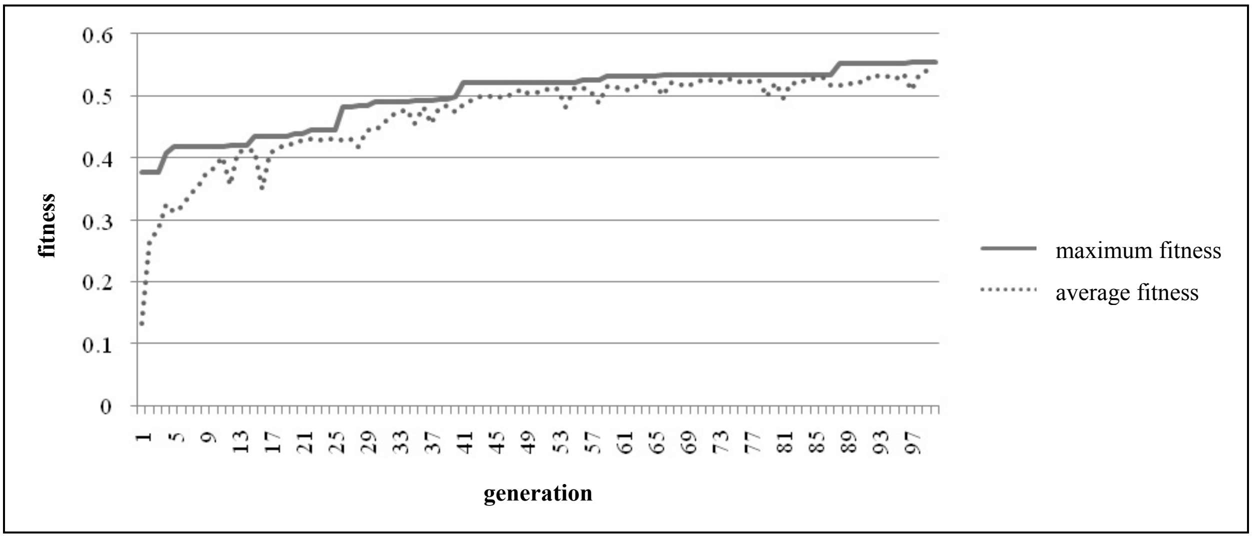


Figure 3. The fitness graph of the evolution. The maximum fitness (solid) and average fitness (dot) are shown.

Table 2. The angle of each joint for each step in the optimized gait

Joint	Adjusted angle of each step (radians)															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0.43	0.61	-0.40	-0.46	-0.31	-0.44	-0.48	0.00	0.62	0.58	0.56	0.62	0.52	0.68	0.58	0.00
2	-0.54	-0.95	0.47	0.50	0.52	0.57	0.62	0.00	-0.90	-0.89	-0.78	-0.89	-0.82	-1.04	-0.31	0.00
3	0.27	-0.01	0.02	0.06	0.08	0.04	0.04	0.00	-1.02	-1.04	-1.00	-1.04	-0.95	-0.97	-0.95	0.00
4	-0.51	-0.35	-0.46	-0.51	-0.36	0.31	-0.10	0.00	0.51	0.35	0.46	0.51	0.36	-0.31	0.10	0.00
5	0.42	0.51	0.47	0.88	0.96	-0.52	-0.16	0.00	-0.42	-0.51	-0.47	-0.88	-0.96	0.52	0.16	0.00
6	-0.96	-0.99	-1.04	-1.04	-1.02	-1.04	-1.00	0.00	0.96	0.99	1.04	1.04	1.02	1.04	1.00	0.00
7	-0.62	-0.58	-0.56	-0.62	-0.52	-0.68	-0.58	0.00	-0.43	-0.61	0.40	0.46	0.31	0.44	0.48	0.00
8	0.90	0.89	0.78	0.89	0.82	1.04	0.31	0.00	0.54	0.95	-0.47	-0.50	-0.52	-0.57	-0.62	0.00
9	1.02	1.04	1.00	1.04	0.95	0.97	0.95	0.00	-0.27	0.01	-0.02	-0.06	-0.08	-0.04	-0.04	0.00

5. Genetic Algorithm

The Matthew's Genetic Algorithm Library (GALib) [15] is employed to implement the genetic algorithm in the dynamic simulation. The steady-state genetic algorithm was used to optimize the parameters of the gait which consist of 65 values. Two of them represent the constant gains of PD-controller. The remaining 63 parameters are used to adjust the angle of each joint. The three-legged robot contains 9 joints. Each step needs 9 desired angles to control the 9 corresponding joints. The gait consists of 16 steps and the first 8 steps are symmetrical with the remaining steps. The 8th and 16th are used to control the robot to the initial joint angle, which are not adjusted. Therefore, the number of angles to be adjusted is 9 angles for each of 7 steps, which resulted in 63 parameters. The values of parameters are encoded as real number in the range between 0 and 1. These values will be mapped into the parameters for the gait optimization.

The run of genetic algorithm was conducted for 100 generations with the population size of 20. The initial population was initialized with the randomized number. The most 10 fit genomes of each generation were preserved to the next generation. The 70% of crossover rate and 1% of mutation rate were used in the evolution. The fitness of each genome is determined by 2 factors. The first is the distance fitness of robot on the desired axis from the origin which is weighted as 70% of the fitness. The second is the fitness of the accumulated side sway range of each robot step which is weighted as 30% of the fitness as the following.

$$f = (0.7f_d) + (0.3f_s) \qquad (2)$$

where f is the fitness of each genome, f_d is the calculated distance fitness, and f_s is the calculated side sway fitness.

The distance fitness (f_d) and the side sway fitness (f_s) are calculated from (3) and (4) as follows.

$$f_d = (d_a - (k_{dl}\, d_m)) \,/\, ((k_{du} - k_{dl})\, d_m) \qquad (3)$$

where d_a is the distance of robot after performing a cycle of adjusted gait with the optimized controller gains, d_m is the distance of the robot after performing a cycle of manual design gait with the manual defined controller gains, k_{du} and k_{dl} are the constant value of upper and lower boundaries used to scale the distance of walking gait. They are defined to be 4 and 1 respectively.

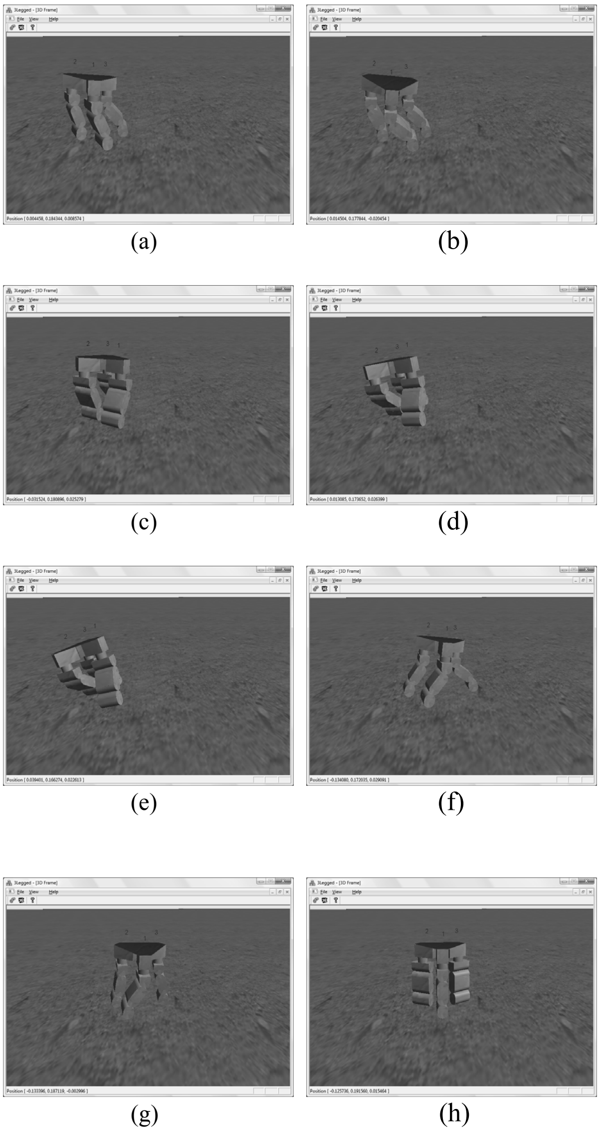
$$f_s = 1 - \quad (s_a - (k_{sl}\, s_m)) \,/\, ((k_{su} - k_{sl})\, s_m) \qquad (4)$$

where s_a is the accumulated side sway range of the robot after performing a cycle of adjusted gait with the optimized controller gains, s_m is the accumulated side sway range of the robot after performing a manual design gait with the manual defined controller gains, k_{su} and k_{sl} are the constant value of upper and lower boundaries used to scale the accumulated side sway range. They are defined to be 2 and 0.5 respectively.

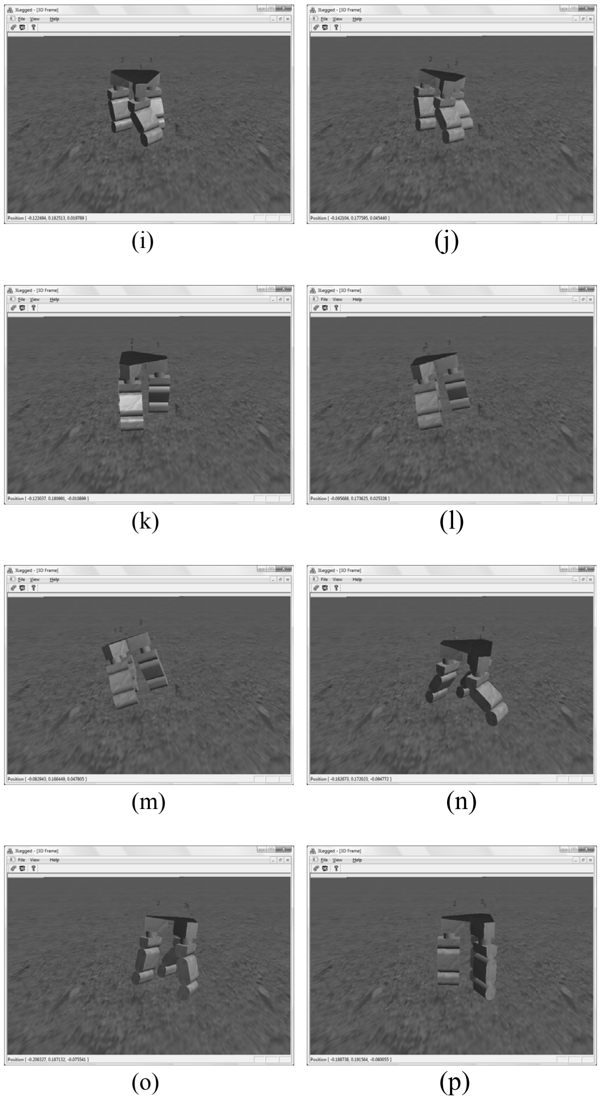
6. Results

The manual gait, before the genetic algorithm has been applied, can move the robot forward around 8.6cm in one walking cycle of the gait. The total of side sway range was around 100cm while the robot maintains its height to be higher than 15cm. After the genetic algorithm was applied, the results are shown in Figure 3. The best genome, which has the greatest fitness score, was decoded and mapped to the parameters of walking gait. The optimized gains of P and D controller are 5.036 and 0.045 respectively. In addition, the angle parameters are also decoded and calculated with the angles of each joint of walking gait. The adjusted angles of each joint for the optimized gait are displayed in Table 2. The optimized gait can move the robot forward about 18.9cm while the accumulated side sway range of the robot is about 55cm. The distance of optimized gait is better than the manual design gait around 120% and the accumulated side sway range is reduced by 45%.

The optimized gait successfully increased the stability of the robot during the continuous walking cycle. The step sequence of the optimized gait is depicted in Figure 4a – Figure 4p.



(a) (b) (c) (d) (e) (f) (g) (h)



(i) (j) (k) (l) (m) (n) (o) (p)

Figure 4. The screen capture of robot for each of the 16 steps of the optimized gait (a-p).

7. Conclusion

This research proposes a symmetrical three-legged robot and its walking gait. The prototype of three-legged robot has been built to study its locomotion. Then the virtual robot, which corresponds to the actual robot, was built in the dynamic simulation system. The initial gait has been manually designed for the virtual robot in the dynamic simulation system. In order to maximize the forward moving speed and to minimize the side sway range of the robot motion. The genetic algorithm was applied to adjust the control parameters and joint angles of the walking gait. The algorithm resulted in an improvement of moving speed and also reduced the side sway range.

The design gait should be directly applied to the actual robot in theory. However, in practice there are many discrepancies between the actual robot and the virtual robot. These will require an adaptation for the obtained gait before it can be successfully applied into the actual robot.

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Topic: Mobile Robotics
Keywords: Tripod Robot, Legged Robot, Gait design, Simulation

Introduction

Most of studies in legged robot are focused on mimicking the existing creatures such as biped, quadruped or hexapod. These robot gaits are usually designed to imitate the gait of their biological counterparts. Biped robot has the advantage of its agile movement but it is more difficult to maintain stability while the quadruped robot is more stable but needs more actuators and power to operate and usually results in slower motion. The trade-off between them emerges an idea of a three-legged robot which minimizes the number of legs that always maintains static stability. The challenge of the three-legged robot is to design its walking gait which cannot be imitated from animals. This research uses a genetic algorithm to design a walking gait for the proposed symmetrical three-legged robot.

Summary

The prototype symmetrical three-legged robot has been built together with the corresponding dynamic simulation system. The actual robot is made of aluminum and driven by 3 motors in each leg. The initial gait is manually designed. The genetic algorithm is applied to adjust the control parameters of the walking gait in the simulation to maximize the forward moving speed and to minimize the side sway of the robot.

Results

The initial walking gait has been manually designed. The initial walking gait can move the robot forward about 8 cm in one walking cycle while maintain the height of the robot to 19 cm. The control parameters of the walking gait are then adjusted using genetic algorithm in the dynamic simulation system. The genetic algorithm is used to maximize the forward distance of the robot in one walking cycle and minimize the side sway of the robot during the walking cycle. The proposed designed gait successfully maintains stability of the robot during the continuous walking cycle.

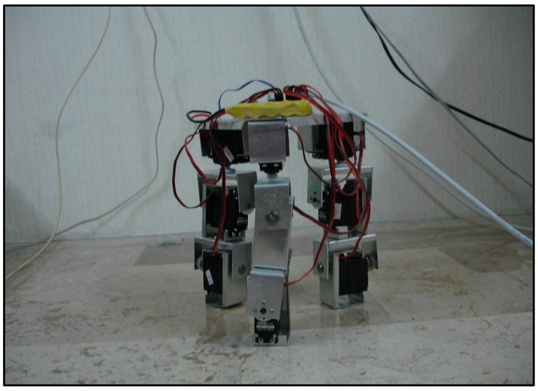

Figure 1. Three-Legged Robot

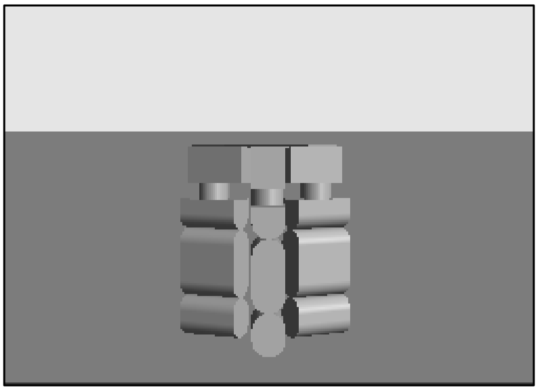

Figure 2. Three-Legged Robot Simulation