Robust Bipedal Walking: The Clyon Project

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ABSTRACT

Bipedal robot walking presents challenges in design, control, balance and practicality. No one element can exclusively define a robust walking platform. With a combination of elements, a robust walking platform may be defined. In this paper, we present the development of a bipedal robot whose easily modifiable gait allows us to study gait performance and bipedal robot balance issues. Robot design, hardware requirements, computer interface and software development phases are also addressed. Overall, the Clyon robot presented in this work is aimed at discovering gaits with minimal hardware requirements to accomplish useful tasks.

Keywords

Bipedal Robot, Humanoid Robot, Robotics, Clyon Project, Zero Moment Point (ZMP), Control, Walking Gait, Controller.

1. INTRODUCTION

Humans walk elegantly with little training after birth. Elegant walk can be fully described by a robot; however, in application there are limitations that outweigh the benefits. Some of the limitations that may occur include the inadequate power to weight ratio, mostly occurring because of the use of many mechatronic components. There are many types of gaits; however, bipedal walking can be broken down into two elements; that is, the problem of balancing and control. This paper sets to examine robust elements that link balance and control. An implementation of a robust gait is also discussed.

2. THE CLYON PROJECT

The Clyon Project started in January 2005 with the ultimate aim of developing simple gaits using as little hardware as possible while maintaining elements required to mimic the elegant human gait. The Clyon robot is defined by two legs that each has three degrees of freedom; a hip, a knee and ankle motion per leg. The hip and knee motions are in the same vertical plane and the ankle motion is in the horizontal plane.

Figure 1 shows the Clyon robot layout. Feedback to the robot is provided by data from two sensors located in the robot feet. Overall the robot is designed with the intention of having light feet; it however gradually gets heavier towards the heaviest part at the torso. The general concept is to approach the gait development as states that the robot needs to assume at least once in each of the two steps, that is while taking a right and left step. Advancing from one step to the next is based on the rate of change from one state to the next. The states are essentially static poses that the robot can assume, carefully chosen as the maximum and minimum stance positions with little or no torque applied to the entire system for balancing. The Clyon robot without any external load attached to the upper torso can assume static poses that demonstrate balancing without torque requirements, which proves advantageous in exploring simple gaits with simple programmable interfaces.

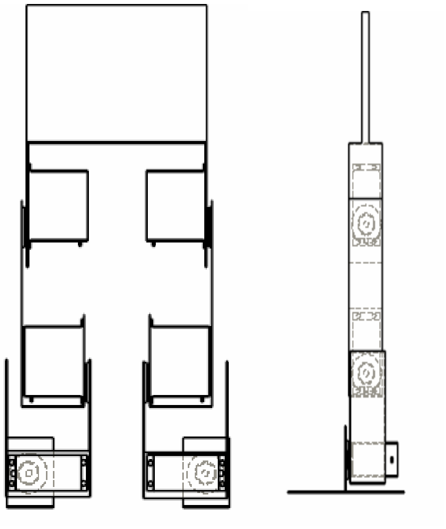

Figure 1: Clyon Robot Layout

The robot employs a simple-to-use configurable controller which controls the six servos and two sensors.

2.1 Robotic Components

A typical robot has a combination of motors and sensors to perform an objective. In a good robot design, the objectives would be carried out by a mechanism that is capable of systematically controlling all the elements in the robot, whether in combination or individually. Robots today are commonly controlled by a microcontroller, a Programmable Integrated Circuit (PIC) or a computer platform.

A microcontroller is by definition a basic computer type circuitry normally placed on one integrated circuit, which has typically a central processing unit, memory, an optional math processing unit and bus connections. Similar to a computer, it has the ability to execute commands and receive data to or from a bus of connected devices[1], such as sensors, motors and servos, in the case of a robot. Microcontrollers are used in other devices other than robots, such as cell phones, digital radios, microwaves, clocks and other electronic devices.

The most commonly used microcontrollers in robots are Programmable Integrated Circuits (PIC) or as they are known in industry; Stamps. It is interesting to note that the word Stamp is used in the microcontroller name to denote the intended size of the PIC. The BASIC Stamp employs code based on the BASIC programming language whereas OOPIC stamps use an object-oriented base approach to programming. The PIC is also capable of using additional programming languages other than BASIC, giving the PIC added flexibility and complexity [1]. All languages convert human-readable code to machine language code. OOPIC is designed primarily as an effective robot microcontroller method.

Sensors in combination with microcontrollers can provide complex, effective and efficient methods of control for different robotic systems. The ActivMedia robot reconnaissance team shown figure 2 is able to map information in a collaborative effort, allowing multiple robots to accomplish the same objectives while maintaining a certain level of autonomous characteristic within each robot.

The computer platform allows added flexibility for software programming while maintaining a set standard in hardware. Most in the computer industry believe in Moore's Law, which is an empiric observation made by the electronic chip manufacturer and Intel's cofounder Gordon Moore, basically quantizing the rate of technological development and advances in the semiconductor industry as doubling every one-and-a-half years in terms of the complexity and speed of the basic computer components, such as the central processing unit. Using the computer platform and its likes would imply from Moore's Law that the platform usefulness in terms of processing abilities will increase sharply overtime yet have the ability to still use the same basic software with improved hardware [2].

Figure 2: ActivMedia Robot Reconnaissance Team

The software usefulness then comes to the fore since we are developing on a computer platform that is dynamically changing its power in 18-month periods. To ensure that one application works on every personal computer platform, there has to be an adequate operating system capable of doing the chores that will enable compatibility. Microsoft Windows and Linux are two of the more competitive Operating Systems (OS) that are able to demonstrate porting of the platform from the software to the hardware in embedded forms [3]. Microsoft has Windows CE and Linux has Embedded Linux which further emphasize the computer platform as being ideal for developing engineering systems for research and testing because after the software methods are developed and tested they can be hard-coded in an embedded circuit or chip with performance optimization and security benefits [4].

Walking algorithms for bipedal robots are often derived from classical control theory, which typically uses a reference trajectory for the robot to follow. A disadvantage for using classical control theory is that reference trajectories can rarely be defined to work in every scenario in the real world. Bipedal robots traversing over an irregular terrain will encounter different obstacles; bipedal robots commonly walk better on flat and smooth surfaces. Many bipedal walking robots have been created in the last 20 years; noteworthy developments being Sony's QRIO and Honda's ASIMO. There are other robots that have similar abilities as Honda's and Sony's robots; however, they seem limited and not as widely known.

Honda's ASIMO robot [5], named after famed chemist and science fiction writer Isaac Asimov (1920 – 1992) was first created in 1986 known as EO. EO had three worthy and successful versions E1, E3 and E6, from 1987 to 1993, bipedal walking proved to be challenging with different and dynamic issues; it took E0 in 1986 twenty to twenty five seconds to make a complete step motion. From 1993 to 1997 Honda developed portions of the robot now known as ASIMO, presented in the new series as the P prototypes. ASIMO presented to the world in 2003 was the last iteration in the P series.

Not to be left out, other companies such as Fujitsu and Sony also developed robots. Sony's dream bipedal machine now known as QRIO demonstrates advance hardware and machine vision capabilities such as jogging, dancing and identifying objects to interact with. QRIO interestingly stands for quest plus curiosity which demonstrates Sony's Corporation further trust into robotics and control technology.

Figure 3: Sony Corporation's QRIO Robot

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[1] The word 'devices' is used in this context to mean not only robotic elements, such as arms, motors, servos, but also typical computer devices such as USB cameras, WiFi, blue tooth, et al.

2.2 Conceptual Design

The concept for the Clyon humanoid robot is to design a bipedal walking robot with a limited amount of servos which would still be capable of mimicking the elegant human walk to a point. The design is thus resolved by cost, effort and implementation. For the design, cost is influenced by the type of controller, which is also primarily determined by the number of servos that can be supported.

The initial design is illustrated in figure 4 which shows concept 1 on the right with 5 degrees of freedom and its corresponding motions.

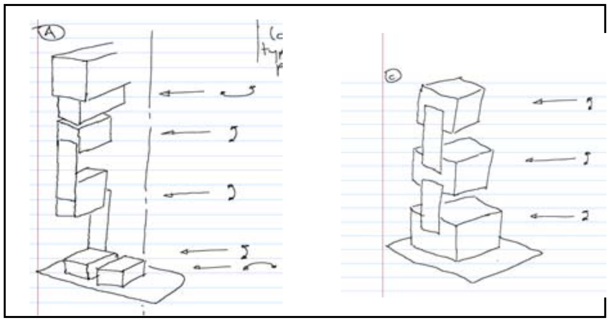


Figure 4: Design Concept 1 and 2

Concept 2 is illustrated in figure 4 also on the left shown as a 3-DOF leg that describes the hip, knee and ankle in a humanoid form.

The final concept chosen is as seen in figure 5. It has the same elements as seen in concept 2; however, the ankle motion is in the horizontal plane. Ankle motions in the horizontal plane were chosen because they're needed to turn effectively during fast strides and also to counterbalance loads in all the robot's described planes of motion. The robot is 11 inches tall by 5 inches in width; its feet are 3.5 inches in width by 1.5 inches in length. The dimensions between the thighs and shins are proportionally correct with respect to the human form, with the tight being longer than the shin.

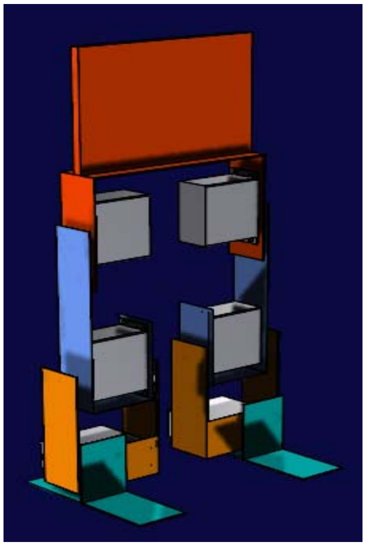


Figure 5: Design Concept 3 with 3 DOF per Leg

The final built prototype as seen in figure 6 also includes sensors in the feet to feedback data on the state positions.

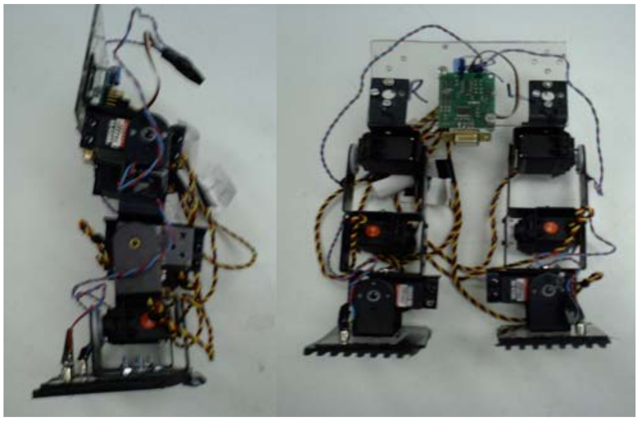


Figure 6: Clyon Humanoid Robot Prototype

3. ROBOTIC KINEMATICS

Humans generally walk with pressure applied generally around the base of their feet, the heels, along the outer edges to the toes. However, while running, humans tend to run on the upper part of the feet, using the toes more as a base. The dynamics involved with running and walking slightly differ in terms of torso balancing and pressure application on the feet.

3.1 Walking States

Normally human muscles are relaxed whenever a state is achieved, such as leaning on one foot or sitting down. At different positions and configurations a robot likewise needs to use different and appropriate torques to maintain balance. The drawback being however that programming the concept of relaxing servos can be computationally taxing for a limited controller; having to calculate all known possible iterations for balance and the required torque. Another approach is to assume basic steps with respect to walking states for a general gait. Figure 7 shows a hypothetical marching gait with possible shifts in the center of gravity from left to right as the robot's feet advance from position 1 to 5.

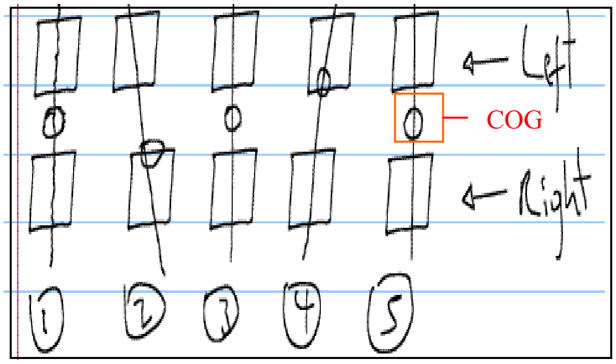


Figure 7: Walking States and Center of Gravity (COG) Shift

The shift in the centre of gravity with respect to walking swiftly or running has been described in more detail with the use of the Zero Moment Point (ZMP) principles [6]. The objective of the ZMP principles is to maintain a stable zero moment point (ZMP) with respect to the bipedal robot's feet trajectory. That is to balance the robot while its center of gravity (COG) shifts during walking. Similarly, walking states describe the walking by using an assumed gait of the robot without concentrating on the details of moving from one state to the next. Walking states resolve into exploiting the inherent robustness and natural dynamics of the robot while experimentally fine tuning the gait [7]. The simple approach lends to walking issues such as changing gaits and walking over irregular surfaces.

3.2 Balancing Walk

Balanced walking with respect to advancing to new states is broken down into three steps, initialization, walking and termination. Considering the marching gait, the states 1 and 3 are defined as initialization and states 2 and 4 are defined as walking and state 5 is defined as termination. The five walking states as seen in figure 8 show the robot taking two steps as in a march. In walking states 1 and 3, the robot assumes a relaxed state while the applied torques are essentially low as compared to the torques applied in walking states 2 and 4. For the Clyon robot the initialization state means all servo torques are zero. The required torque during states 2 and 4 can be assumed to be equivalent to the torque required to maintain a static stride stance. The required torque during termination is assumed the greatest as it has to maintain the robot's balance while exiting a dynamic walking state.

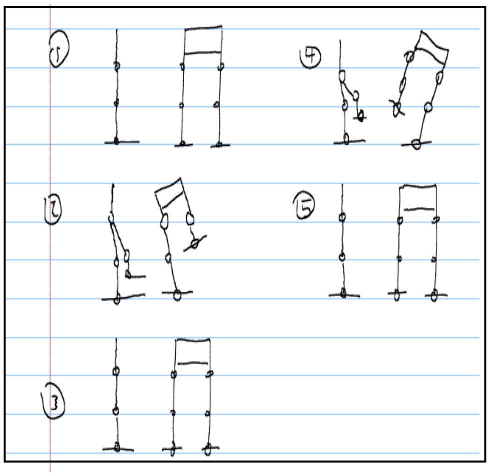


Figure 8: Front View of the Five Walking States

Figure 9 describes the mechanical elements of the Clyon robot, flexibility for the torso is negligible and it is assumed solid. Based on the configuration of the Clyon robot we initially hypothesize the following shifts in the centre of gravity with respect to a x, y and θ reference points.

1. $(x, y, \vartheta_a)_{COG} \approx (0,0,0)$
2. $(x, y, \vartheta_a)_{COG} \approx (1,-1,1)$
3. $(x, y, \vartheta_a)_{COG} \approx (0,0,0)$
4. $(x, y, \vartheta_a)_{COG} \approx (-1,1,-1)$
5. $(x, y, \vartheta_a)_{COG} \approx (0,0,0)$

The centre of gravity (COG) shifts from the mean position (0,0,0) to left and right positions represented as -1 and 1 respectively as shown in figure 8. The trace of the motion in the image represents the maximum orientation of the robot's torso in any direction without toppling. The orientation of the COG with respect to the vertical plane is described with θ with respect to the foot contacting the surface. The aim is to maintain the centre of gravity meanly within the trace area with respect to each advance state. The motion creates a movement trace with respect to the torso as seen in figure 9. The changes in the states are linearly developed from one state to the next noting the minimum speed required to change the state as being related to the weight of the robot.

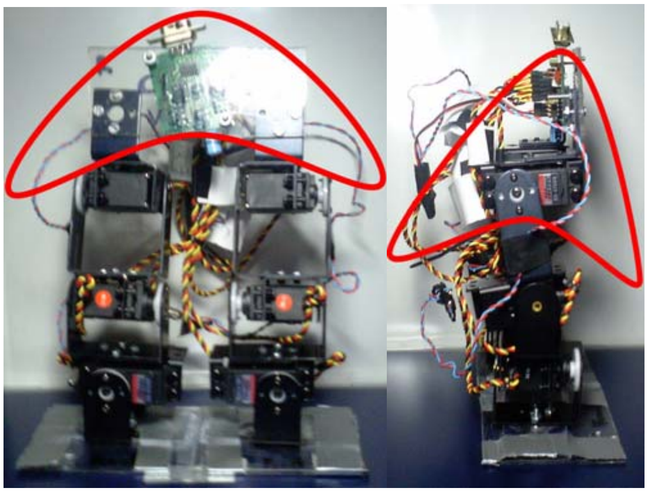


Figure 9: Movement Trace

The initial orientation of the robot is as shown in figures 9 and 10, where l_{tr} - torso length, l_{th} - thigh length, l_{sh} - shin length, m_{tr} - torso mass, m_{th} -thigh mass and m_{sh} - shin mass. The center of gravity area, Area$_{COG}$ that we are concerned with is balanced within the torso area; it is given as

$$gM_{tr}(l_{tr} + l_{th} + l_{sh}) = Area_{COG}$$

Equation 1: General COG Area

As seen in figure 9, the center of gravity is roughly within the center of the robots torso's mass. To balance states 1, 3 and 5 the area COG is given as

$$Area_{COG} = 2g(M_{th} + M_{sh})(l_{th} + l_{sh})$$

Equation 2: COG Area at Standing States

For states 2 and 4 the area COG is given as

$$Area_{COG} = \pm 2g(M_{th} + M_{sh})(l_{th} + l_{sh})f$$

Equation 3: COG Area at Stride States

where f are the factors associated with leading foot, such as stride length and stride velocity and g is the gravitation constant.

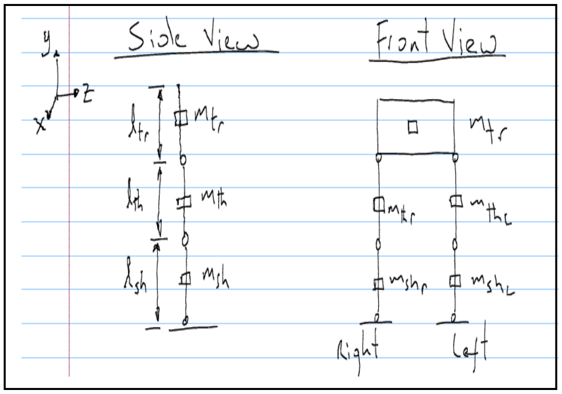


Figure 10: Terminology Used for Clyon's Elements

4. SOFTWARE ALGORITHM

The software algorithm revolves around defining states that the robot has to go through in order to maintain balance and walk. The initial state (state 1) is essentially the same in all gaits to get the robot to assume a balancing stance. The states between state 1 and the ending state are linearly extrapolated within the algorithm. To define the gait more elegantly requires more states between the end and start of the gait. Figure 11 represents the general gait.

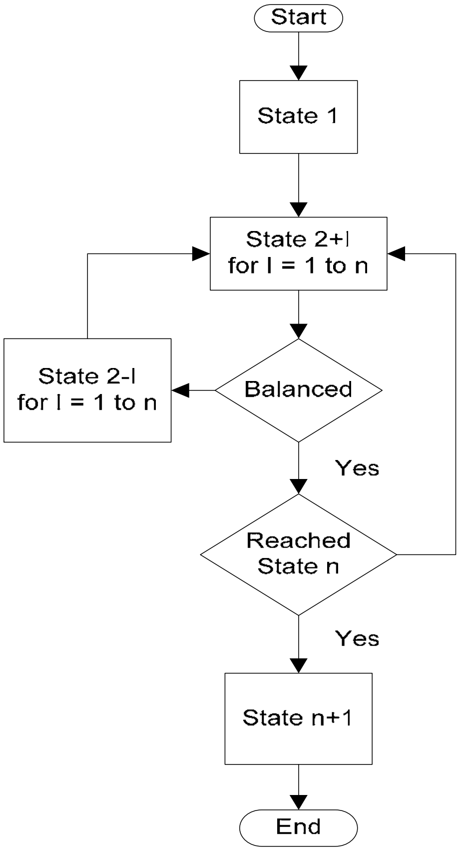


Figure 11: Algorithm of General Gait

4.1 Robot Limitations

The limitations of the robot are factored into the gait, and in practice the limits are not normally reached; however, knowing the limitations provides additional elements that can be used in other gaits, as the following sections will explain. The limitations of the robot are easily found by directly measuring the maximum and minimum angles that each joint will be able to attain. In the Clyon robot software this is accomplished by noting the positions of the servo limits.

4.2 Sumo Taut

The Sumo Taut is a simple gait that explores the ankle servos of the Clyon robot. The ankles in general serve the purpose of turning during a quick stride or running. The principle is that the ankle shifts the weight of the robot to the left or right, depending on the direction of turn. The Sumo Taut works by actuating both ankles and feet on the ground initially, after which the robot raises one leg higher than the next and slowly uses the ankle with the feet on the ground to slowly lower the robot's other left foot to the ground. Figure 12 shows a photo of the Clyon robot in mid Sumo Taut.

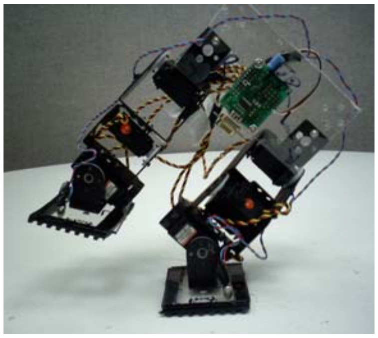


Figure 12: Mid Sumo Taut

4.3 Elegant Walk

During elegant walk, humans tend to walk on their heels, realizing more of the balancing effort on the calf muscles and the knee joints. Figure 13 shows left knee inflexed to maintain balance during the elegant gait. The torso is maintained as straight as possible.

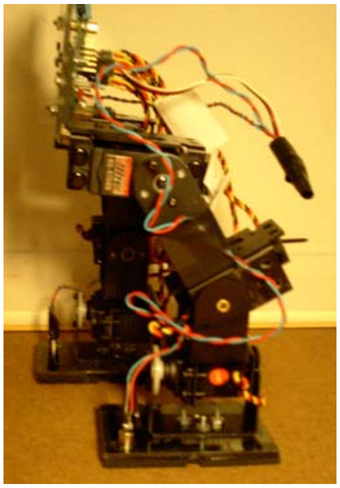


Figure 13: Clyon Left Knee Inflexion

4.4 Robot Stride

For humans to run or stride, the upper torso leans forward and the balancing effort is appreciated from the top of the feet, the toes. Similarly with the Clyon robot, the robot leans forward and runs on the front most tips of its feet as shown in figure 14.

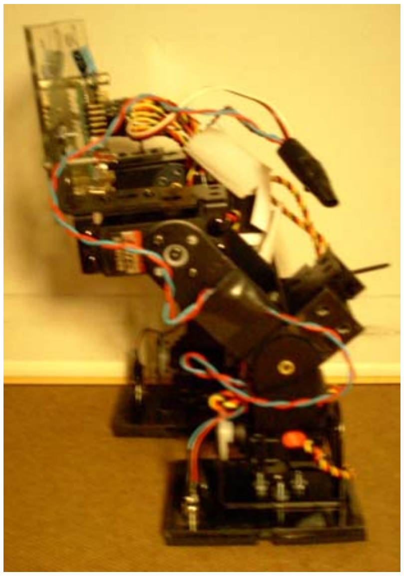


Figure 14: Clyon Robot Stride

5. ROBUST WALKING

Robust walking is defined as the optimal gait being able to adapt to as wide a range of gaits. With the Clyon robot, walking elements have been analyzed in three categories; which are with respect to the hardware setup, range of the gait and software implementation.

5.1.1 Hardware Setup

The Clyon robot is adjustable at the torso and at the feet. The torso width determines the lateral balance and as such influences the required speed of the gait. With a narrower torso balance on one ankle is done with less effort than with a wider torso. With a narrower torso and wider feet, the robot is able to approach elegant walk more strictly with the given hardware configuration; however, during longer strides balance issues arise. The balancing factors during longer strides require either a wide torso or a counter balance on a narrow torso. For the wider torso, the robot is capable of increasing the stride length, but has to compensate by increasing speed of changing from one state to the next.

5.1.2 Range Of Gait

The main gait of the Clyon robot has the ability to elegantly walk and make longer strides; however, the hardware as it is now limits the robot from using extreme gaits as shown in figure 15. Figure 15 shows an extreme stride which allows the robot to momentarily have both feet off the ground.

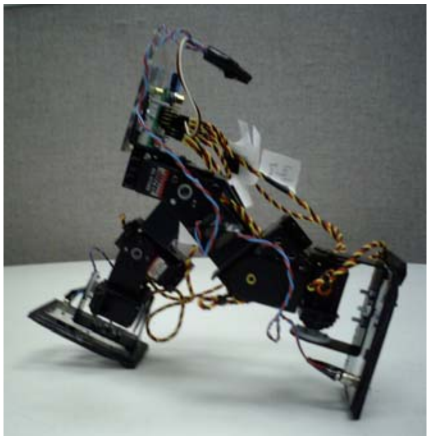


Figure 15: Long Stride

5.1.3 Software Implementation

The software implementation for the Clyon robot takes the states approach in defined steps; at the end of each state the robot tends to an out of balance pre state in order to use the shift in the COG to the advantage. For state 1, the robot assumes an initial balancing position, with the torso tending to be out of balance in the direction the robot needs to go. Figure 16 shows an exaggerated turn to the left during a stride.

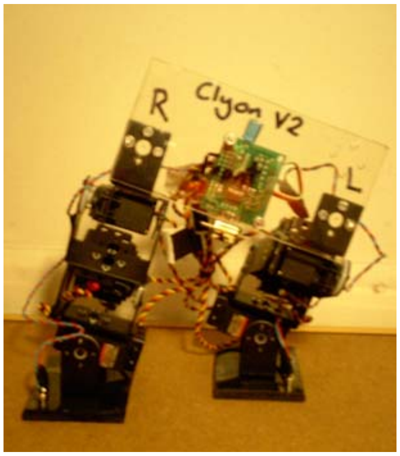
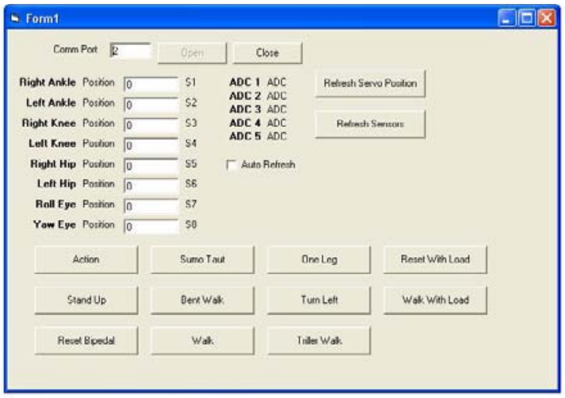


Figure 16: Turning to the Left

Defining more states would imply that the robot approaches a more stable and smooth gait, but in practice defining states as movie frames may not be practical. One approach has been to use simulation software to demonstrate each frame of the gait and then translate it into the software for implementation [8]. Understanding the limiting position of each state makes it easier to program the robot linearly considering only the required time to change the states and the position and torques of the servos for the states. For example during the marching gait, only two steps are defined for each phase of the gait, which is to step with the right then the left or vice verse. The states between each step is repeated and controlled with respect to the hardware setup.

In defining the states, the approach used in the Clyon project is to manually configure each defined state, read the servo position at the state and then linearly extrapolate the actions needed from one state to the next. For one step it involves adjusting each leg twice that is for the first state the legs tend to shift the torso out of balance, and then the next state requires counter balance on the lead stride leg and outer balance on the following stride leg, then balancing on both legs. The software implementation is shown in figure 17. The screen shot shows the software ability to quickly edit values of each joint servo, giving the benefit of tuning each gait quickly.



Comm Port 2
Right Ankle Position 0 S1
Left Ankle Position 0 S2
Right Knee Position 0 S3
Left Knee Position 0 S4
Right Hip Position 0 S5
Left Hip Position 0 S6
Roll Eye Position 0 S7
Yaw Eye Position 0 S8
ADC 1 ADC
ADC 2 ADC
ADC 3 ADC
ADC 4 ADC
ADC 5 ADC
☐ Auto Refresh

Figure 17: Software Interface Screenshot

5.2 Walking Applications

Bipedal walking robots have potential applications that could give them a capability humans have or even exceed [9]. Some of the applications that bipedal robots can be primarily geared toward include exoskeleton aid that is for the bipedal robot to be attached to a human frame for support; another application would be military applications that involve carrying heavy gear across intricate paths or service operations that would normally endanger a soldier investigating the surroundings. Figure 18 shows the Clyon robot carrying a battery load that is approximately twice its weight.

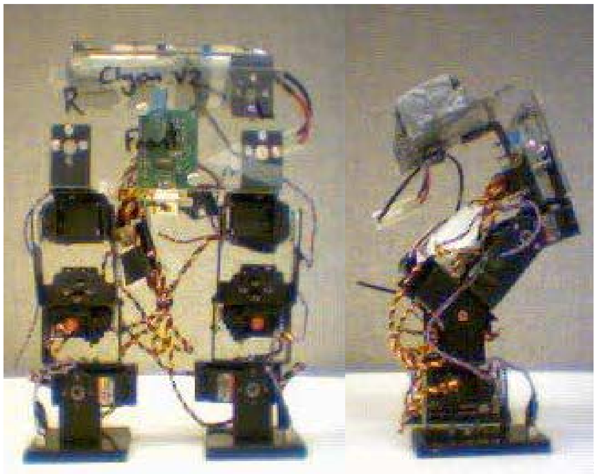


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Figure 18: Clyon Loaded

6. CONCLUSIONS

Bipedal robust gaits involve appreciation of the software implementation, the hardware configuration and the dynamics of human walking. The concept that is primarily employed in robust walking involves understanding the modes of balance for different objects; for walking elegantly, the aim is walk with the torso upright making the balancing effort aligned with the heel of the feet and the torso's center of gravity. For swift strides, the aim is to employ walking on the front tip of the feet tending to lean out of balance while adjusting the rate of change from state to state.

The concept of states employed within the Clyon project works by defining the initial, moving and final states as balancing states. The initial state makes the robot balanced and then tends to make the robot out of balance in the direction the robot intends on moving. The moving state is based on using as few as possible frames for switching balance from the left leg to right leg. For the final state, the robot comes out of the moving state tending towards a balanced configuration that will halt the gait without tipping over the robot.

Under load carrying conditions the robot's center of gravity is shifted towards the combined torso and load center of gravity, for the Clyon robot the shift tends to make the robot lean forward counterbalancing with the knee servos. The lateral ankle motions in general tend to make the center of gravity shift towards the left or right, creating a turning motion in the tipped direction.

7. FUTURE CONSIDERATIONS

Future work for the Clyon humanoid robot involves making the robot autonomous, being able to move around or follow objects. That part of the project will encapsulate artificial intelligence using machine vision techniques and a newer controller. On the hardware side, the robot will have the ability to be configurable, by either adjusting the width of the torso or adjusting the width of the feet. Other hardware implementation includes the use of additional sensors, such as gyroscopes to enable maximum usage of the area COG concept.

Further analysis of the robot's feet design will potentially provide information on balancing dynamics as the robot descents and climbs grades [10]. Also for future consideration is the reduction in the energy requirements used [11]. Some state positions already used in the Clyon control paradigm require no energy.

8. ACKNOWLEDGMENTS

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