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ODYSSEUS AUTONOMOUS WALKING ROBOT: THE LEG/ARM DESIGN

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ABSTRACT

ODYSSEUS is an autonomous walking robot, which makes use of three wheels and three legs for its movements in the free navigation space. More specifically, it makes use of its autonomous wheels to move around in an environment where the surface is smooth and not uneven. However, in the case that there are small height obstacles, stairs, or small height unevenness in the navigation environment, the robot makes use of both wheels and legs to travel efficiently. In this paper we present the detailed hardware design and the simulated behavior of the extended leg/arm part of the robot, since it plays a very significant role in the robot actions (movements, selection of objects, etc.). In particular, the leg/arm consists of three major parts: The first part is a pipe attached to the robot base with a flexible 3-D joint. This pipe has a rotated bar as an extended part, which terminates in a 3-D flexible joint. The second part of the leg/arm is also a pipe similar to the first. The extended bar of the second part ends at a 2-D joint. The last part of the leg/arm is a clip-hand. It is used for selecting several small weight and size objects, and when it is in a "closed" mode, it is used as a supporting part of the robot leg. The entire leg/arm part is controlled and synchronized by a microcontroller (68CH11) attached to the robot base.

Keywords: Autonomous Walking-Wheeled Robots; Robot Design; Robot Leg/Arm;

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1. INTRODUCTION

The study of autonomous walking robots (AWR) is a very attractive area of research and human challenge, since AWRs provide a better mobility in terrains with irregularities than wheeled robots. In particular, in buildings with many floors and stairs, with no access to elevators (in case of fire or earthquake), or floors with surfaces of different levels, wheeled robots are almost useless beyond a one-level surface. Moreover, if for some reason there is a blocked corridor, (e.g. because of a low height obstacle dropped accidently), a wheeled robot has to return to look for another open corridor in order to reach the destination point. On the other hand, on floors with no irregularities wheeled robots (so far) move faster than walking robots and the control of their motion is simpler than walking ones.

A variety of AWRs have been designed, constructed or proposed to fulfill either new challenging ideas or application needs [1-8]. In particular, the NOMAD walking robot was constructed by undergraduate students for participation in a walking robots competition [1]. It consists of two triangular platforms, where each platform carries three legs located at the triangle's corners. Nomad walks by rotating around its legs. This design presents difficulties, however, such as instability on uneven terrains. The AMBLER walking robot is under development for the exploration of the planet Mars [2]. It uses six legs, three from each robot side. The robot will move by rotating the legs and follows a direction within an angle of 30 degrees. The robot's size is very large, with each leg having a height of seven meters. It has the ability to step over objects three feet high. This robot project, however, stopped due to the infeasibility of transferring a large and very heavy structure with today's space capabilities. Another walking robot is MRSR [3]. It was developed for the Mars space project and uses two platforms. The square platform holds four legs at its corners, and the triangular platform carries three legs at its own corners. The triangular platform surrounds the square one. It walks by moving triangular platform ahead and when it is stable the square platform follows by rolling on a common rail bar. It is a stable robot with the capability to walk on uneven terrain. A small walking robot with six legs was constructed by Brooks to study the integration of a complex robot machine within a large number of sensory inputs [4]. The robot uses six legs (three on each side) and is about 35 cm long. Each leg is rigid and is attached at a shoulder joint with two degree of rotation freedom, driven by two orthogonally mounted model airplane position controllable servo motors. Due to the small size of this robot it can be used as a tool for the study of microrobotics [9].

Since the walking robot research field is "open" with unsolved problems and new challenging ideas, a new hybrid (wheeled/legged) robot, called ODYSSEUS, is presented [10,11]. It uses a triangular platform on which three autonomous-extended wheels are attached at its corners, while three legs/arms are located at the middle of each triangle side. Note the first version (wheeled) of ODYSSEUS was constructed by accommodating the study and design of distributed sensory input data (sonar, vision) for the extraction and abstract modeling of the navigation space [10,12,13], and other important navigation issues.

In this paper the structural design and the first stage feasibility simulation of the leg/arm of ODYSSEUS are presented. A brief description of the main features of ODYSSEUS is given firstly. The design section includes the detailed description of the leg/arm parts (joints, motors, shoulder, elbow and hand). The functional section includes the operation of each part and the conditions under which these part function. The last section provides a simple simulation of the leg/arm global operation.

2. ODYSSEUS ROBOT

In this section the main structural and operational features of the autonomous mobile robot, called ODYSSEUS are presented briefly.

2.1 STRUCTURAL DESIGN

2.1.1 Triangular Base

The choice of the base configuration was determined by the robot's primary objective of being capable of climbing stairs. Additionally, it was desired that the robot to have accessibility to as large an area as possible. After a careful consideration it was concluded that the triangular base (Figure 1) would best meet our objectives. Unlike a circular base, the triangular base can reach a corner in a room.

Attached to the base are the legs, arms, power supply, navigation system, and control units. Underneath the base, in the center, a battery is attached. The battery is the power supply of the robot. At the robot's base corners, autonomous, programmable legs/wheels are connected to a rail system. Three legs/arms will also be attached appropriately to the middle of the base's sides, Figure 2. On the top of the base are the navigation systems, the main processor and slave processors.

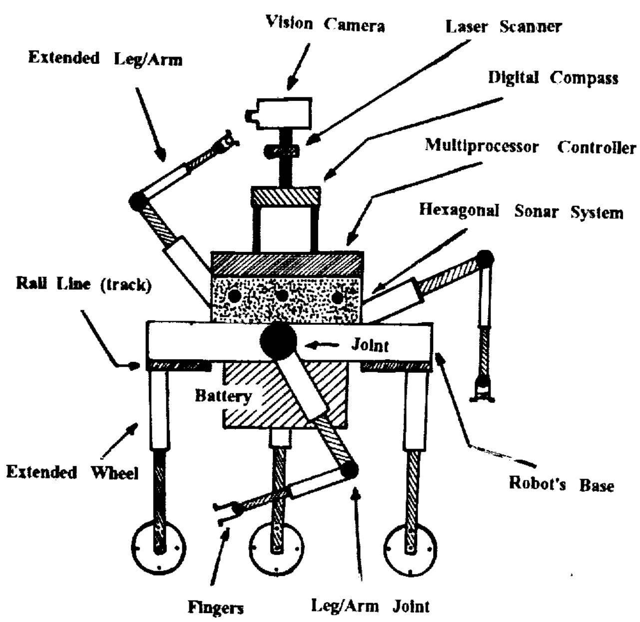

Figure 1: The ODYSSEUS Robot.

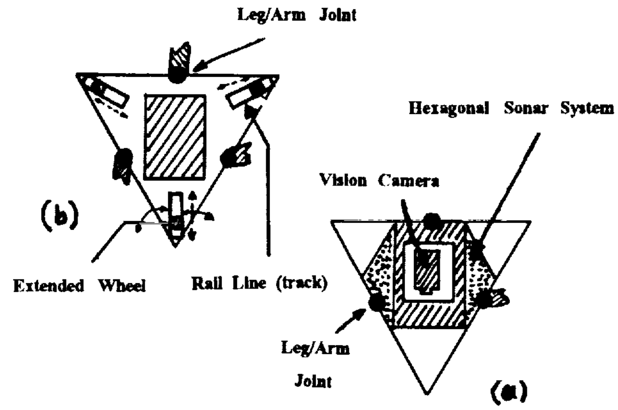

Figure 2: a) Robot's top view. b) Robot's bottom-up view

2.1.2 Navigation System

By using a digital compass the robot has the ability to orient itself in an environment. The compass utilizes three magnetic sensors to produce a digital readout of the robot heading. A laser sensor is used to measure the distance from various objects. The distance from the objects is combined with the view from a camera to provide a three dimensional image of the space [14]. This image assists the robot in its planning strategy.

2.1.3 Extended Autonomous Leg/Wheel

The extended wheel consists of three main parts. The first part, called the basic-pipe, is attached underneath the robot's base to a rail-line. The rail-line starts from the corner of the base and ends at a distance $dr \geq ww + sw$, where "ww" represents the maximum diameter of the wheel and "sw" is a safety factor. Inside the basic-pipe is the second part, called the extended-pipe. This feature allows the leg/wheel to be extended or shortened. At the other end of the extended-pipe, the third part, a wheel, is attached. Four holes in the wheel are used in the calculation of distance traveled and velocity of the robot. The wheel also has the capability of rotating. Determination of rotation angle is calculated by the main processor.

2.1.4 Extended Autonomous Arm/Leg

A detailed description of the leg/arm is provided in this report. It has the capability of grabbing and moving an object. Additionally it also has the capability of assisting the legs when the robot is in the stair climbing routine [11].

2.1.5 Distributed Multi-microprocessor System

Since each robot part has its own associated microprocessor, a multi-microprocessor distribution system is formed. Each microprocessor (in particular a Motorola 68CH11) controls and processes information related to that robot part. A central master microprocessor is used to establish communication with all the other microprocessors. The master microprocessor will synchronize and optimize the operation of the distributed microprocessor system.

Specifically, the main processor will receive processed information from the associated microprocessors, combine the information, and make the appropriate decisions for the next robot action (movements, selection, rotation, synchronization of the wheels, etc.). The master processor shares common memories with each of the associated processors.

3. DESIGN OF THE EXTENDED LEG/ARM

The design specifications for the extended leg/arm are explained in this section.

3.1 Brief Overview

A design of the entire arm is shown in Figure 3. It basically contains six motors: two dual purpose motors (labeled motor one and motor two), three elbow motors, one at each joint, and one motor for the hand. Clearly the elbow motor at the base is more powerful than the motor at the hand. This design also includes two extension units that are used during stair climbing programs. The bearing lock system provide motors 1 and 2 the additional capabilities of extending and twisting the arm.

3.2 Detailed Design of the Extended Leg/Arm

A primary concern in the design of the arm was how to avoid the "Popeye syndrome". If one can recall Popeye's forearms were much larger than his upper arm. In this deign we wanted to minimize the weight at the end of the arm to limit excessive stress on the components. However, the arm must still be able to support at least a third of the robot body weight.

3.2.1. Joint Design and Operation

The elbow joint, shown in Figure 4, consists of a motor inside of a shell. The shell has two parts; an inner shell which is mounted to the motor and an outer shell which is free to rotate about the center line of the motor. On the outside of the elbow motor are two plate mounts which can be used for additional sensory components in future design revisions. The outer shell is attached to one of these plates and the inner shell is attached to the other. When the motor rotates, the rotating gears (which are fixed in the motor) rotate, one in the opposite direction with respect to the other. Both of these gears are connected to a third cylindrical gear called the shell gear. The motor's rotation causes the plate mounts to move in opposite

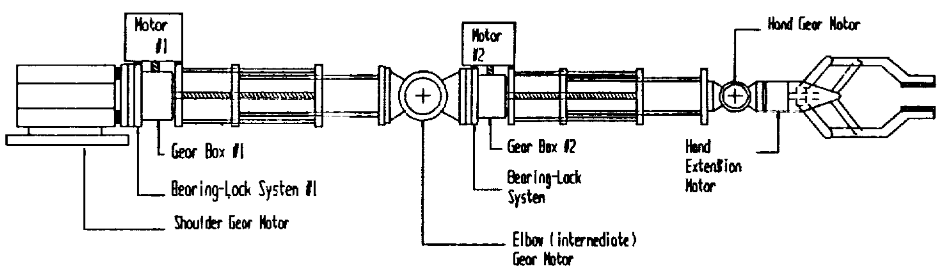

Figure 3: The Leg/Arm design

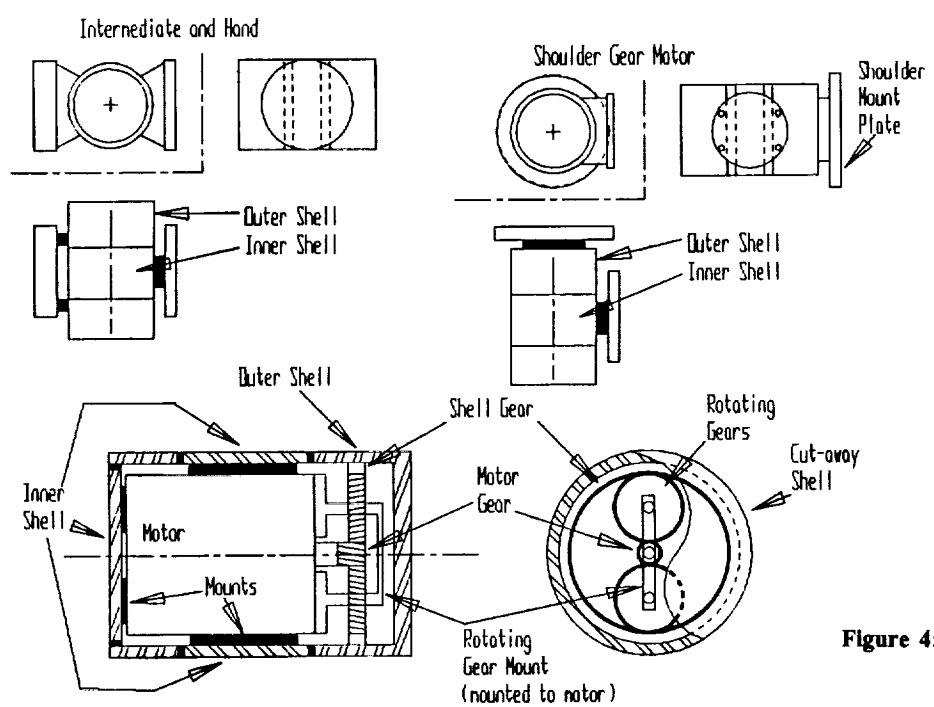

Figure 4: The gear motor designs

rotational directions. A primary concern of this system is the torque developed. This will depend on the motors used and on the gear ratio of the motor gear to the cylindrical shell gear. We will use this type of system for each elbow location (i.e. shoulder, intermediate, and hand joints). Obviously the hand will have the smaller and lighter system compared to the shoulder.

3.2.2. Shaft Design and Operation

This section contains an explanation of the extension units, the bearing lock systems, and motors one and two. The extension units consist of four plates, six support rods and one large threaded shaft. This unit is shown in Figures 5 and 6. Plates 1 and 3 are secured to each other via support rods. The same applies to plates 2 and 4.

The concept of this design is very simple. The threaded shaft rotates while plates 2 (which is also threaded) and 4 ride on this shaft. They extend or contract depending upon the rotation of the threaded shaft. Assuming that the screw will have a right hand thread, this system will extend when the shaft is rotating counter clockwise and will contract when the shaft is rotating clockwise.

Plate 1 is a mount plate that will be mounted on the gear box. The mount plate has three mount holes and one large shaft hole that should be larger than the threaded shaft. Plate four has the same purpose as plate 1. Plates 2 and 3 have the dual role of supplying support and being able to move. It is anticipated that all plates and shafts will be constructed from 6061 Aluminum.

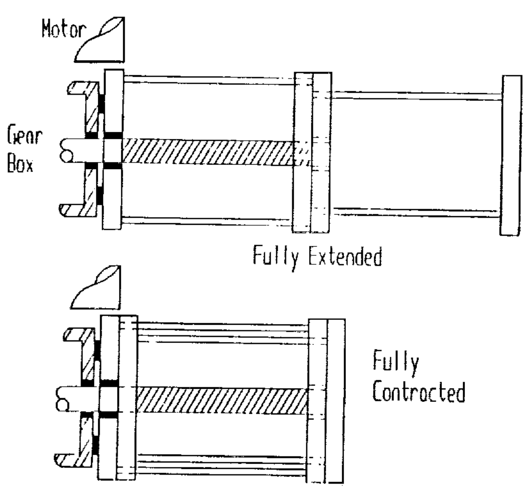

Figure 5: The extension unit

By using the isosceles plate and rod design instead of the cylindrical shaft inside a shaft design we minimized the weight of the unit. Our design should supply ample support in all directions. Three support rods, instead of two, are used to assure support when twisting torque is applied to the extension unit. However, we sacrifice speed when we use the screw style extension unit. The reason behind the loss of speed is the steep screw pitch that is required to support the weight.

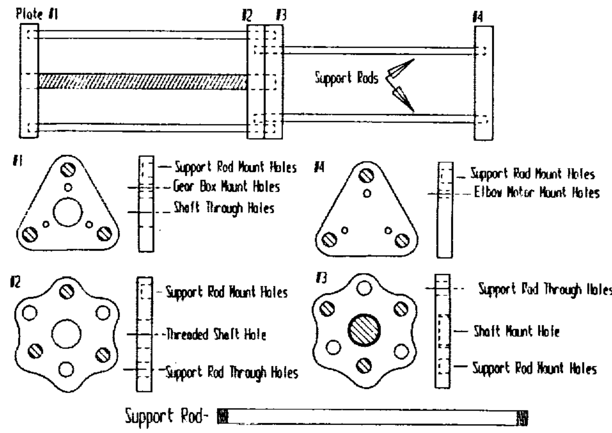

Figure 6: The extension unit detail design

The bearing lock system is probably the most complex component of the arm. It can be observed in Figure 7. Its purpose is to allow motors one and two to operate to two degrees of motion. One, an extension motion explained earlier in this section, and the second a twisting motion explained later. Using one motor for two purposes simply eliminates the need for another motor and reduces the overall weight of the arm.

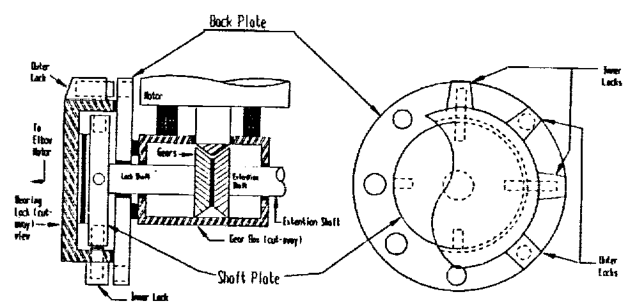

Figure 7: Bearing lock system

The bearing lock system consists of a gearbox which contains one shaft that goes to the extension unit and another very short shaft that becomes part of the lock system. The lock system consists of the two mount plates, six shaft locks, three inner locks, and three outer locks.

The bearing lock that is shown as a cut away will be mounted to the elbow motors at both the base and the intermediate positions. Locking the outer locks will secure the back plate and therefore the motor, gear box, and the extension unit to the elbow motors. When this is done, the inner lock should remain unlocked. This allows the motor to be used for extension purposes. Locking the inner lock and unlocking the outer locks will cause the small lock shaft to be secured to the elbow motors. At this time, when power is supplied to the motor, the motor gear box and extension shaft rotate around the fixed lock shaft. This supplies a twist to the components of the arm that are beyond the bearing lock system. It should be noted that this system does not give freedom of either the extension operation or the twisting operation. The extension units will be in motion at all times. However, this should not hinder the arm's performance significantly since the arm will extend very little with any twist.

In addition the bearing lock system can also be used for locking the extension unit. It is required that the extension unit will be locked without twisting in order to support a large amount of weight. This is accomplished by simply locking both locks.

Several of the bearing lock faults should be noted. Besides the difficulty in manufacturing the system, a performance flaw exists. Each lock needs to locate a hole in order to serve its purpose. Alignment of these locks may become very difficult. Especially if the extension unit is extended all the way and the lock's cannot be aligned with the hole. In this case the extension unit would have to be contracted in order to align the holes. This difficulty can easily be corrected by having a alignment solution program in the arm's microprocessor.

Another problem is with the locks. The ones initially chosen were magnetic locks. However, their locking power is in question. Also, when supporting a large portion of the robot weight, unlocking may not be feasible. In future design revisions a gear lock may be more suitable in alleviating these two problems.

The final component of the arm is the hand. It can be seen in Figure 8. Here again, simplicity is evident. When the driver bolt moves on the threaded shaft, the slotted rods ride on the fixed pins and force the fingers open or closed.

The major problem with the hand is structurally it is the weakest part of the arm yet is still needs to support a large amount of weight. Therefore, a different material (i.e. stainless steel) will be used for the hand.

Grabbing strength of the hand depends on the torque of the motor, the pitch of the screw threads, and grabbing method design. Since the motor of the hand will be the smallest one on the arm, it will not have the same strength as the other motors. A steep thread pitch is needed to assure grabbing strength.

4. FUNCTIONAL DESCRIPTION OF THE EXTENDED LEG/ARM

This section provides a macroscopic view of the arm design as it applies to the two major functions of the arm; grabbing and assisting the robot in climbing stairs.

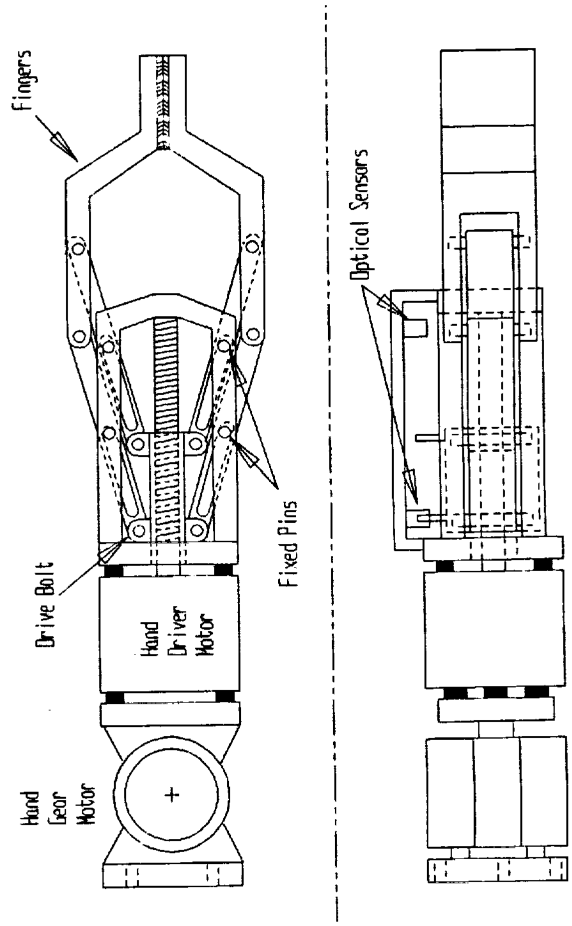

Figure 8: The hand

4.1 Extended Arm/Leg Functional Parameters

It is required, during stair climbing, that the arm design be capable of lifting the Odysseus robot upward approximately one foot. Since there will be three arms on the robot, two of these will be used at any time for the lifting operation. The Odysseus robot is expected to weigh 150 pounds in the worst case. During the lifting operation about 1/3 of the robots weight will be supported by the hind leg. This requires the use of motors one and two during this movement.

During the time that the arm is used to simply grab and lift objects, all components of the arm are utilized during this simple operation. Several limitations exist during the arm grabbing operation. The designed arm can contract to 35 inches and extend to 47 inches when straight. It can grab as wide as your average soda can. Since the shoulder only has one degree of freedom, this limits its grabbing reach. From any one side of the base of the robot the arm has the capability of reaching as far out as the lower portion of the arm allows. This translates into a 27.5 inch reach with a 360 degree swing around the shoulder axis, as seen in Figure 9.

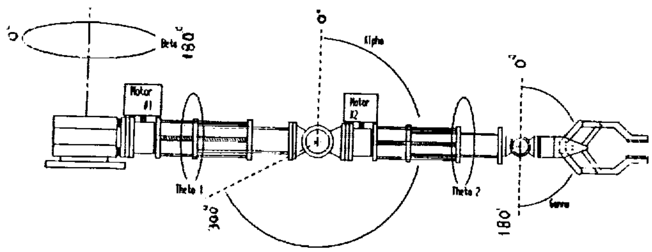

Figure 9: The rotational views of the leg/arm

4.2 Operational Conditions

The only operational procedure of the arm that we will discuss is the one needed for climbing stairs. It is required that an arm support 1/3 of the robot's weight during this procedure. To do so, the arm will be in a straight down position (see Figure 9). The shoulder angle ß must be in the 180° position (provided that the straight up vertical position is defined as the 0° position). The elbow joint must be in the 90° position as well as the hand joint. The hand must be fully closed and both extension units must be extended to the necessary length and locked at that length. Angles Θ_1 and Θ_2 are not important because they rotate axially and do not affect the length. Therefore, the inner locks of both bearing lock systems should be unlocked until the desired extension length is achieved. At that point both the inner and outer locks will be locked.

When the arm is functioning as an arm, and not a supporter, the angles, extensions, and lock positions will vary depending on the situation. We will not cover that situation in this paper.

4.3 Micro-controller Operation and Interface with Arm/Leg Components

In order to perform a micro-controller operation and interface with the arm/leg parts, a major concern is the maximum degree of rotation of the shoulder(ß), the elbow(α), the wrist(gamma), and the twisting of the upper and lower arm extension (Θ_1 and Θ_2). From the arm design shown in Figure 11, it can be seen that the maximum degrees of rotation are as follows:

$\beta = 360°$
$\alpha = 300°$
Gamma = 180°
$\Theta_1 = 360°$
$\Theta_2 = 360°$

This section contains the basic design of a position/rotation sensing system. The position/rotation information will be processed by the microprocessor to aid in the control of the arm. This system will use a series of simple optical sensors, magnetic sensors, and digital logic.

The arm is designed such that each joint and extension will contain a motor to control its degree of rotation. Note that 12 Volt motors will be used. Since a high supply of amperage is required a H-bridge, consisting of four power transistors, is used to supply power and control the motors.

Two bits are use to control the rotation of the motor. A digital 10 combination represents forward rotation and a 01 allows backward rotation. Using 00 halts the motor. To prevent the power transistors from burning out 11 should never be used.

Position sensing logic that is needed to control the twisting action is defined by the lock configurations of the bearing lock system. These locks will have a digital readings of (1) locked and (0) for unlocked. It was previously stated that for the twisting motion to occur, the inner lock must be locked and the outer lock must be unlocked. The slave processor must register this for the motion to occur. Another input that is needed for position sensing of the twist is the motor's direction. If the motor rotates in a forward direction, the arm will twist clockwise and vice versa if it indicates a backward motion. The degree of twist can be measured by the number of rotations of the motor shaft as detected by a rotational counter that is mounted on the motor shaft. This counter has the ability to detect fractions of turns. The angle can be determined by the gear ratio of the motor gear to the lock shaft of the bearing lock system. For example, if the gear ratio of the motor gear to the lock shaft is n:m, than the angle of rotation (a) of n with respect to m is:

$$a = [360(n/m)]*[\#\text{ of revolutions of } n] \quad (1)$$

The upper and lower extensions must also contain length controllers. The motor's rotational counter can be used for this. It was stated previously in section three that the extension units will always be functioning whenever the motor is turning. For every rotation of the motor shaft, the extension shaft rotates a fraction of a revolution dependent on the gear ratio. For every rotational motion of the extension shaft, the extension unit extends or contracts some distance depending on the thread pitch. Therefore if the gear ratio, the motor's rotational direction, and thread pitch are known, determination of the extension unit's position is calculated by:

$$\text{Ext. unit dist.} = \#\begin{bmatrix}\text{of turns of}\\ \text{motor gear}\end{bmatrix}\times\begin{bmatrix}\text{gear}\\ \text{ratio}\end{bmatrix}\times\begin{bmatrix}\text{thread}\\ \text{pitch}\end{bmatrix} \quad (2)$$

Equation 2 gives the distance traveled by the extension unit for a certain number of rotations of the motor shaft. However, nothing is said about the original position of the unit. By using the microprocessor logic this problem can be resolved. By calibrating the logic to use the fully contracted shaft as the relative starting point, then all other positions can be calculated by using the equation above.

Position control of the hand is determined by an optical sensor. One optical sensor placed at both extremities of the drive is sufficient. To trigger the sensors the drive nut must have a trigger lip. When the drive nut is against the motor, the hand is closed and a (01) will be sent to the slave processor. When the drive nut is all the way forward, the hand is completely open and a (10) is sent to the slave processor. Any positions between the two extremes will register a (11).

5. FEASIBILITY SIMULATION

Mechanical feasibility was tested in simulation to anticipate possible difficulties in construction. Starting from a downward vertical (standing) home position, the arm is programmed to transfer weight to the wheels, maneuver into positions near an intended object, open and close the hand, and return to home. The simulation plots arm movement in the fourth quadrant of the x and y axes, where point A represents the shoulder, B the first extension unit, C the elbow, D the second extension unit, E the wrist, and F and G the fingertips.

The open_hand and close_hand operations assume a line running between points D and E as the center about which the grasp angle ϕ is measured. The law of cosines is employed to find the orientation of the DE vector with respect to the origin, θ, as calculated in Equation 3 and shown in Figure 10:

$$\theta = acos((c^2-a^2-b^2)/2ab) \ . \qquad (3)$$

Defining the distance from E to F or G as L1, the new F and G coordinates for close_hand are then found as:

$$F_x = G_x = L_1 \cos(\theta) + E_x \ , \qquad (4)$$

and

$$F_y = G_y = L_1 \sin(\theta) + E_y \ , \qquad (5)$$

and for open_hand:

$$\begin{matrix} F_x \\ G_x \end{matrix} \ SCALESYM200\} = L_1 \cos\ (\ \theta \pm \phi\ ) + E_x \qquad (6)$$

and

$$\begin{matrix} F_y \\ G_y \end{matrix} \ SCALESYM200\} = L_1 \sin\ (\ \theta \pm \phi\ ) + E_y \qquad (7)$$

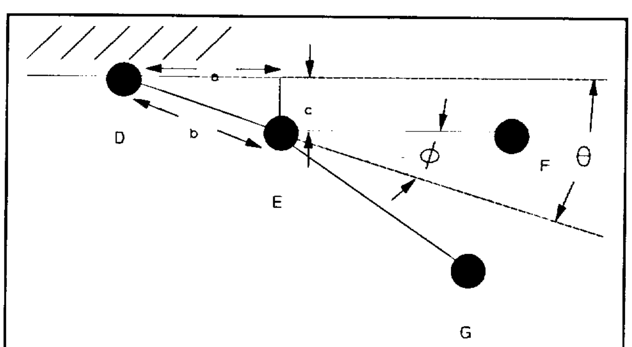

Figure 10: Open_hand and close_hand angles.

Rotations about point A, executed as subroutines swing_left and swing_right, simply rotate all other points about A as origin, as illustrated in Figure 11. Subroutines swing_up and swing_down similarly rotate all points distal to point C as origin. The simulation will redraw the arm when angles rotate or extensions along the AB and DE vectors are user-specified. Safety checks are added to ensure that workspace and robot geometry constraints are not violated, but forces, weights, and frictions are not yet taken into consideration. Coordinates of the sample simulation shown in Figures 12 through 15 were based upon the maximum possible extension of the arm in inches.

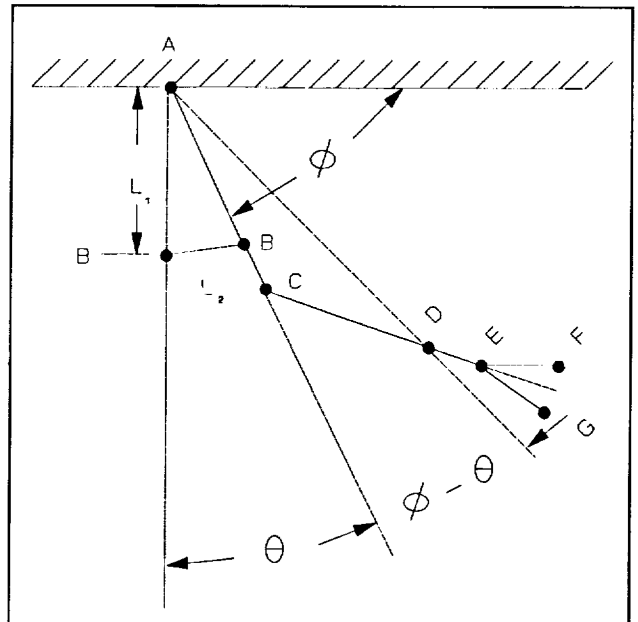

Figure 11: Swing_left and swing_right angles and lengths.

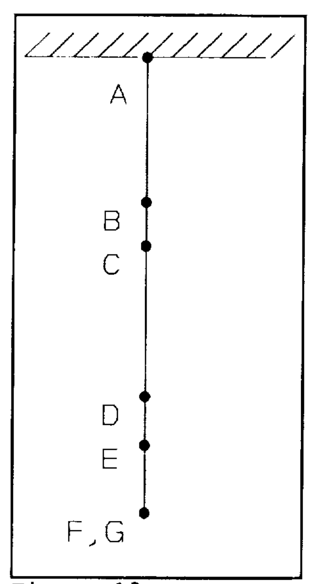

Figure 12: Home Position.

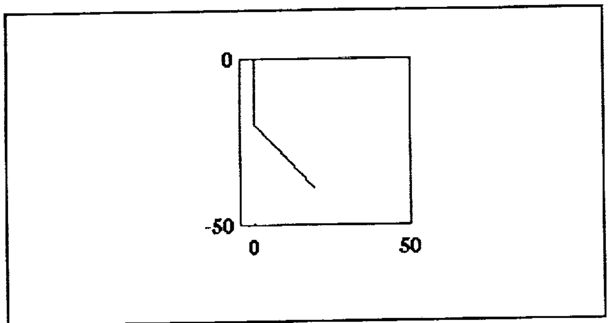

Figure 13: Swing_left of 45 degrees.

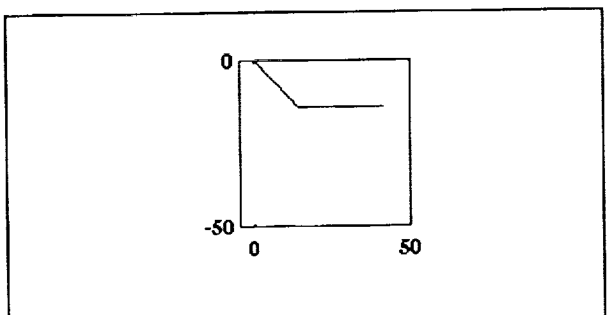

Figure 14: Then a swing_up of 45 degrees.

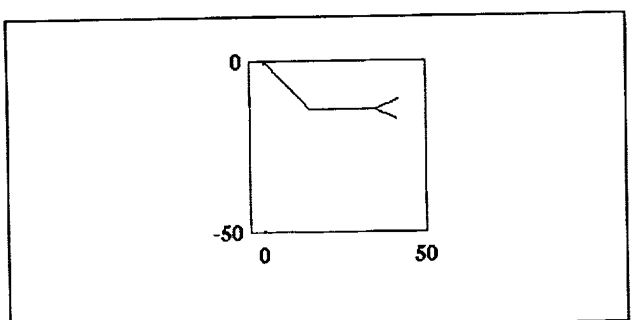

Figure 15: And an open_hand of 45 degrees.

6. CONCLUSIONS

In this paper the structural design and the functional modes of an extended leg/arm used by an autonomous legged/wheeled robot (ODYSSEUS) have been presented. The leg/arm part of the robot plays a very important role by supporting the robot to step over obstacles and climb stairs. The construction of the leg/arm is in progress at the AAAI research lab. The authors wish to thank all the undergraduate students for their work on the ODYSSEUS robot.

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