NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

THE IMPLEMENTATION AND TESTING OF A ROBOTIC ARM ON AN AUTONOMOUS VEHICLE

by

Hyun Il Jun

December 2007

Thesis Advisor:	Richard Harkins
Second Reader:	Peter Crooker

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2007	**3. REPORT TYPE AND DATES COVERED** Master's Degree

4. TITLE AND SUBTITLE: The Implementation and Testing of a Robotic Arm on an Autonomous Vehicle	**5. FUNDING NUMBERS**
6. AUTHOR(S) Hyun Il Jun	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

An articulated arm with three degrees of freedom is implemented and tested on an autonomous robot. Kinematic equations of motion for the arm are modeled and tested. A communication architecture is successfully implemented for wireless manual control of the arm. Visual and thermal cues are realized with an onboard camera and a collocated thermal sensor. Future work suggests investigations for full autonomous arm control without manual operator intervention based on sensor cues and visual scene correlation.

14. SUBJECT TERMS Robotic Arm, Autonomous, Kinematics	**15. NUMBER OF PAGES** 51
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

THE IMPLEMENTATION AND TESTING OF A ROBOTIC ARM ON AN AUTONOMOUS VEHICLE

Hyun Il Jun
Lieutenant, Republic Of Korea Navy
B.S. Electrical Engineering, R.O.K Naval Academy, 1997

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN APPLIED PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
December 2007

Author: Hyun Il Jun

Approved by: Richard Harkins
Thesis advisor

Peter Crooker
Second Reader

James Luscombe
Chairman, Department of Physics

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

An articulated arm with three degrees of freedom is implemented and tested on an autonomous robot. Kinematic equations of motion for the arm are modeled and tested. A communication architecture is successfully implemented for wireless manual control of the arm. Visual and thermal cues are realized with an onboard camera and a collocated thermal sensor. Future work suggests investigations for full autonomous arm control without manual operator intervention based on sensor cues and visual scene correlation.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank LT John Frederick Herkamp for all of his previous work with BigFoot. I would also like to thank you to LTCD Kirk Volland for his assistance in the implementation and testing of a robotic arm. I thank my advisor, Professor Richard Harkins, for allowing me to do this project and for his support. Finally, I want to thank my wife Hyun Jung Lee for her continued love and support.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Robots used in military operations and applications continue to be a rich environment for research. Recently, robots have proven their worth in battlefield by saving lives and providing critical support capabilities for missions such as Improvised Explosive Device (IED) detection and defeat, reconnaissance, Explosive Ordnance Disposal (EOD), Force Protection (FP), countermining and Unexploded Ordnance (UXO) clearance [Ref. 1]. Consequently, the "Numbers of Unmanned Ground Vehicles (UGVs) procured and deployed by Department of Defense (DoD) have increased from less than a hundred in 2001 to a number of that will approach the 4,000 mark by the end of calendar year 2006" [1].

The increased role of robots in the battlefield has resulted in an analogous increase of the capability requirements for these robots. To accomplish this, the Joint Ground Robotics Enterprise (JGRE), which began life as the Joint Robotics Program (JRP) in 1989, was reorganized in 2006. "The JGRE mission is to advance Departmental ground robotics initiatives, focus ground robotics technologies on the warfighter capability needs, and assess/mature selected ground robotics technologies to meet identified capability gaps" [2]. Those technologies include robotic platforms with navigation technologies, communications, payloads, and control systems.

A. PREVIOUS NAVAL POSTGRADUATE SCHOOL (NPS) PROJECTS

The NPS Small Robot Technology (SMART) program develops prototype robotic platforms for military applications.

This project's development (Figure 1) started with a prototype in 2003, known as Bender, see Figure 2. Bender was not developed for a specific objective, but was intended to make a platform based on autonomous architecture. It had a box shape with a hardened track chassis and could move to designated destinations autonomously via waypoint navigation. It viewed obstacles through a web-cam and avoided collisions using ultrasound sensors during movement. All elements were controlled by a

microcontroller (a commercial BL2000 by Z-World) programmed by the Dynamic C language [3]. Dynamic C is a C based programming language with a development environment tailored to program a suite of microcontrollers developed by Z-World. It includes a fully functional programming library and well-developed documentation.

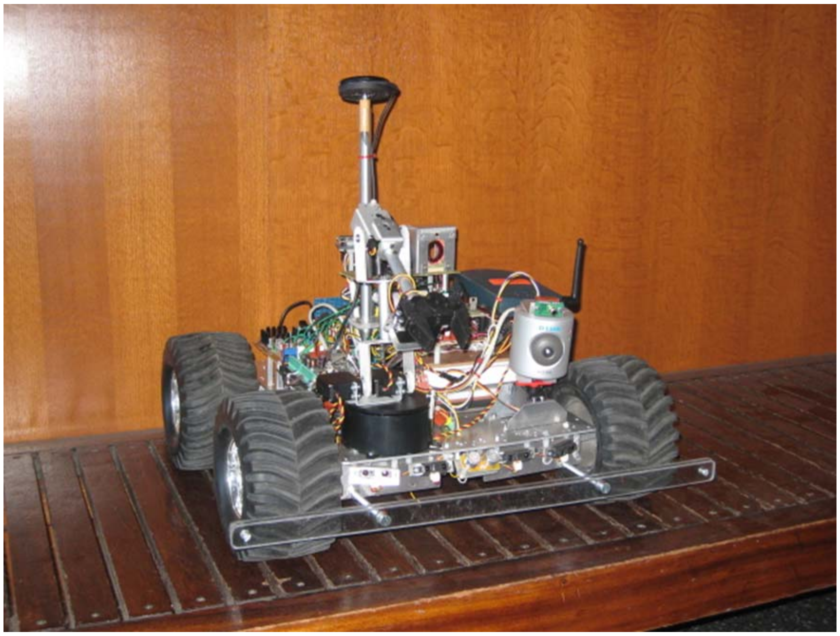

Figure 1. BigFoot.

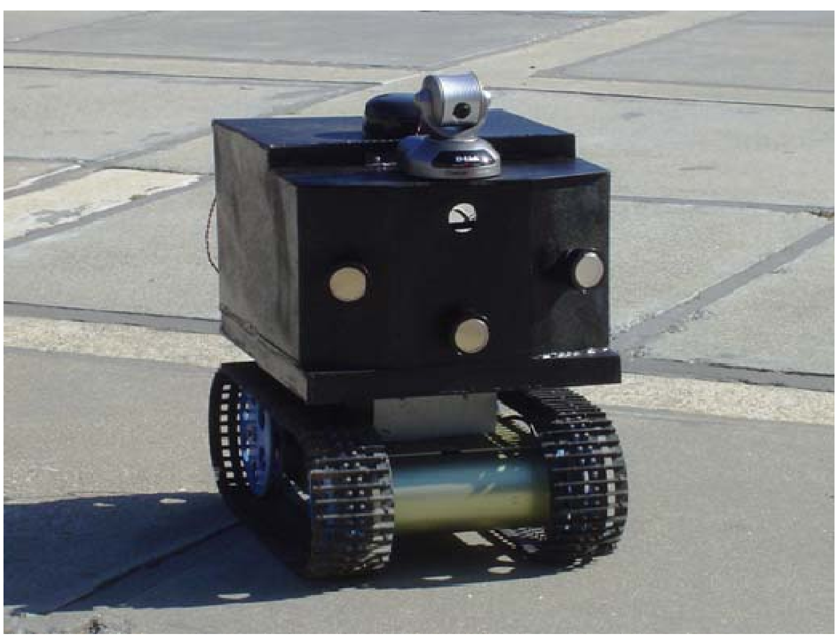

Figure 2. Bender (From [3]).

A second generation robot, known as Lopez, was prototyped for surf-zone operations. The mission included general reconnaissance and beachhead surveillance. While this prototype did not have full mobility, the robot began to take its final shape in Figure 3. Lopez was used to finalize the control interface, test components and increase the motor control of the robot [4].

Figure 3. Lopez (From [4]).

The third generation prototype, named Agbot, was a collaborative effort between the Naval Postgraduate School and Case Western Reserve University. "The robot was designed to work in soft soils encountered in agricultural beach head settings. Agbot has an aluminum chassis and features a much more powerful motor than the previous prototype" [4]. Figure 4 shows Agbot prepared for a test run. Both Lopez and Agbot were designed to run via a remote Java user application. These platforms both incorporate the same basic components (GPS, onboard computer, compass, and router) as BigFoot.

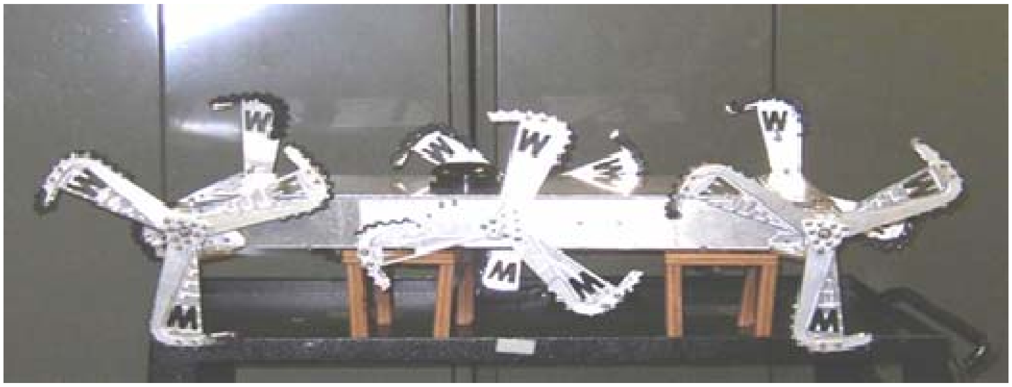

Figure 4. Agbot (From [4]).

The fourth generation of the SMART robot was the Autonomous Ground Vehicle (AGV), created by MAJ Ben Miller US Army. AGB was a wheeled platform and was equipped with acoustic and IR (infrared) detectors to detect motion. AGB had the capability to report images to remote monitoring stations via a web camera. The concept of operations for AGV was to assist in the interdiction of IED placement [3]. Figure 5 shows AGV on the ground. The AGV platform was too small and slow to perform Bigfoot's mission, but was the basis for BigFoot's development.

Figure 5. AGV (From [3]).

B. MILITARY INITIATIVES

An IED can be almost anything with any type of material and initiator. It is a "homemade" device that is designed to cause death or injury by using explosives alone or in combination with toxic chemicals, biological toxins, or radiological material [5]. Since October 2001, improvised explosive devices (IEDs, roadside bombs, and suicide car

bombs) have been responsible for many of the more than 3,000 combat deaths in Iraq and many of the more than 240 combat deaths in Afghanistan [6].

TALON is a robot equipped with a two-stage arm to relocate suspected IEDs or to place an explosive charge on previously located IEDs. TALON was used in military operations in Bosnia in 2000, was deployed to Afghanistan in early 2002 and has been in Iraq since the war started. The mission of TALON is to assist with improvised explosive device detection and removal. It was used in about 20,000 missions in Iraq and Afghanistan by the end of 2004 [7]. Talon weighs less than 45 kilograms. Figure 5 shows a TALON with the articulated arm.

Figure 6. TALON (From [7]).

Another robot, called the PackBot Figure 7, has also been used to clear bombs and explore suspected terrorist positions. PackBot is equipped with dual rotating flippers that allow the robot to negotiate stairs, maneuver over rocks and rubble, and navigate narrow, twisting passages. It is designed to handle a range of Improvised Explosive Devices (IEDs) and conventional ordnance disposal challenges [8]. PackBot Weighs less than 24 kilograms fully loaded.

Figure 7. PackBot (From [8]).

For Explosive Ordnance Disposal (EOD) missions, the arm is used to place shaped charges on previously identified IED’s.

II. THEORY

This chapter discusses robot autonomy and movement of the arm. It focuses on the kinematics related to the position of the arm.

A. ROBOT AUTONOMY

Autonomy refers to systems having the ability to operate in a real environment for long periods of time without external support. To date, fully autonomous robots have not yet been realized.

Autonomy requires the implementation of sensors and actuators to gather information from the environment and to act on that information to perform given missions.

Movement and path planning is a discipline that must be mastered to realize robot autonomy. The purpose is to convert mission objectives into a high level programming language and then program the robot to convert these objectives into low level movements for mission accomplishment via platform mobility and motion of a device like an arm, leg or wheel.

B. THEORY OF ARM MOVEMENT

A robot arm is a manipulator. The links of such a manipulator are connected by joints that allow rotational motion or translational displacement. The links of the manipulator can be considered to form a kinematic chain. The end of the kinematic chain of the manipulator is called the end effector. Figure 8 shows a model robotic arm identifying the kinematic chain and the end effector.

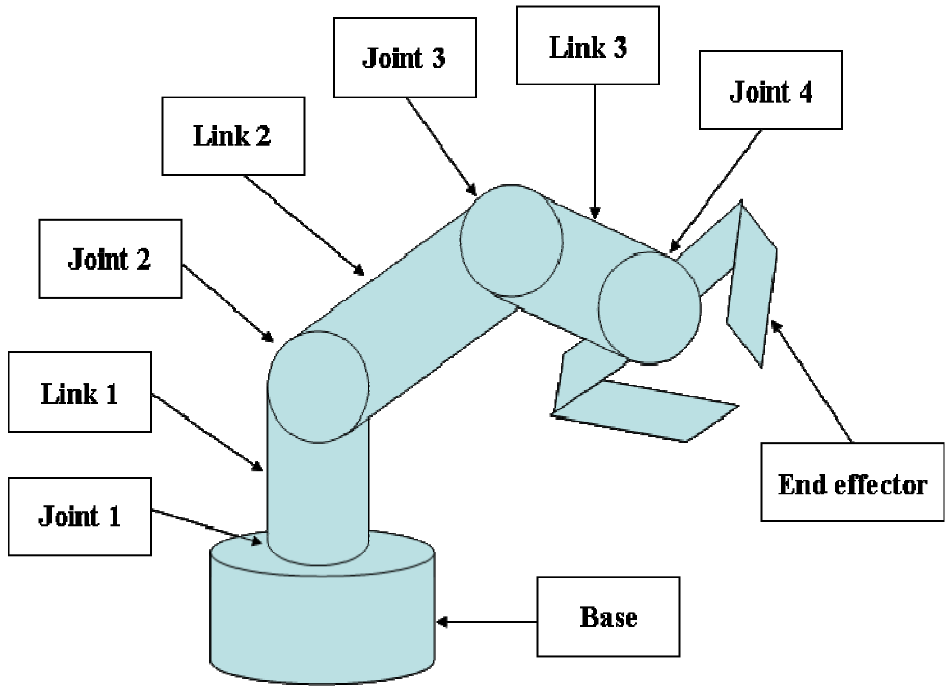

Figure 8. Model Robotic Arm

Degrees of freedom (DOF) are the set of independent rotations or displacements that specify the position and orientation of the body or the system. This concept is fundamental in understanding the mechanics and implementation of a robotic arm on an autonomous robot.

For an arm to perform specific tasks, the location of the end effector relative to the base is established first. This technique is the called the kinematic analysis problem. There are two types of kinematic analysis problems: (1) direct kinematics and (2) inverse kinematics. For direct kinematics, the joint variables are given and the problem is to find the location of the end effector. For inverse kinematics, the location of the end effector is given and the problem is to find the joint variables necessary to bring the end effector to the desired location [9].

1. Position and Orientation

The position of any point with respect any reference frame can be described by a 3×1 position vector. For example, the position of a point P can be expressed as ${}^{A}P$.

This means that the components of ${}^{A}P$ have numerical values that indicate distances in the frame of {A}. A point ${}^{A}P$ is represented as an ordered set of three numbers. Where the subscripts x, y and z are individual elements of a vector in a Cartesian coordinate system:

$$ {}^{A}P = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \qquad (2\text{-}1) $$

The orientation of a body, then, can be described with a coordinate system attached to the body relative to the earth or fixed reference frame. In Figure 8, coordinate system {B} has been attached to the body relative to {A} and allows us then to give the orientation of the body.

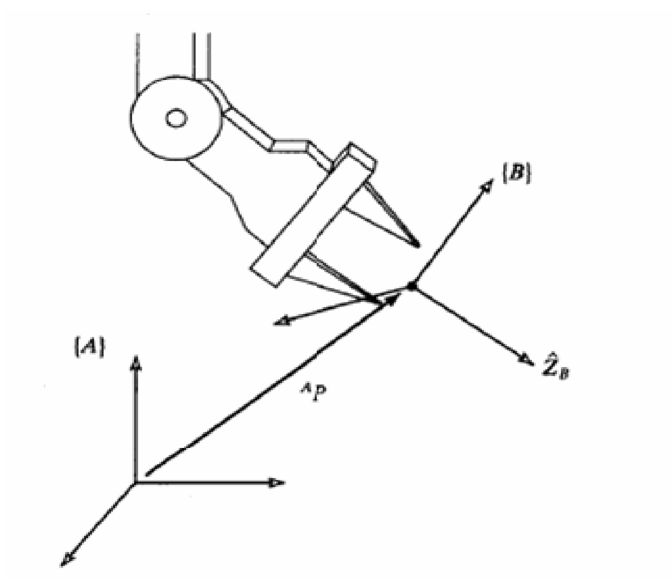

Figure 9. Locating an object in position and orientation (From [10]).

Thus, positions and orientations of bodies are described as an attached coordinate system. So we can describe the body attached coordinate system {B} as the unit vectors of its three principal axes in terms of the coordinate system {A}.

The unit vectors giving the principal directions of coordinate system {B} are denoted as $\hat{X}_B$, $\hat{Y}_B$, and $\hat{Z}_B$. In terms of coordinate system {A}, they are called ${}^{A}\hat{X}_B$,

${}^{A}\hat{Y}_B$, ${}^{A}\hat{Z}_B$. These three unit vectors can be described by the columns of a 3×3 matrix, in the order ${}^{A}\hat{X}_B$, ${}^{A}\hat{Y}_B$, ${}^{A}\hat{Z}_B$. We call the matrix ${}^{A}_{B}R$ the rotation matrix of coordinate system {B} with respect to {A}. The leading super and subscripts indicate the order of transformation:

$$ {}^{A}_{B}R = \left[{}^{A}\hat{X}_B \quad {}^{A}\hat{Y}_B \quad {}^{A}\hat{Z}_B \right] = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}. \tag{2-2} $$

2. Kinematics

Kinematics deals with the aspects of motion without regard to the forces and/or torque that cause it. The science of kinematics deals with the position, velocity, acceleration, and higher-order derivatives of the position variables with respect to time or other variables. Hence kinematics is concerned only with the geometrical and time properties of a motion. The joint variables of a robot manipulator are related to the position and orientation of the end effector by the constraints imposed by the joints [9].

a. Link Parameters

A manipulator may be thought of as a set of links connected in a chain by joints, see Figure 10. Joints form a connection between neighboring link pairs. In a manipulator, each link has four link parameters. (1) Link length, (2) link twist, (3) link offset, and (4) joint angle. Length and twist describe the link itself and offset and joint angle describe how neighbor links are connected to each other. Figure 10 illustrates the four link parameters

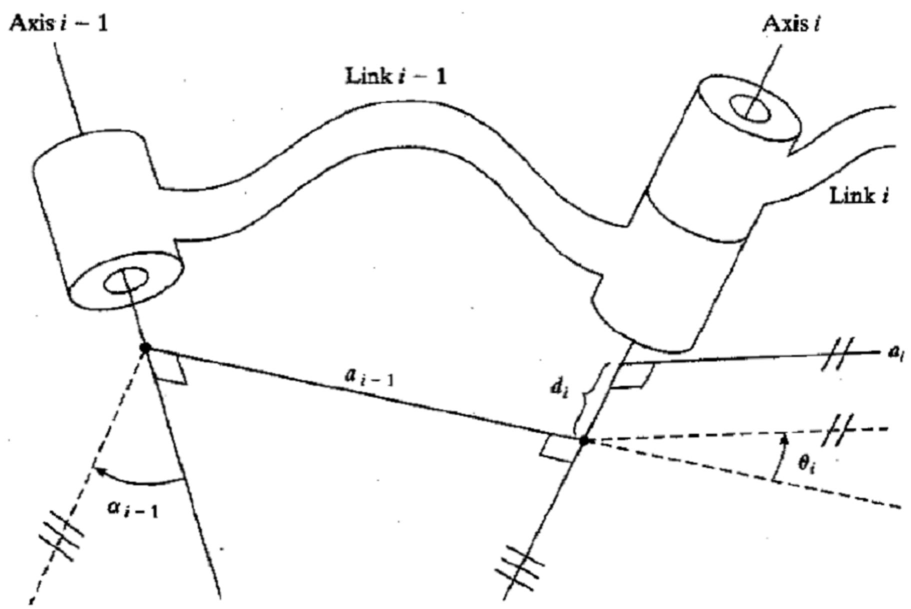

Figure 10. Link Parameters (From [10]).

The **Link length** is the length of a line that is mutually perpendicular to both joint axes. For example, the link length between joint axes i and $i-1$ is called a_{i-1}, as shown in figure 9.

The second parameter is **link twist**. Link twist is the a_{i-1} angle, measured from axis $i-1$ to axis i, using the right-hand rule. Link twist defines the relative location of the two axes.

The third parameter is **link offset**. Link offset is the distance measured along the axis between two neighbor links, from the point where a_{i-1} intersects axis i to the point where a_i intersects axis i. The link offset at joint axis i is called d_i.

The fourth parameter is the **joint angle** θ_i referring to the relative angle between one link and its neighbor. Figure 9 illustrates the link parameters of one link of a manipulator.

b. Convention for Affixing Frames to Links

To describe the location of each link relative to its neighboring links, a frame attached to each link is defined. See Figure 11 for the i and $i-1$ link frames in a kinematic chain. The link frames are numbered according to the link to which they are attached. That means frame $\{i\}$ is attached to link i. This convention is followed to locate frames on the links.

Now, the $\hat{Z}$ -axis of frame $\{i\}$, called $\hat{Z}_i$, is in the same direction with the joint axis i. The $\hat{X}$ -axis of frame $\{i\}$, called $\hat{X}_i$, is pointing towards the direction of a_i, the length from joint i to joint $i+1$. The direction of the $\hat{Y}$ -axis of frame $\{i\}$, called $\hat{Y}_i$, and is determined according to the right-hand rule.

The following definitions of link parameters are given below according to the frame convention as identified in [Ref 10].

- a_i is defined as the distance from $\hat{Z}_i$ to $\hat{Z}_{i+1}$ measured along $\hat{X}_i$.
- α_i is defined as the angle between $\hat{Z}_i$ and $\hat{Z}_{i+1}$ measured along $\hat{X}_i$.
- d_i is defined as the distance from $\hat{X}_{i-1}$ and $\hat{X}_i$ measured along $\hat{Z}_i$.
- θ_i is defined as the angle from $\hat{X}_{i-1}$ and $\hat{X}_i$ measured along $\hat{Z}_i$.

Figure 11 illustrates link parameters according to the frame convention.

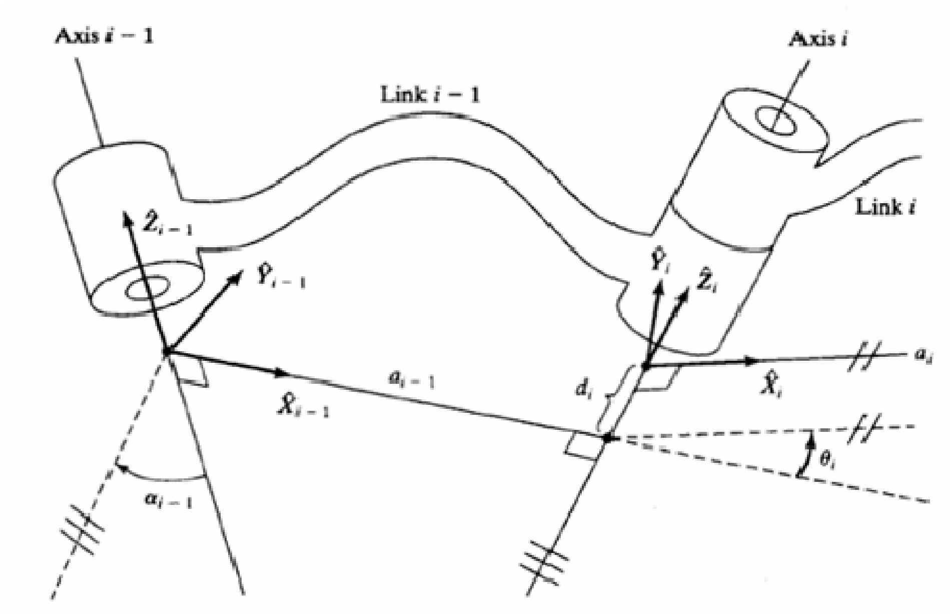

Figure 11. Link frames are attached so that frame{ i } is attached to link i (From [10]).

c. Mapping Involving general Frames

Before the mathematical model for arm position and orientation is explained, we need to first understand the mappings for translated and rotated frames as identified by traditional transformation matrices.

For pure translation, a point P in space, relative to the fixed frame {A}, is:

$$ {}^{A}P = {}^{B}P + {}^{A}P_{BORG} \tag{2-3} $$

Where ${}^{A}P$ is the vector that locates point P relative to frame {A}, ${}^{B}P$ is the vector that locates point P relative to frame {B}, and ${}^{A}P_{BORG}$ is the vector that locates the origin of frame {B} relative to frame {A}, see Figure 12.

In case of pure rotation, a point P in space, relative to the fixed frame {A}, is given as:

$$ {}^{A}P = {}^{A}_{B}R\,{}^{B}P \tag{2-4} $$

Where ${}^{A}_{B}R$ is the rotation matrix of the moving frame {B} with respect to the fixed frame {A}.

Figure 12 illustrates both translation and rotation. The mapping of a vector from one frame to another frame is described as follows:

$$ {}^{A}P = {}^{A}_{B}R\,{}^{B}P + {}^{A}P_{BORG} \tag{2-5}$$

Or

$$ {}^{A}P = {}^{A}_{B}T\,{}^{B}P \tag{2-6}$$

Where

$$ {}^{A}_{B}T = \begin{bmatrix} {}^{A}_{B}R & {}^{A}P_{BORG} \\ 000 & 1 \end{bmatrix} \tag{2-7}$$

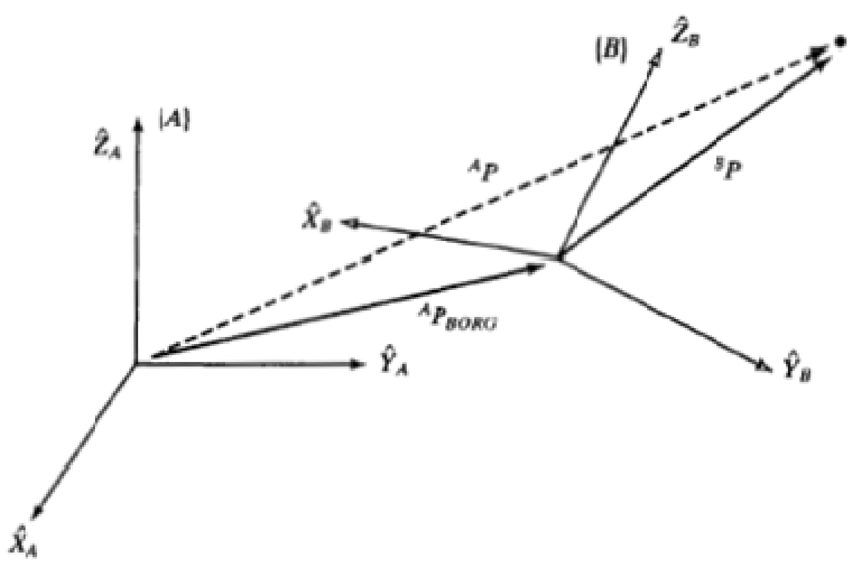

Figure 12. General Transformation of a vector (From [10]).

This 4 ×4 matrix (2-7) is called a homogeneous transformation, which can make the rotation and translation of the general transform into a single matrix form. We observe that transformation matrices can be used to specify a frame. For manipulator kinematics, the transformation matrix, relating two frames attached to neighboring links, is given by:

$$
{}^{i-1}_{i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i \cos\alpha_{i-1} & \cos\theta_i \cos\alpha_{i-1} & -\sin\alpha_{i-1} & -d_i \sin\alpha_{i-1} \\ \sin\theta_i \sin\alpha_{i-1} & \cos\theta_i \sin\alpha_{i-1} & \cos\alpha_{i-1} & d_i \cos\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2-8}
$$

To develop the kinematic equations, we define the link frames and the corresponding link parameters. From these, we can derive the individual link-transformation matrices. Then, by multiplying the link transformation matrices from ${}^{0}_{1}T$ to ${}^{N-1}_{N}T$, the single transformation matrix ${}^{0}_{N}T$ can be obtained as follows:

$$
{}^{0}_{N}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \cdots {}^{N-2}_{N-1}T\,{}^{N-1}_{N}T\,. \tag{2-9}
$$

C. PRIOR WORK

BigFoot was developed by LT John Frederick Herkamp as a logical follow-on to the prior work done on Bender. It employs two modes for navigation: autonomous and manual. The operator can choose one of two modes via a Java Graphic User Interface (GUI) on a laptop computer.

In autonomous mode, BigFoot navigates to way-point destinations autonomously and avoids obstacles, on the way, using ultrasonic and infrared (IR) rangers.

In the manual mode, the operator drives BigFoot directly to remote destinations via a wireless, stateless, UPD/IP network protocol.

The robot is equipped with a web camera and a thermal sensor to get environment sensor data of surrounding terrain and obstacles. The camera sends streaming video as well as pictures. The thermal sensor, mounted on the camera, shows correlated thermal information with the visual image.

BigFoot's arm is built as a proof of concept. So the majority of BigFoot's remaining work is in development of the arm.

THIS PAGE INTENTIONALLY LEFT BLANK

III. EXPERIMENTAL SETUP

Before explaining the arm installation, it is helpful to understand the communication architecture of the arm, the camera and the thermopile. These three sensors are necessary to accomplish the proposed mission of BigFoot as a concept of operations. In order to avoid communication interrupt, different communication paths for sensors are chosen and especially the arm is directly controlled by the operator. Figure 13 shows the block architecture diagram for the arm, camera and thermopile.

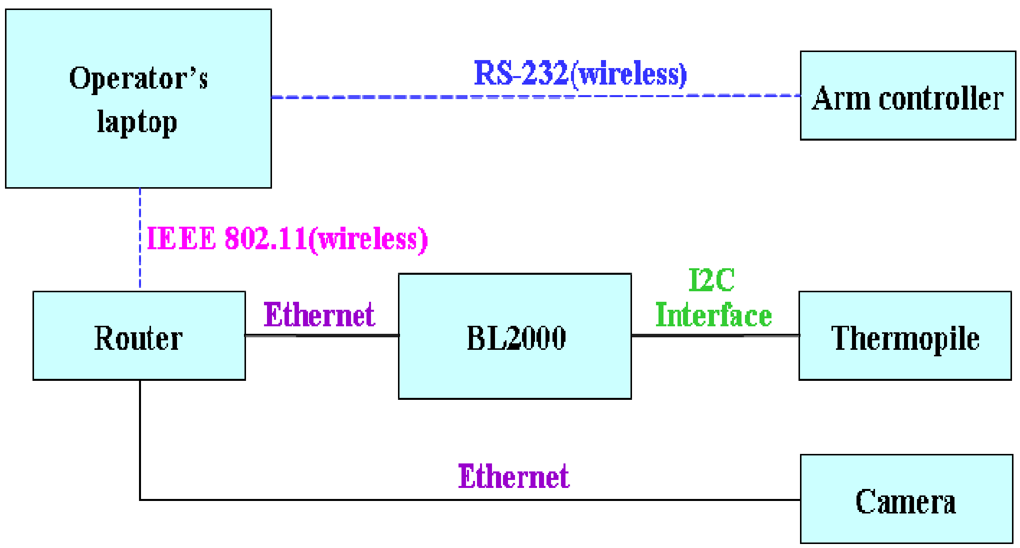

Figure 13. Block Diagram for the Arm, Camera and Thermopile.

A. ARM INSTALLATION

BigFoot's arm is a Lynxmotion servo erector set with 3 degrees of freedom [10]. The arm consists of a rotatable base, shoulder, elbow and a functional gripper which are controlled by the arm controller. Figure 14 shows BigFoot's arm.

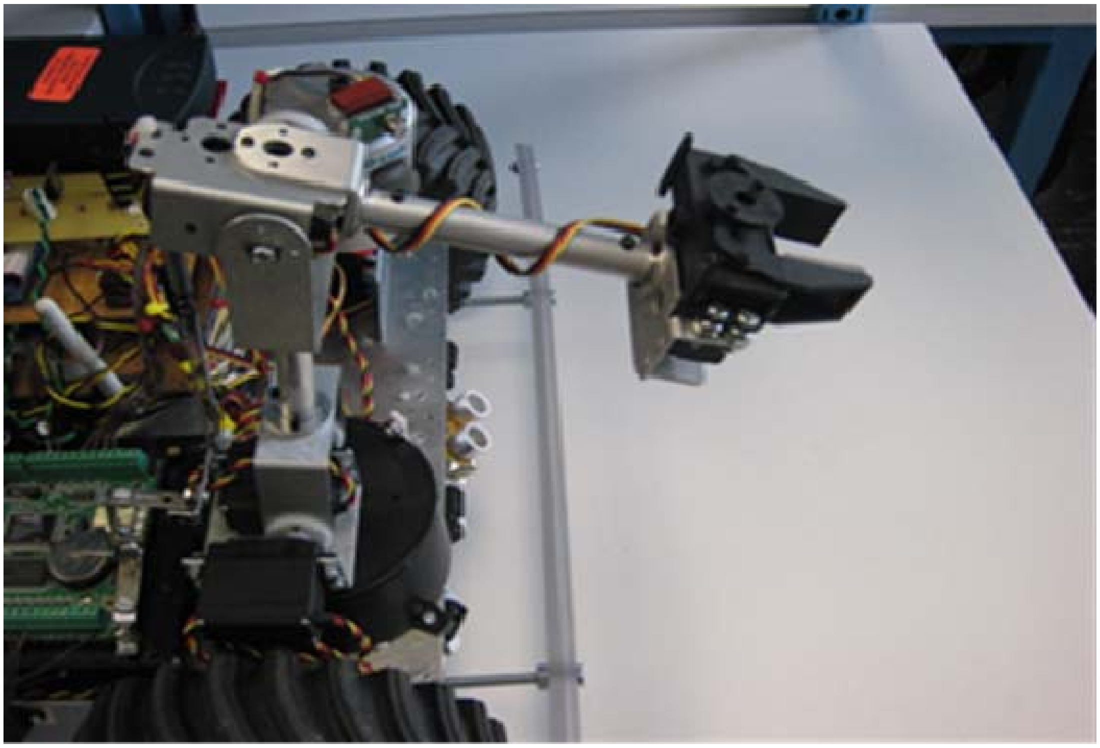

Figure 14. BigFoot’s Arm.

1. Mechanical Components

The base, mounted on a servo, can rotate without having to move and has five 6mm bearings to reduce the friction during rotation.

The shoulder, elbow, wrist and gripper are connected using aluminum tubings, tubing connectors and servo brackets.

2. Servos

BigFoot uses Hitec digital servos (HS-645, HS-475) to control the base, the shoulder, the elbow and the grip.

The HS-645 servo, used for the base, shoulder and elbow, provides up to 180° range of rotation and supports 133 oz.-in. torque. The HS-475 servo, used for gripper, provides a 180° range of rotation and supports 76 oz.-in. torque.

B. ELECTRICAL

1. Batteries

The robot uses two kinds of batteries. A 24 VDC 4 Ahr NIMH battery pack for the motors is arranged in a 2×10 array of C batteries weighing about 3lb 8oz. This battery pack is mounted on the underside of BigFoot's base. A 15VDC 11 Ahr Lithium Ion battery, mounted on the upside of BigFoot's base, is used for electronics.

2. Power Regulation and Power Distribution

The 15V battery for the electronic power is regulated to 12V via a standard 7812 voltage regulator, to 6V via a L4964 high current switching regulator and then from 12V to 5V via a standard 7805 regulator. To protect the 5V bus, a 330μF capacitor is connected between the 5V regulator and the 5V bus. The camera uses a separated 5V regulator not to overload the primary 5V regulator.

Figure 15 shows a diagram of the power regulation system and Figure 16 shows the power regulator.

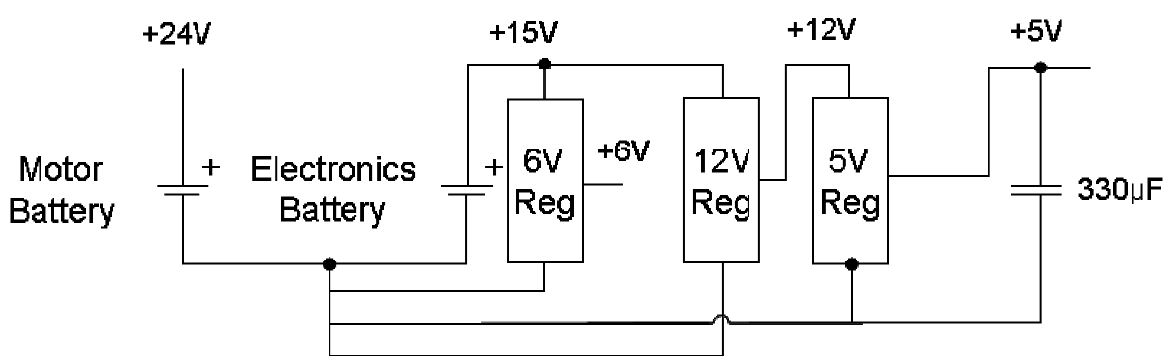

Figure 15. Power Regulation System Diagram.

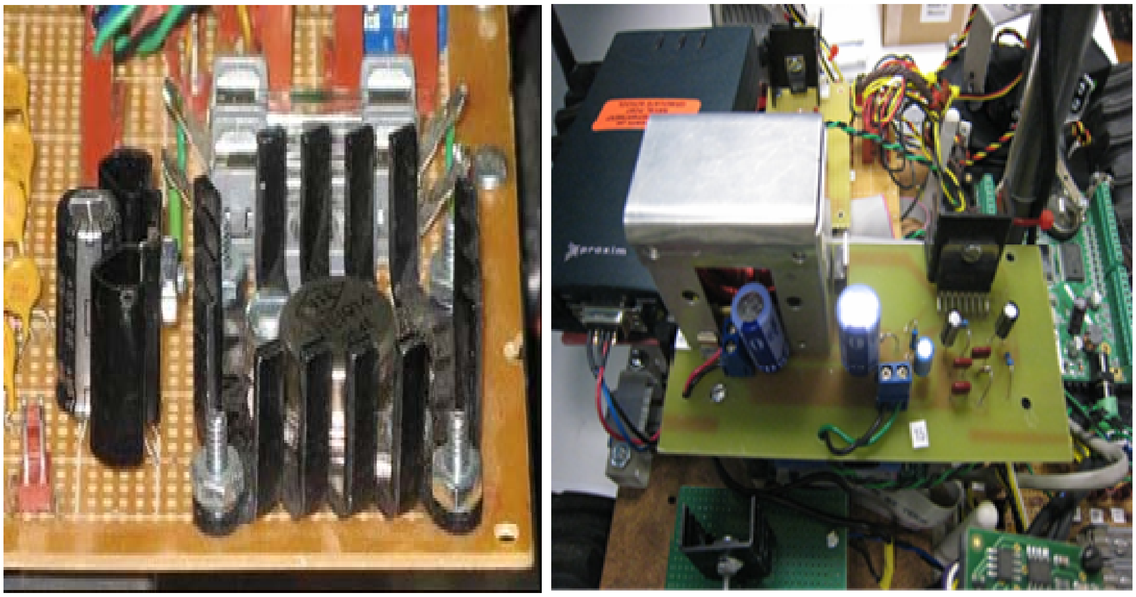

Figure 16. Power Regulator.

Figure 17 shows BigFoot's power distribution diagram. The power distribution of BigFoot is split into two parts. The first power distribution portion is for motor power. Motor battery power is sent through a double pole switch which has three positions with the center being the off position. When the switch is up, the motor battery power is directed through a pair of 25A fuses to the motor controller's input terminals. When the motor switch is down, the battery is connected to a pair of red and black terminals so a battery charger can be connected.

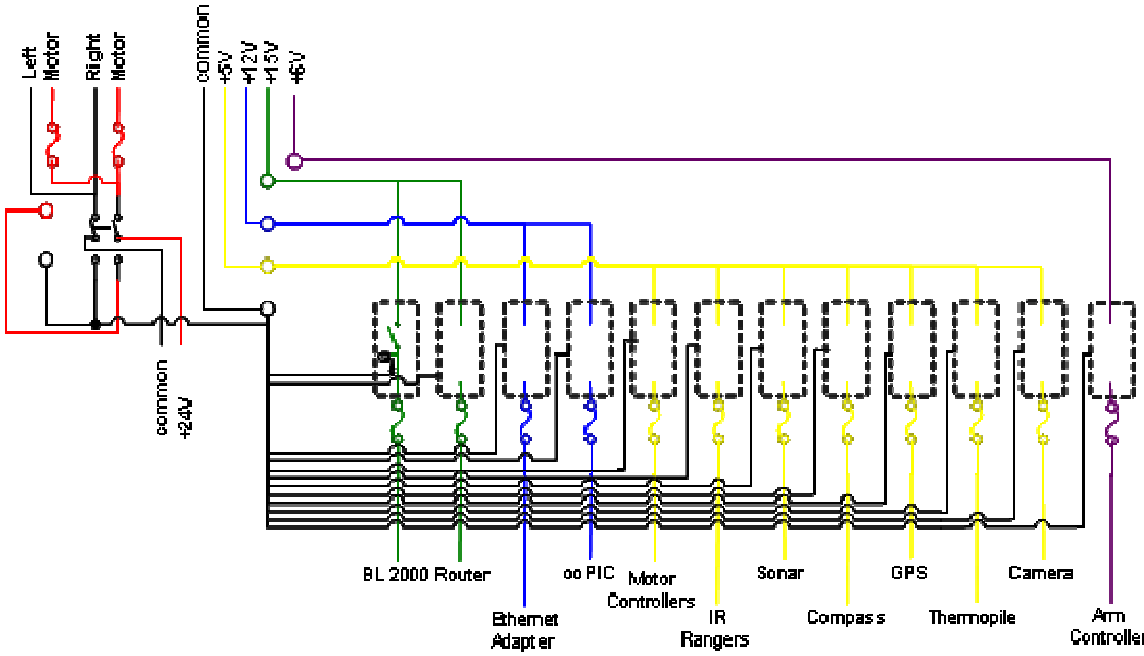

Figure 17. Power Distribution Diagram.

The second power distribution portion is for the electronics bus. The electronics battery power is distributed through 12V, 6V and 5V regulators to electronic loads via individual switches. The voltage testing terminals are connected to the switch panel (Figure 18). The various colors of terminals indicate different voltages. 24V power is red, 15V is green, 12V is blue, 6V is violet, 5V is yellow and common is black. When the switches are turned on, power is sent to the power panel (Figure 19) where the power is directed through fuses or poly-switches for 5 V, 6V, 15 V and 12 V loads. Light Emitting Diodes (LEDs), connected to the switches, emit light when power is distributed to loads. The poly-switches and fuses are connected by quick connectors for easy removal or testing.

Connections to the 5V bus include the BL2000, the compass and the sonar, and the I2C serial data port. The white wire of the I2C bus is used for serial data (SDA) and the purple wire is used for serial clock (SCL). The master device of I2C is the BL2000.

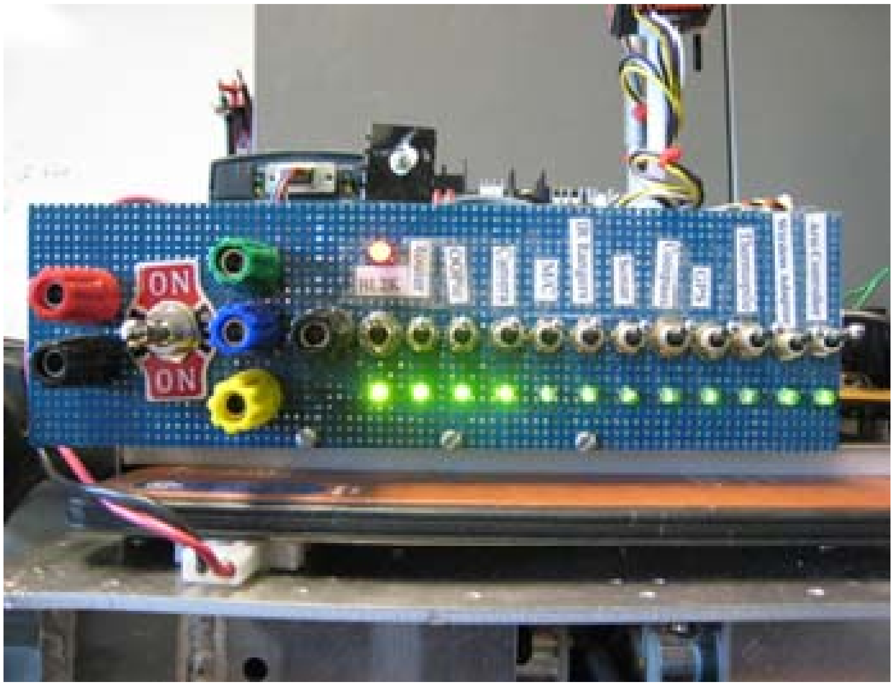

Figure 18. Switch Panel.

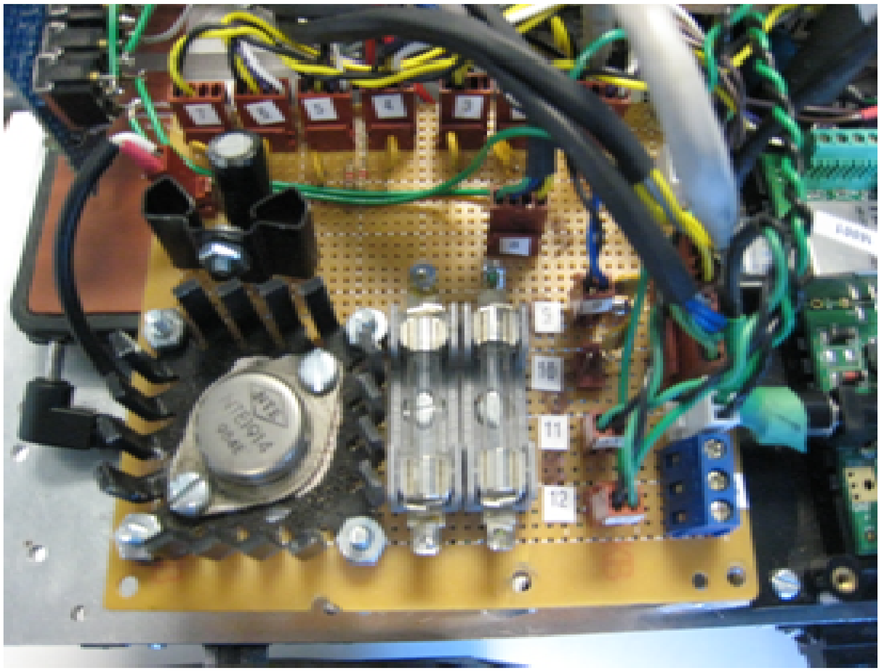

Figure 19. Power Panel.

C. MICROPROCESSOR

1. Arm Controller

The arm controller for BigFoot is the Lynxmotion SSC-32 servo controller. The servo controller is connected via a DB9F connection to the wireless adapter for RS-232 serial communications with the operator laptop. The controller can control up to 32 servos. Figure 20 shows the Lynxmotion SSC-32 servo controller.

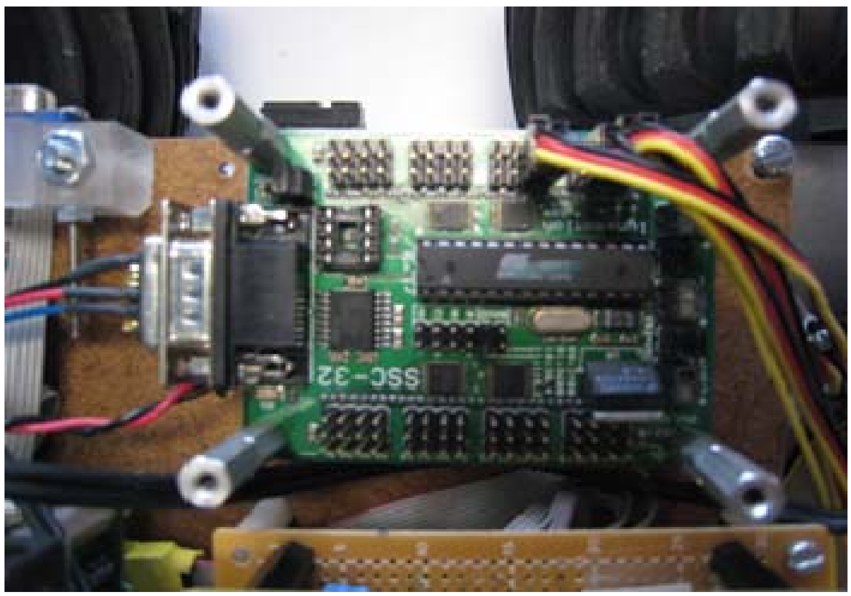

Figure 20. Lynxmotion SSC-32 servo controller.

The Servos are controlled with a 5VDC positive-going variable pulse width that repeats every 20mS and recognizes a range of 0.9mS to 2.1mS and provides a +/- 45 degree range of motion. The controller can provide the servo an extra range of about180° [11]. Figure 21 shows the normal and extended ranges of the servo.

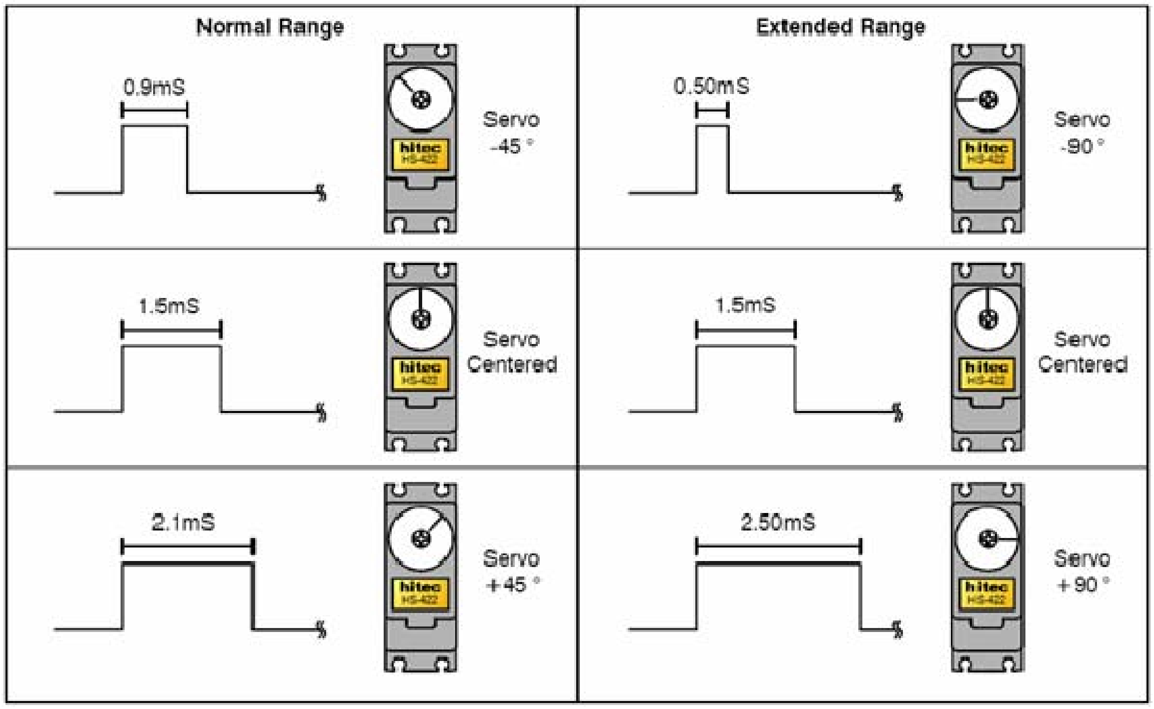

Figure 21. The normal and extended range of the servo (From [11]).

2. OOPic

The Object Oriented Programmable Interface Controller (OOPic) is used for a servo mounted directly below the camera via a Java GUI. BigFoot has an OOPic II+ utilizing B.2+ firmware version. The OOPic II+'s memory is arranged as 512 byte RAM plus a 256 byte EEPROM. The OOPic II expansion card, providing connections for servos, IR detectors, and LCD module, and other loads is connected via the interface board to OOPic II+. BL2000 is also connected via the interface board to OOPic II+. Figure 22 shows the connections among OOPic II+, OOPic II expansion card and interface board.

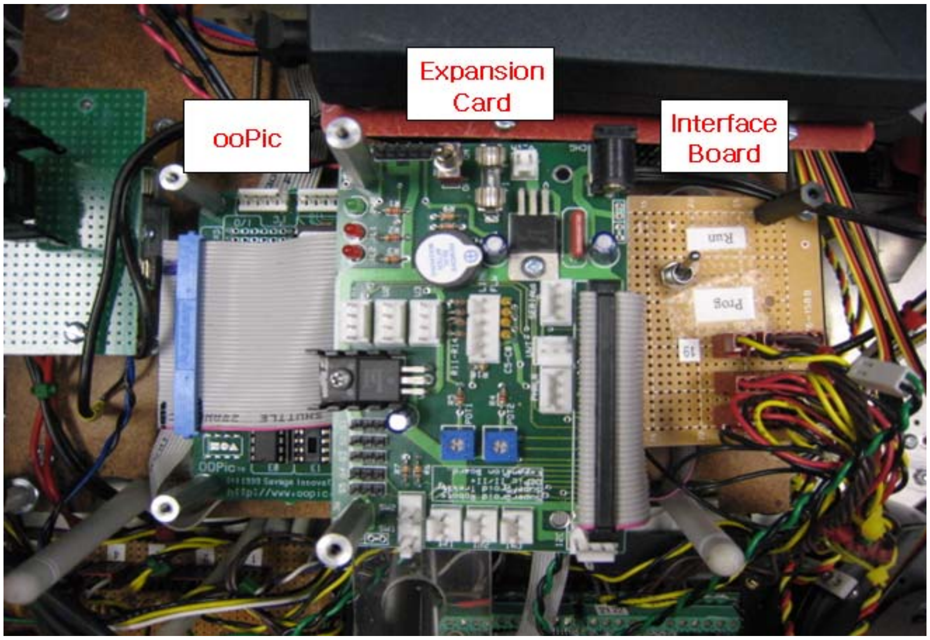

Figure 22. OOPic II+, OOPic II Expansion Card and Interface Board.

D. SENSORS

1. Thermopile

To get thermal information, BigFoot employs a Trekker Thermal Array Sensor TPA81 (Figure 23) mounted on the camera as shown in Figure 24. The thermal sensor detects infrared in the 2um-22um range. It has eight thermopiles arranged in a row and can measure the absolute temperature of eight adjacent point simultaneously [12]. This thermal sensor has an I2C interface and is programmed to address 0xD0.

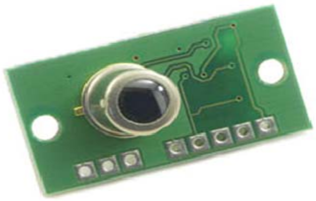

Figure 23. Trekker Thermal Array Sensor TPA81 (From [12]).

2. Camera

BigFoot's camera, D-Link DCS-900, is mounted on a servo in front of the base to permit rotating to view BigFoot's surroundings without any movement of BigFoot. The camera can send not only streaming video but also pictures to the Java based GUI on a laptop computer. The camera has a manual focus with 320×240 and 640×480 pixel resolution [13]. The camera uses a separate 5 V voltage regulator and is connected directly to the router. Figure 24 shows the camera mounted on a servo.

Figure 24. Camera mounted on a servo.

E. COMMUNICATIONS

BigFoot uses two Proxim RangeLAN2 Ethernet Adapters 7910 to communicate with the SSC-32 servo controller. The adaptor supports point–to-point and point-to-multipoint wireless configurations and can be either a master or a slave station using the station/master rotary switch.

The adaptor uses the frequency hopping spread spectrum technology (FHSS) in the 2.4GHz range [14]. The speed of data transfer is 1.6Mbps. Figure 25 shows Proxim RangeLAN2 Ethernet Adapter 7910.

Figure 25. Proxim RangeLAN2 Ethernet Adapter 7910 (From [14]).

F. JAVA GUI

The Java GUI was originally developed at NPS by LT Kubilay Uzun [Ref.15] and rewritten and modified by LT John Herkamp [3]. LT Herkamp organized the GUI window using three tabs (Navigation tab, Arm tab, Sensors tab) but Navigation and Sensors tabs are only used with this project. The arm is controlled with another application. The application will be explained in the next chapter. BigFoot is controlled by the operator via a Java GUI on a laptop computer. The GUI allows the operator not only to drive BigFoot autonomously using waypoints for navigation but also to control BigFoot in manual mode using drive buttons and joystick mode.

Figure 26 shows the sensor tab. A drawing of BigFoot is shown at the left side of the window. An arc in front of BigFoot moves according to the pointing direction of the camera and thermopile. The right side of the window displays the images with camera buttons and temperature information. The snap photo button allows the images to be saved on the hard drive of the GUI laptop. The pan left and right button control the servo for BigFoot's camera. The eight blocks, located at the bottom of the right side of

the window, give temperature information from the thermopile. The temperature information is displayed with the numerical Centigrade temperature and colors. 0 degrees represent white and 255 degrees represents red.

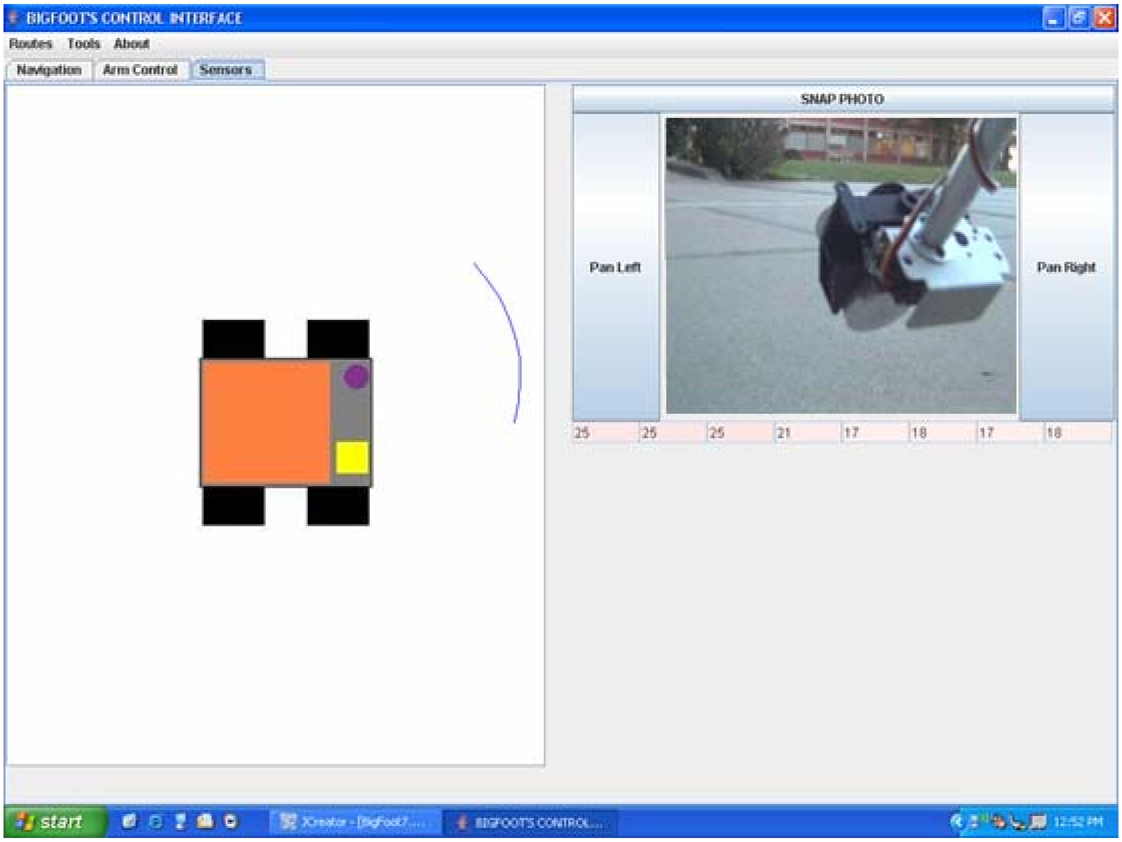

Figure 26. Sensor Tab.

G. ARM WORK

The Lynxmotion Robotic Arm Interactive Operating System (RIOS) is Windows program for controlling the arm with the SSC-32 servo controller. The RISO can set all servos to 1.5mS in order to make sure the arm is configured for the RIOS software [Ref. 11]. The figure 27 shows Lynxmotion RIOS SSC-32 arm control software.

The range of the servo is specified using the SSC-32 configuration application (Figure 27). A position value of 500 corresponds to 0.5mS pulse, and a position value of 2500 corresponds to 2.5mS pulse. The control bars caused the selected servo to rotate to

any position among the specified range. There are also configuration settings for servos on channels 7 and 8, which are not used for the arm. BigFoot uses the channel 7 to control the servo mounted under the camera.

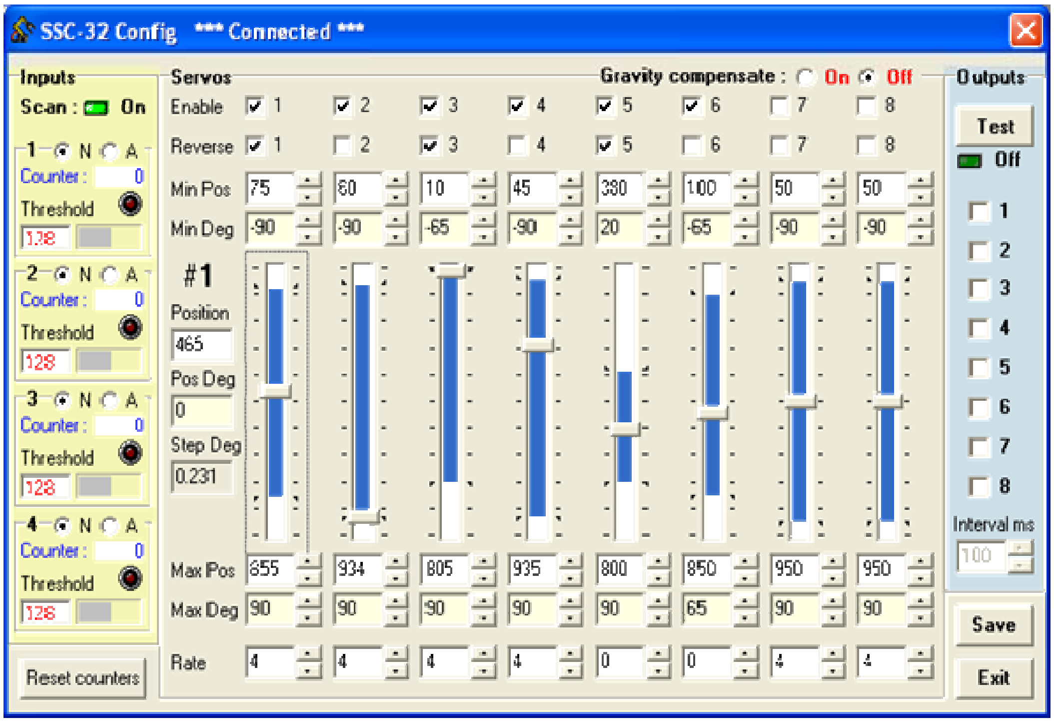

Figure 27. SSC-32 config.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. RESULTS

In order to better understand the rotational motion and translational displacement of BigFoot’s arm a simulation (Figure 28) was built using MATLAB program. This simulation gave insight into BigFoot’s arm performance and will serve as a basis for understanding the kinematics to employ the arm in full autonomous mode in the future. This Model shows the arm moving through a full range of motion for rotation and extension validating the conceptual design for our platform.

Field tests have shown that the arm can be successfully employed against a mock IED in manual mode, Figure 29. Our results also show that the length of the arm link from elbow to effector needs to be longer. We have also noted that the position of the arm on the robot needs to change to a more central location on the platform. This will allow for an ability to place or pick up objects from other than the forward position.

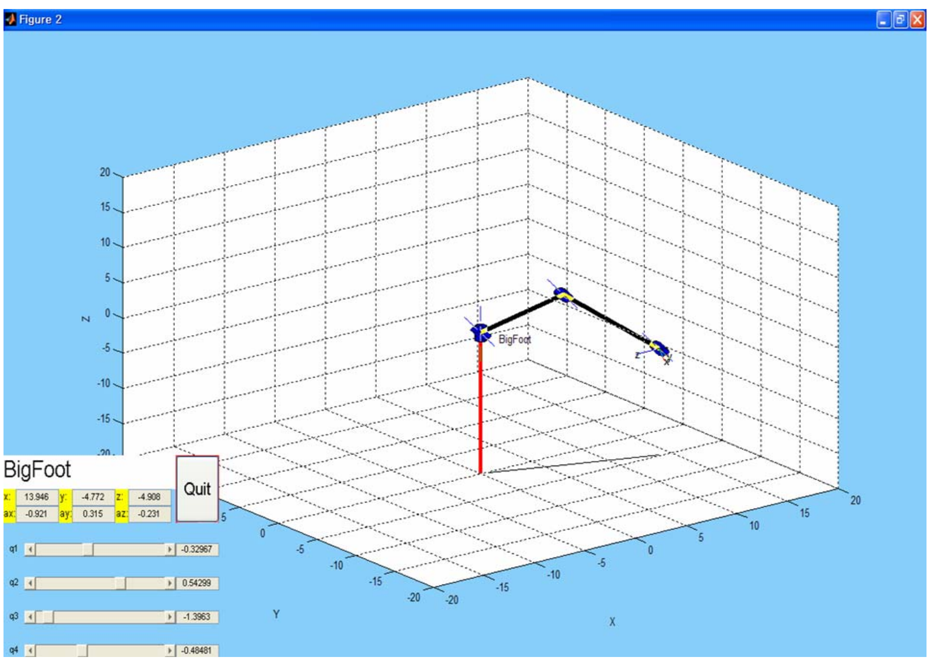

Figure 28. Simulation Model for BigFoot’s Arm.

The Wireless communications architecture for manual control of the arm was satisfactory for the expected communication ranges (line of sight) for the robot.

Mechanically the arm performed well with the expected loads for the arm. The translation and rotation servos mounted on the arm were well controlled with variable pulse widths that repeat every 20mS.

As shown in Figure 29, BigFoot's arm carries and places a shaped charge model on a mock IED in the field. The size of the shaped charge model is 3.5cm diameter × 5.0cm length.

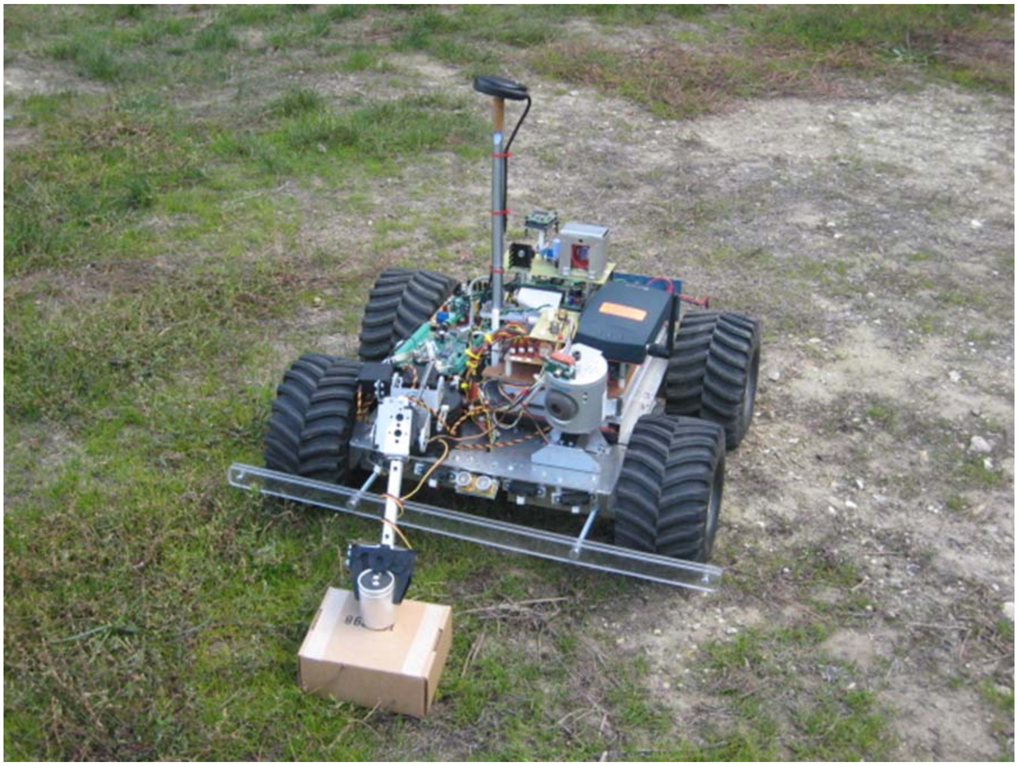

Figure 29. BigFoot launched a shaped charge model on the suspected IED.

V. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

The ability to employ robotic arms on mobile platforms is not new. The ability for an articulated arm to maneuver, pick up and place an object, from visual or other sensor feedback is also not new. The combination of these two abilities in a robot that can sense its environment, make decisions, and then pick up or place objects with little to no operator interaction is new. This thesis is a first step into better understanding the solution to this problem.

B. FUTURE WORK

Future work includes, principally, the development of autonomous arm motion and control models and algorithms for arm control and employment. Additionally, sensor interpretation and data fusion, which is fed into to the arm algorithm, still needs to be explored to fully realize actual autonomous behavior. The choice of proper sensor arrays will be critical to accomplish this and appears to be a daunting task.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

[1] Department of Defense. Joint Ground Robotics Enterprise 2007 http://www.jointrobotics.com/UGV%20Congressional%20Report%20-%20Final%20(October%202006).pdf , October 2007.

[2] Department of Defense. Joint Ground Robotics Enterprise. http://www.jointrobotics.com, October 2007.

[3] J. Herkamp. Deployment of shaped charges by a semi-autonomous ground vehicle. Master's Thesis, Naval Postgraduate School, June 2007.

[4] T. Dunbar. Demonstration of waypoint navigation for a semi-autonomous prototype surf-zone robot. Master's Thesis, Naval Postgraduate School, June 2006.

[5] GlobalSecurity.org. http://www.globalsecurity.org/military/intro/ied.htm, October 2007.

[6] U.S. Department of State. http://fpc.state.gov/documents/organization/57512.pdf, October 2007.

[7] GlobalSecurity.org http://www.globalsecurity.org/military/systems/ground/talon.htm, October 2007.

[8] Army-technology.com. The website for the defense industries – army. http://www.army-technology.com/contractors/mines/i_robot/, October 2007.

[9] Lung-Wen Tsai. Robot Analysis: The Mechanical of Serial and Parallel Manipulators, Wiley, New York, 1999, pp 46.

[10] LYNXMOTIONT. SES Series of Aluminum Robot Arms. http://www.lynxmotion.com/Category.aspx?CategoryID=108, October 2007.

[11] LYNXMOTIONT. SSC-32 Servo Controller. http://www.lynxmotion.com/images/data/ssc-32.pdf, October 2007.

[12] Superdroid Robots. TPA81. http://www.superdroidrobots.com/shop/item.asp?itemid=667&catid=35, October 2007.

[13] D-Link. DCS-900 http://www.dlink.com/products/resource.asp?pid=270&rid=807&sec=0, October 2007.

[14] Data Connect Enterprise.RangeLAN2 7910/11 Series Serial Adapter. http://www.data-connect.com/RangeLAN2_7910-11_Serial_Adapter.htm, October 2007.

[15] K. Uzun. SE4015 Class Presentation (June 2003).

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Professor Richard Harkins
   Department of Applied Physics
   Naval Postgraduate School
   Monterey, California

4. Professor Peter Crooker
   Department of Applied Physics
   Naval Postgraduate School
   Monterey, California

5. Physics Department
   Naval Postgraduate School
   Monterey, California