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## Mimicking Robotic Backhoe

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# MIMICKING ROBOTIC BACKHOE

by

Taylor Chad Bybee

Thesis submitted in partial fulfillment  
of the requirements for the degree

of

DEPARTMENTAL HONORS

in

Electrical Engineering  
in the Department of Electrical and Computer Engineering

Approved:

~~Thesis/Project Advisor~~  
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UTAH STATE UNIVERSITY  
Logan, UT

Spring 2015

Taylor Bybee  
Kelly Hathaway  
12 December 2013

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## Mimicking Robotic Arm

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# I. Project Summary

The proposed project is to design and create a small robotic arm that mimics movements of a similar physical model. The manual model can be manipulated by a human. Sensors inside the manual model will detect the position in each part of the arm. The information from the sensors will then be relayed, processed, and forwarded to the mimicking model. The mimicking robotic model will appropriately respond to match the smaller model, thus mimicking its position and movements.

This mimicking technology is helpful in a variety of applications where maneuvering a replica of an object is easier or safer than controlling it by other means (i.e. levers or a joystick). For instance, it allows for remote control of a backhoe when being close to the work is dangerous or inconvenient. This project creates base ideas that may be used to implement the system into actual backhoes that will be used for excavation. It will allow a novice to operate the equipment in a more natural way without the need for excessive training or experience.

The project incorporates the areas of electrical and mechanical engineering for design. The focus of the project will be electrical engineering and will be a beneficial learning experience for the designers.

## II. Introduction

In accordance with requirements for a bachelor's degree in Electrical Engineering at Utah State University, this project is being undertaken as a senior design. This project interests the designers, Kelly and Taylor, in several ways. First, the project is a hands-on experience for implementing the knowledge and skills gained while at Utah State University. Second, the project allows the designers to follow the engineering steps of problem identification, problem modeling, designing a solution, and implementing a solution. In this case, the design solution will incorporate several areas of electronics, controls, and power engineering.

The project is intended to be an educational pursuit. It will, however, lay groundwork for further area of study in the general areas of robotics and power.

The mimicking robotic arm project will be beneficial to the education of the designers.

## III. Problem

This project is being undertaken, in part, due to its general application. Throughout the history of the industrial revolution, and perhaps because of the implementation of assembly lines, repetitive, dangerous, and otherwise undesirable work has been performed by humans. In order to mitigate human involvement in these activities, the field of robotics has emerged to replace machines in dangerous and repetitive situations.

Excavation is sometimes one of these dangerous and repetitive situations. In many low-key cases, excavation is relatively safe to the operator. However, in cases where the operator is put at high-risk, it becomes necessary to remove the human from the situation in order to preserve life and well-being. This begs a situation where the operator can control the excavation equipment from a distance.

The mimicking robotic arm project will serve as a basis for allowing an operator to be removed from the situation, especially in the instance of excavation. It will, however, serve as an important base for other applications where remote control is required.

## IV. Objectives

The objectives of this project include designing and building a robotic arm, designing and building its associated control system, and designing an associated power system.

The deliverables for the project include:

- The Robotic Arm
- Documentation of Backhoe System
- Poster explaining the project

In addition to the deliverables, several other goals will be used as a metric for success:

- The robotic arm will be optimized to produce ideal mimicking behavior; it is expected that a human observer will not be able to detect a significant difference between the manual arm and the mimicking arm during nominal movements.
- The power system will be able to convert power with 90% efficiency and provide required power for the system in a timely manner.

Based on this criterion, the mimicking arm will be designed and built.

## V. Solution

The mimicking arm implements several areas of electrical engineering, including, but not limited to, control theory, micro-electronics, mechatronics, and power. Designing the project from a systems approach greatly simplifies the complexity of the project as a whole and creates a model that is easily adaptable. One spin-off benefit of the project is the creation of a multi-purpose controller that can be installed on any mimicking system, including a backhoe (or other excavation) system of nearly any size with minimal changes made to the controller. Designing each subsystem independently will allow fluidity and generalization for a variety of applications.

The mimicking robotic arm system can be divided into several subsystems: (1) Control, (2) Sensors, (3) Power, and (4) Mechanics. These subsystems are intimately related. Figure 1 shows the robotic arm being applied to a robotic backhoe.

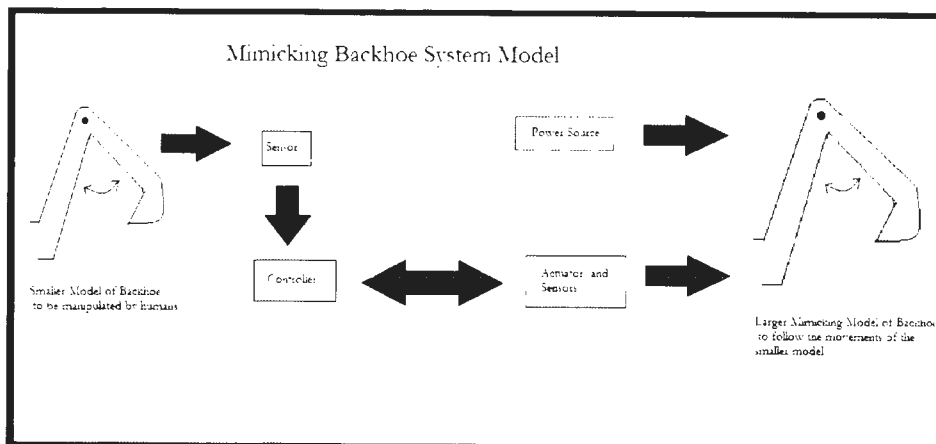


Figure 1. The Mimicking Backhoe System Model.

Each subsystem has a unique purpose and function:

- (1) Control Subsystem: The control subsystem takes information about the mechanical system (e.g. size, weight, types of power sources, and types of sensors) as well as information from both the larger and smaller models through the sensors subsystem. The controls subsystem determines the correct commands to be sent to the actuators and power sources to drive the mechanical system to behave correctly.
- (2) Sensors Subsystem: The sensors subsystem detects the current positions of each model and relays information about position to the controller. The sensors determine the relative position of each part by measuring the angle on the components of a joint.
- (3) Power Subsystem: The power subsystem physically realizes the commands given by the controller. This subsystem interfaces with the controller and mechanical subsystems as a one-way translator.
- (4) Mechanical Subsystem: The mechanical subsystem consists of the physical parts of the arm including the upper and lower arms, joints, as well as the interface with the power subsystem (e.g. motors and hydraulic or pneumatic rams).

The manual model will be small enough to be easily manipulated by a human. It will have four degrees of freedom with respect to the motion of the arms. Sensors on the arm will detect the current angular position between the arms. This information will be fed into a controller to be processed. The controller will probably be designed to function in a microcontroller or a computer, but may be done as an electric circuit. The controller will issue commands to the actuators on the larger model where a power source will drive the arms and booms to the desired position within a reasonably short amount of time. The actuators and power source(s) may be chosen to be a series of electric motors, hydraulic rams, pneumatic rams, or any combination of those and other means. The mimicking model will have a range of motion similar to that of excavation equipment; i.e. swing side to side (range of approximately 180 degrees), and produce typical arm movements.

Once the proposal is written and approved, the system will be modeled. This is most easily done in a computational software program. Once the modeling is complete, design specifications will be determined, and specific hardware will be chosen based upon the design specifications and constraints. The hardware will be assembled and tested. The controller will also be tested—first in simulation and second on hardware. Once these tests prove successful, the entire system will be assembled and tested. The system tests consist of manipulating the smaller model in the standard movements of the desired range of motion. These tests primarily measure the speed of the system response, the range of motion of the joints, and certain corner conditions. Documents will then be compiled and completed.

Once documentation is complete, the project will be finished. However, further steps may be taken to implement the system on a full-size model, such as a backhoe.



This would require very few, if any, changes to the upper-level systems, and minor changes in the details of each subsystem.

## VI. Methods

A system level design approach will be used throughout the project. Mathematical models will be developed to accurately predict the dynamic behavior of each sub-system. These mathematical models will be implemented in a software environment such as MATLAB and Simulink to verify their behavior. In this software environment, controller designs will be tested and validated before being implemented in the hardware systems. An entire system model will be implemented in software to test and validate the system as a whole.

Consideration of design specifications will be taken into account during the design process. Any results not meeting specifications will be evaluated and design re-iterations will be executed as needed.

## VII. Resources

Resources will be obtained from dealers and the ECE Store at Utah State University. Help needed from the students will be obtained through the faculty in the Department of Electrical and Computer Engineering at Utah State University. As part of their responsibilities, Dr. Don Cripps is the Senior Design advisor and Jolynne Berrett will be the technical writing advisor.

Additional help may be obtained from other sources where expert help is needed.

## VIII. Schedule

The estimated project timeline is found in Table 1. This timeline may be adapted as unforeseen circumstances and situations arise. However, the hard completion deadline of April 15, 2014 will be held except in an extreme case.

*Table 1.* Project Steps Timeline

<b>Process</b>	<b>Estimated Begin Date</b>	<b>Estimated Completion Date</b>
System Model	December 16, 2013	January 15, 2014
Sub-system Models	December 18, 2013	January 15, 2014
Hardware Design	January 1, 2014	January 31, 2014
Order Hardware	n/a	February 1, 2014

Develop Controller	January 15, 2014	February 1, 2014
Assemble Hardware	February 15, 2014	February 22, 2014
Test Hardware	February 22, 2014	February 28, 2014
Test Controller	February 1, 2014	February 28, 2014
Assemble Entire System	March 1, 2014	March 22, 2014
Test Entire System	March 22, 2014	March 31, 2014
Document System	April 1, 2014	April 15, 2014
PROJECT COMPLETION	April 15, 2014	

The afore-mentioned steps will be divided into three phases: (1) Modeling and Design (2) Programming and Assembly, and (3) Testing and Documentation.

The approximate dates for each phase are summarized in table 2 below:

*Table 2. Project Phase Timeline*

	<b>Description of Work</b>	<b>Start and End Dates</b>
Phase One	Modeling and Design	Dec 8, 2013 – Feb 1, 2014
Phase Two	Programming and Assembly	Jan 15, 2014 – Mar 22, 2014
Phase Three	Testing and Documentation	Feb 22, 2014 – Apr 15, 2014

## IX. Qualifications

The project will be managed by two senior Electrical Engineering students: Taylor Bybee and Kelly Hathaway. Each has direct interest in different parts of the project and general interest in all parts of the project. Mr. Bybee has a background in signals, mechanical systems, physics, and controls. Mr. Hathaway has a background in power, controls, embedded systems, and micro-electronics. These complementary sets of skills and interests will prove to be valuable in the course of the project.

## X. Costs

The project resources yet to be purchased and the estimated costs are found in Table 3.

Table 3. Estimated Costs of Resources

Resource	Anticipated Cost
Mechanical System	\$300
Controller System (processor/hardware)	\$80
Power System	\$150
Sensors	\$75
Documentation Printing Costs	\$20
<b>TOTAL ESTIMATED COST</b>	<b>\$625</b>

The project will not include any labor expenses. Funds for the project will come from the project designers. The funds will be used in an efficient manner. As funds for this project come from the designers, the money spent will be as little as possible. Design constraints may be changed to reflect a lower-cost design.

## XI. Conclusion

The Mimicking Robotic Arm project is being undertaken by Taylor Bybee and Kelly Hathaway for a senior design project to be used mainly as an educational pursuit. The project timeline will be followed and any completions ahead of schedule will be welcomed. The project will be an excellent learning tool to see a design from start to finish. Skills will be acquired in a variety of areas outside of electrical engineering, including mechanics, modeling, professionalism, technical writing, and public speaking and presentations, in addition to budget and cost-planning.

The designs to be developed in the project have place in several fields where it is dangerous or not practical to have an operator close to the work. The control system developed will be adaptable to be used in excavation, manufacturing, remote surgery, and other fields where remote robotics can be utilized. Applying the Mimicking Robotic Arm control system to excavation machines is the prime goal of the project.

**ECE CAPSTONE PROJECT**  
**MIMICKING BACKHOE ARM**

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## **1. EXECUTIVE SUMMARY**

This document summarizes the efforts of two engineering designers as part of their senior capstone project at Utah State University. It outlines the goals of the project, the methods used to create the project, and the results and implications of the project.

The project, the Mimicking Robotic Backhoe Arm, is designed from an electrical engineer's point of view. The designers used their skillset to create a mimicking robotic backhoe. That is, a remote-controlled miniature backhoe arm. The user controls the backhoe arm by manipulating a similar arm with sensors. This project incorporates embedded systems, power, and mechatronics.

## 2. INTRODUCTION

Due to the often dangerous conditions in which heavy equipment operates, this project exploits controlling a mechanical system remotely. This project demonstrates a solution by implementing a small robotic backhoe controlled by a similar arm from a distance.

Electrical power conversion is all around us. In our homes we use many electronic systems, most of which require a low voltage DC power source. These all receive power from a high voltage AC source converted to a low voltage DC. A typical backhoe system may already have a DC source such as a 12 V battery and an electronic control system would require an efficient DC to DC conversion to a lower voltage. For this project, an efficient DC-DC converter is implemented to supply power for the robotic backhoe.

The scope of these concepts goes beyond what was demonstrated in this project. Remote mechanical control encompasses many aspects not included in this project and leaves much room for future development.

The implementation of these principles is shown in the deliverables for the project. These include this document, a poster, the physical device and the software on the device. This project allows the user to remotely control a small robotic backhoe arm. It also allows efficient voltage conversion using the buck converter.

## 3. METHODS

This project is centered in an embedded system and a power system. In short, position data from the user arm is gathered using rotary potentiometers found on the joints of the arm. The data is converted into digital codes representing the position of the arm. These codes are relayed over a serial connection from one microcontroller unit (MCU) to another which converts the code into a command for the actuators on the robotic backhoe. The second MCU receiving the data also controls a buck DC-DC converter to supply power for the robotic backhoe.

The design method followed a spiral design process. Each iteration consisted of testing, development, and planning. This allows for a fluidic view of the system. The designers abstracted the project into three design areas: (1) the mechanical system, (2) the electrical system, and (3) the software system. Each of these systems is described in the following pages.

### **Mechanical System Overview**

The mechanical system of this device is very simple. It consists of two arms: the user arm and the control arm. These arms are essentially the input and output of the system. That is, the operator manipulates the user arm, providing an input signal. The system then relays and processes the position of the arm to the control arm. The control arm adjusts its position to match the position of the user arm.

The user arm (shown in Figure 1) is built from wood, with rotary potentiometers used as both joints and position sensors. Because the user arm is not subject to any extraneous circumstances, its durability is sufficient. (Naturally the design would be improved for any mass-production of the system.) The user arm is easily manipulated by a human, and is small

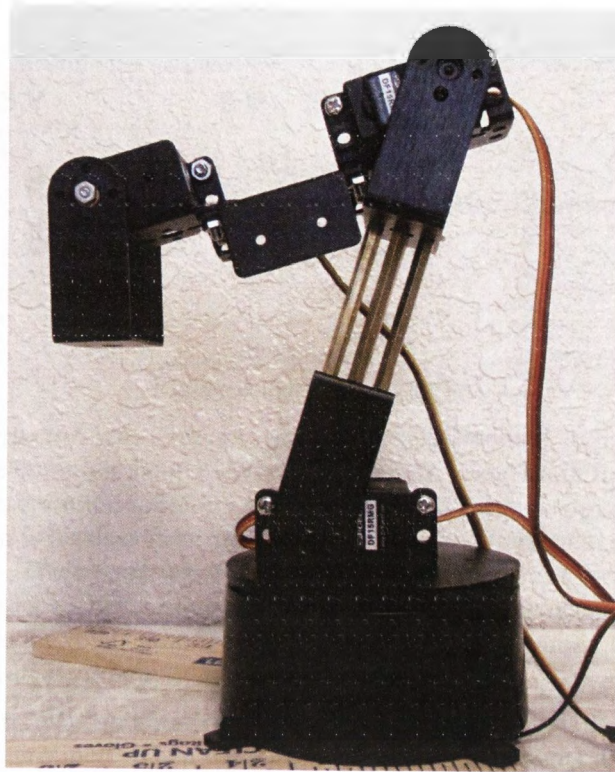
enough to be placed in one's lap or tabletop. Conceptually, it is easy to handle, and the movements are much more natural than a series of levers used in hydraulic excavation equipment.



*Figure 1. User Arm*

The control arm (shown in Figure 2) is used in this project to represent a real-world backhoe arm. The control arm in this case is approximately the same size as the user arm, for purpose of demonstration as well as feasibility of this project. It primarily consists of brackets and servos formed together to resemble a backhoe arm, having similar movements. The servos are sized according to the relative torque load of each joint. For example, the servo actuating the bucket has less torque than the servo lifting the entire arm.





*Figure 2. Control Arm*

Each servo operates within an angular range. The range limitations of a real-world backhoe are implemented both in hardware and software. The control arm is balanced using a wide base, much like the real-world backhoe is balanced using stabilizers.

The calibration for the servos/potentiometers was done by placing the corresponding joints of the both arms into the same position, usually at the end of the range of motion. The potentiometer value was read and the PWM pulse-length corresponding to the servo position was determined. The joint was then moved to another position and similar readings were taken. A linear relationship for each servo-potentiometer was determined. After that, fine-tuning calibration was done by adjusting these values.

### **Electrical System Overview**

The electrical system primarily consists of three subsystems: (1) sensors, (2) buck converter, and (3) actuators.

The sensors subsystem consists of four potentiometers on the user arm. These potentiometers output a voltage proportional to angular position. This voltage is buffered using a unity-gain voltage follower op-amp configuration before going into an on-board analog-to-digital converter (ADC). The ADC converts an analog signal into a 12-bit digital signal. The ADC successively converts each input voltage, and does so indefinitely. The potentiometer resistance was chosen to be a high value to reduce the amount of current used. The schematic for a single potentiometer, impedance buffer, and ADC channel is shown in Figure 3.





Figure 3. Sensor Schematic

The buck DC-DC converter was chosen to step down a DC voltage to 6 V for the robotic backhoe servos. The complete buck converter subsystem is shown in figure 5. The buck converter is a simple, common topology and is well suited for this application. The basic principle of operation is lossless filtering of a square wave voltage generated by high frequency switching. The square wave is produced by two transistors switching alternately on and off. A second order LC filter is utilized to filter this square wave and produce a steady voltage and current to the load. Another LC filter is placed at the input to filter pulsating input current to the transistor pair.

Design of the converter was an iterative process. First the required voltage conversion and power levels were determined. Then the output LC filter components were chosen to limit the inductor current ripple and output voltage ripple at the rated power. Power N-channel MOSFETs were chosen to reduce conduction losses when turned on at a desired gate voltage of at least 5 V. Input LC filter components were then chosen to reduce undesirable effects of the inevitable pulsating currents into the drain of the high-side MOSFET. Once all these components were chosen their characteristics were collected the performance of the circuit analyzed. These steps were repeated until a desired converter was designed. A printed circuit board was designed for the buck converter and control MCU.

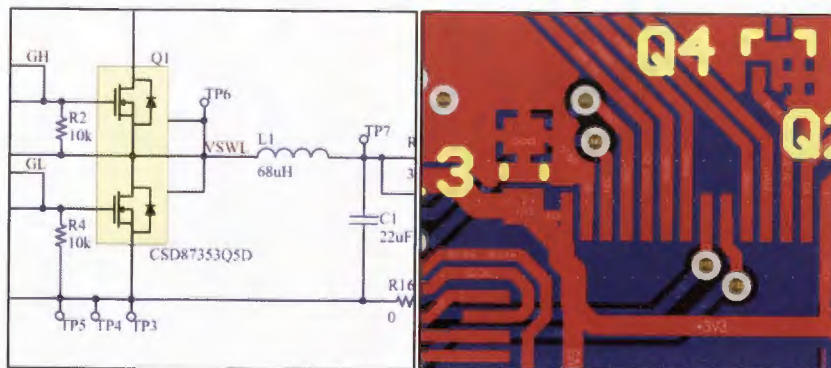


Figure 4. Schematic capture and PCB layout of the buck converter board

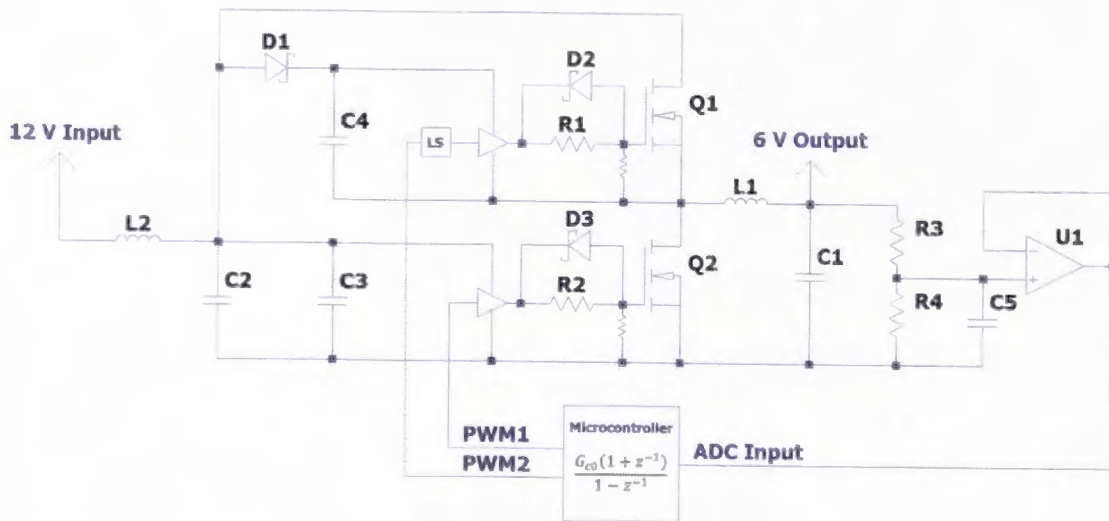


Figure 5. Complete buck converter system

The actuation subsystem consists of the servos on the control arm. These servos operate on a voltage range of approximately 6 V and the torque produced is proportional to the supply voltage. The command signal to these servos consists of a pulse-width modulation (PWM) signal with a period of 20 ms, and duty cycle range of 2-10% of the period. The duty cycle is proportional to the angular position of the servos. The PWM signals are generated from the MCU and sent to the servos.

### Software System Overview

The software system consists of the software on two microcontrollers: the user board and the control board. The user board contains the interface to the user arm as well as to the operator. The control board contains the interface to the control arm in addition to the buck converter. Both the control board and user board follow similar software architectures – they are primarily interrupt-driven code. Interrupts trigger all important functions.

The purposes of the user board are to provide a simple interface to the operator, retrieve the input signals from the user arm, and provide communication to the control board. The purposes of the control board are to provide signals for control arm actuation, control the buck converter, and provide communication to the user board.

### Sensors

As afore-mentioned, the ADC converts the potentiometer readings on four channels. The ADC on the chosen micro-processor uses direct-memory-access (DMA) to store the values read on each channel. The DMA places the ADC data into memory, waiting to be sent via a serial connection.

### Buck Converter Control

The buck converter was controlled in software by sampling the output voltage with the 12-bit ADC and compensating for the error with the desired reference. In the continuous domain

the controller is a simple integrator. This was converted to the digital domain with a sampling frequency of 100 Hz. The resulting difference equation is:

$$u[k] = G_{c0}(e[k] + e[k - 1]) + u[k - 1].$$

#### Serial Communication

The position data is sent in a packet over an RS-232 Serial cable at 115,200 baud, with one start bit and no parity. The packet consists of a four-byte unique word and eight bytes of position data. This is shown in the following figure.

Unique Word	Potentiometer #1	Potentiometer #2	Potentiometer #3	Potentiometer #4
	Position	Position	Position	Position
[4 bytes]	[2 bytes]	[2 bytes]	[2 bytes]	[2 bytes]

Figure 6. Data Packet

A packet is sent whenever the ADC end-of-conversion interrupt occurs. The ADC is set up to trigger every 50 ms. Thus, the packets are sent every 50 ms. The control board enters an interrupt at every received byte. These bytes are shifted into a circular buffer. When the software detects the unique word at the end of the buffer, it determines with confidence that the remaining data in the buffer is the position data. The position data is then transformed into a PWM signal.

## 4. RESULTS

### Buck Converter

The buck converter was tested for efficiency and for transient load response. Figure 8 shows the total measured efficiency of the buck converter as well as the estimated transfer efficiency where transfer efficiency is defined as the efficiency of the transfer of power from the input to the output, not including estimated power consumed by control circuitry.

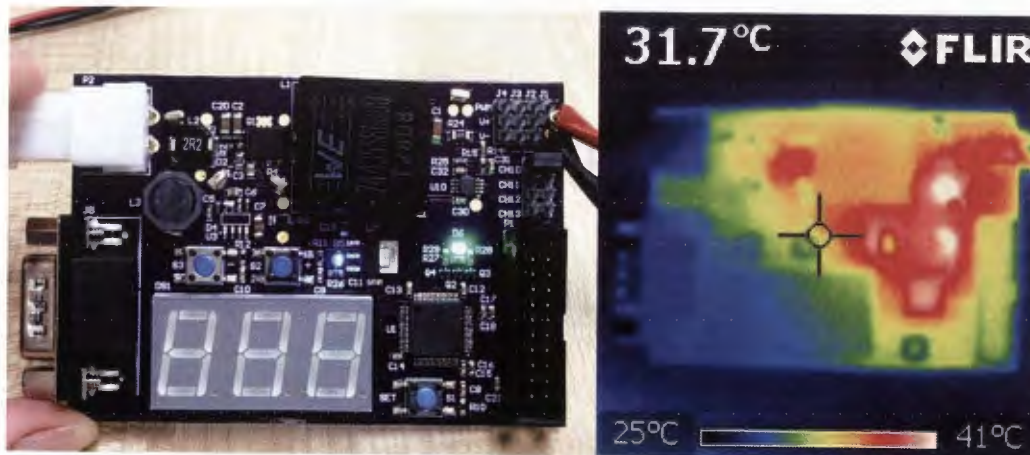


Figure 7. The buck converter board and thermal operating image.



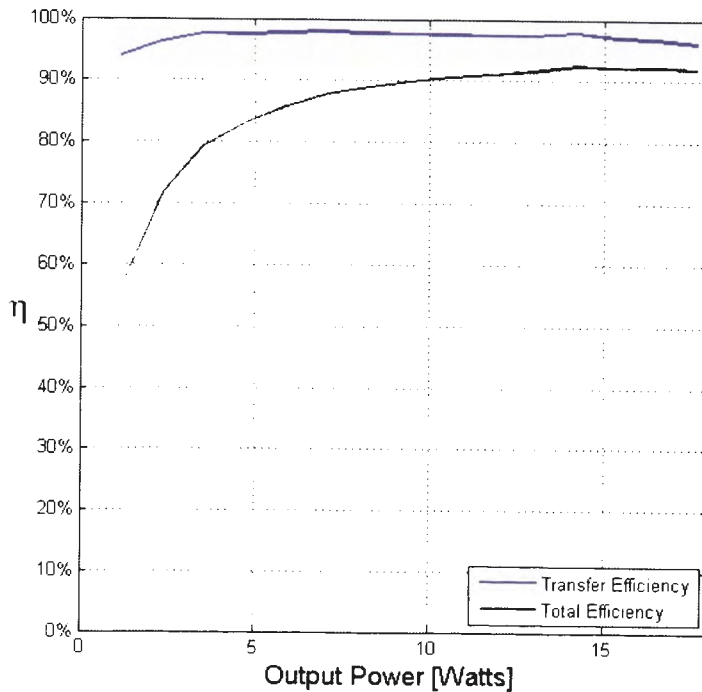


Figure 8. Buck converter efficiency

A thermal image was taken of the converter board to demonstrate the safe temperatures of the components while operating at the max power rating of 18 watts. This image is shown in Figure 7. The hottest components on the board are not components found in the DC-DC power stage. Figure 9 shows the 3 amp load step response of the converter output voltage controlled in closed loop.

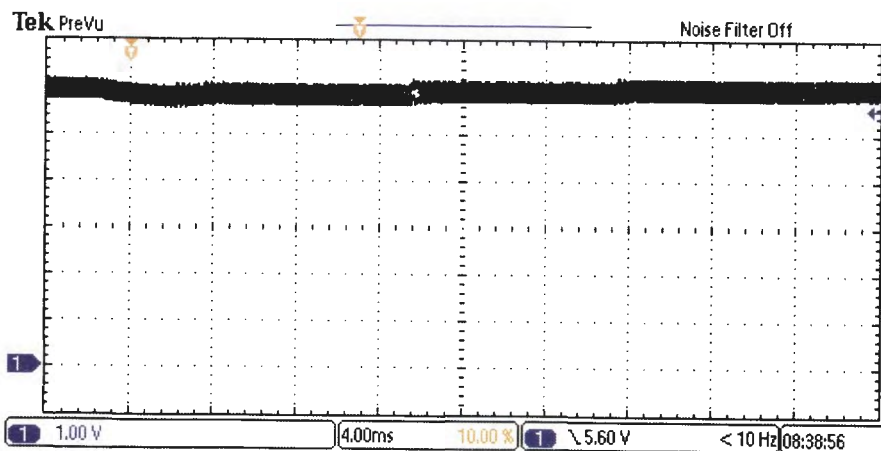


Figure 9. Three Amp load step response of the output voltage

## Sensor Calibration

The sensors were calibrated by placing the user arm in several positions, and reading the potentiometer values from these locations. The same positions were located for those servos. A linear functions was determined between the two sets of points. Each potentiometer-servo has a different line, so a look-up-table was used in code to determine which calibration values to use. These calibration values are shown in Table 1 below:

Table 1. Servo-Potentiometer Calibration Values

	Base POT PA0, ADC1_CH0	Lower Elbow POT PA1, ADC1_CH1	Upper Elbow POT PC4, ADC1_CH14	Bucket POT PC5, ADC1_CH15
Potentiometer Reading 1	0x058C	0x0526	0x052E	0x0163
PWM Pulse Length 1	0x06A4	0x09C4	0x0528	0x09C4
Potentiometer Reading 2	0x0A40	0x0EC2	0x0C82	0x0650
PWM Pulse Length 2	0x0B54	0x044C	0x0B40	0x0320

The servos performed acceptably well with these values in mimicking the user arm.

## 5. DISCUSSION

The completed project met the basic requirements for the design. It accomplished the goals of (1) making a mimicking backhoe arm and (2) powering it with a buck converter. The final design differed from the original idea in terms of scale and implementation. The original idea included electric linear actuators on a much larger backhoe arm. For feasibility reasons, the backhoe arm was decreased to its final size. Despite the size differences, the basic concept is the same.

The buck converter design worked very well for this project. Operating over 10 watts, the converter was performing with over 90 % efficiency. The power rating for the converter was designed to be higher than was needed by the servos. Power used by the robotic backhoe rarely exceeded 6 watts. At this power level, the converter could run with no feedback and still provide a fairly consistent output voltage. This open-loop operation was not tested in the lab, but by design and observation from other transient response tests.

Based on observation, the mimicking behavior is very effective. There is some noise in the potentiometer signal, which causes jittering in the servo. A low-pass filter could be

implemented to remove the jittering and higher quality wiring and sensors would reduce noise. Apart from the issues just mentioned, the mimicking behavior is performed successfully.

Ideal motion is difficult to quantify effectively in an open loop system when the human is in control. There are no feedback sensors, so judgment of the system's quality is determined by the user. From the user's point of view, it operates quite well. This project does a good job at open-loop control of a mechanical arm.

## **6. CONCLUSION**

This project provided a good learning experience on designing, creating, and documenting a project in all phases. It gave the designers grounds for basic understanding of systems engineering and working as a team, in addition to technical skills learned. The skills used included printed circuit board design, embedded C programming, controls, and microelectronics.

The project design is reliable. At the engineering design demonstration night, the public was able to operate the arm to move pieces of candy from one bucket to another. The system worked very well and received many compliments.

The project can serve as a base for future developments in the areas of remote mechanical control including excavation, remote surgery, and animatronics. Potential features may include adding 'force' feedback to the user, wireless communication between boards, incorporating recorded movements, adding connections to the internet or a personal computer, and adding additional degrees of freedom to replicate the mechanics of an actual backhoe.

The Mimicking Robotic Backhoe system is valuable in providing a safe environment for the operator and has great potential for excavation equipment.



# Mimicking Robotic Backhoe

Kelly Hathaway and Taylor Bybee

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## 1. Introduction

Due to the often dangerous conditions in which heavy equipment operates, this project exploits controlling a mechanical system remotely. This project demonstrates a solution by implementing a small robotic backhoe controlled by a similar arm from a distance. It also incorporates a buck converter to power the robotic backhoe.

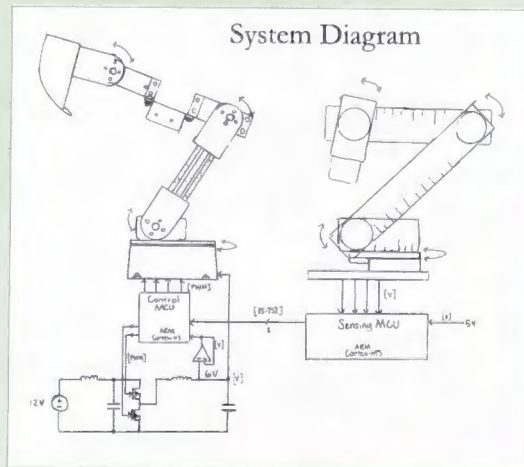
## 2. Operation

The operation for the system is very simple. Manipulate the wooden arm, and the robotic arm follows its movements in four degrees of freedom. It was designed such that the user needs to have both arms in sight.



## 3. System Overview

Rotary sensors gather position data on the sensing arm. This data is related via RS-232 to the control processor. The control processor outputs a command signal to servos dictating the desired position.



The buck converter steps the voltage down from 12 V to 6 V for the servos. The buck converter was built on a PCB.

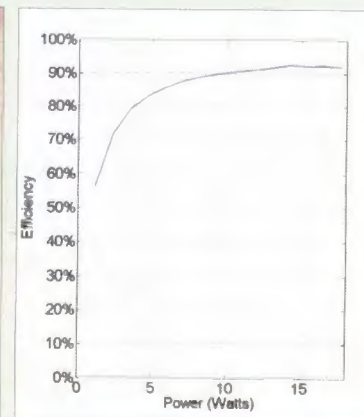
## 4. Results

The mimicking backhoe mirrored the movements of the user's control very well due to the fast response of the servos. The buck converter powered the backhoe arm with high efficiency.

Completed PCB



Buck Converter Efficiency



## 5. Conclusion

Remote controlled mechanical equipment can be applied in a variety of fields, including excavation, remote surgery, and animatronics. This project allows for remote control of a small backhoe-like arm. Potential developments could include adding 'force' feedback to the user, wireless communication between boards, incorporating recorded movements, adding connections to the internet or a personal computer, and adding additional degrees of freedom to replicate the mechanics of an actual backhoe.

This project was done as an engineering senior capstone project at Utah State University, Spring 2014. It incorporated the areas of embedded systems, power electronics, and mechatronics.



## Acknowledgements

Don Cripps  
Jolynne Berrett