A.R.E.S.  
(Assisted Robotic Exo-Skeleton) 
Wrist and Elbow Configuration

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ABSTRACT
Exo-skeleton suits are a rising trend in the military today. Scientists are striving to develop the newest and greatest strength and performance enhancing suit. However, many of these concepts seen in today’s experimentation leave the operator open to injury. While current suits offer great amplification of strength they are at a loss when it comes to portability due to the power needs of the suit. A different type of exo-skeleton that would provide 360 degree protection while maintaining a full range of motion was devised utilizing engineering design processes.

Required safety factor for this exoskeleton was calculated using a standard of repeated loading and minor combat situation loading. The total safety factor maintained is at least 4 times the loading condition of 150 pounds in every direction. Close to a full range of motion was maintained to successfully complete the testing set before it as mentioned in this report.

The components were designed for manufacturability and structural integrity utilizing standard fasteners. The final assembly meets required weights and degrees of freedom. Using modern machining methods the design team fabricated a working prototype that proved successful in all testing parameters.
INTRODUCTION

BACKGROUND
In recent years many companies have been experimenting with the concept of making a person stronger and protected with the use of a mechanically enhanced exo-skeleton. Some groups have focused on the mechanical aspect of the project while others have focused on the armor. The main goal is to combine the mechanical enhancement with full protection to allow a person to work in a hostile environment safely; however, variations have been used in other fields such as medicine and material handling.

The definition of an exo-skeleton is “an artificial external supporting structure” (1). Many thoughts about exo-skeletons have included armored suit ideas from movies, comic books and science fictional television shows. Real life armored suits actually date back nearly 1000 years and have ranged from leather protectors and bone chest plates to a full suit of armor used by medieval knights, but few give the user both the protection and the needed range of motion to utilize the armor to its fullest extent.

The project will be split up into two sections: Upper Arm and Lower Arm. Although both team members will help each other with certain portions of their designs when needed, the final report will be broken into the following sections: Frank Ricciardi – Upper Arm and Elbow, Nick Plataniotis – Lower Arm and Elbow.

In the research that follows, Troy Hurtubise’s Trojan suit is the closest fit to the definition. This project will show proof of concept by designing and creating a functional right arm assembly. This arm structure will be designed for structural integrity and durability. Total range of motion will consist of eight degrees of freedom, two of which will be powered enough to support its own weight allowing it to apply zero resistance to the operator. There will not be any type of strength enhancement nor armor included in the prototype.

RESEARCH OF CURRENT SOLUTIONS

Current exo-skeleton designs can be grouped as personal protection devices, material handling devices and medical devices. Some of the following examples bridge between different groups, proving that the concept of an exo-skeleton can be utilized in many different fields.
Trojan Suit
The Trojan Suit, developed by Troy Hurtubise of North Bay, Ontario Canada, is an armored exo-skeleton designed for riot control and military. The Trojan suit itself, as seen in Figure 1, is not actually bullet proof, however the armor designed by Troy, called “Shadow Armor”, can stand up to point blank gunfire from a 9mm, .357, .44 magnum and 12 gauge sabot slug.

Combining this bullet proof armor with the Trojan suit design would enable the user to engage in hostile riot situations and combat scenarios.

The Trojan suit design is considered by some to be over engineered due to its assortment of extra gear.

“Some of the Trojans key features are a laser tracking system, 5 L.E.D. light spectrums, a voice recorder, a voice activated pedometer, a digital electronic compass, built in compartments for salt tablets and morphine pills, a digital thermometer, a built in intake cooling fan which runs on solar power, a throwing and knife, a medical emergency light transponder and much more.” (2)

Removing many of these unneeded features may reduce the suit’s footprint, allowing for a more robust structure.
EXO Suit
EXO 1 and EXO 2 are strength enhancing suits developed by Sacros. The suit is able to mimic the users actions and amplifies their strength substantially. Mounting on the outer most area of the operator as seen in Figure 2, the bulky mechanical device enhances the user’s strength and greatly reduces the effects of fatigue. The bulkiness of this suit may inhibit some of the user’s motion and will greatly increase their size.

Figure 2 - EXO 1 Suit

Both EXO suits require a hard line power source to test the suit’s capabilities. In one field test, the EXO 1 was able to lift 200 pounds for 500 repetitions, and the suit could have possibly performed more but the operator decided to stop. “it should be noted that the reason for stopping was out of boredom and not due to fatigue.” (3) This shows that the suit is able to maintain a constant increase in strength to allow the user to perform extra ordinary tasks. Unfortunately, because of the suits large power consumption it cannot stray too far from the tethered power line. The next major step for Sacros is to develop a power source that is capable of powering the EXO suits for up to 24 hours. This will allow the suit to be utilized in field combat scenario, but until then the suit’s most acceptable function’s will be for loading and unloading convoys, aircrafts and other heavy objects.
**Industrial Manipulator**
An industrial manipulator, seen in Figure 3, is a big help in an industrial environment. This mechanism allows an operator to lift an object that is beyond an average person’s strength capacity.

![Figure 3 - Industrial Manipulator](image)

With different end-of-arm attachments for different jobs, lifting and orienting parts or components is seamless and precise. Manual controls located on or near the handles enable the user to maintain control of the load and manipulate it in all directions.
HAL Suit
The HAL Suit (Hybrid Assistive Limb) is a cybernetic suit which senses muscular impulse biosignals and consequently causes the suit’s limbs to move with the user. Though faint, the HAL system “catches these signals through a sensor attached on the skin of the wearer. Based on the signals obtained, the power unit is controlled to move the joint unitedly with the wearer’s muscle movement…” (4) This control enables the suit to react with the user instantly.

With a battery life of just under three hours, the HAL suits intended purpose is to help in heavy labor, rescue and medical support. As seen in Figure 4, the suit’s modular design assists in each limbs independent movement.

These modular components allow for quick and easy repair. While the battery life and overall design would not be idea in a combat situation, the versatility in many support roles is applicable.
HULC and E-Legs
Berkeley Bionics created a type of strength enhancement device for the lower half of the human body. HULC (Human Universal Load Carrier) can enable the user to carry a large amount of weight effortlessly. The frame design, as seen in Figure 5, transfers more of the weight off the user to the ground.

Similarly the E-Legs, seen in Figure 6, act as a support for a user who has lost much of the use of their lower body.

The device allows people who would otherwise be restricted to a wheelchair stand and walk. Controls in the arm crutches command the leg brace, “arm movements tell a back-pack computer how to move battery-powered legs” (5). With a price tag comparable to a high end powered wheel chair, these E-legs give paraplegics the chance walk again.
LUKE Arm
The “Luke arm”, named for its resemblance to the robotic arm in the movie “Star Wars”, was developed by Dean Kamen for people with amputated arms. The Luke arm, seen in Figure 7, uses sensors on the amputated limb as well as control pads elsewhere on the body, such as the foot, to control the mechanism.

![Figure 7 - Luke Arm](image)

The smooth control system reacts with the user's body signals and can simulate “normal” arm functions. With time and practice the user can appear to move as if they had a real arm.

Mayo Clinic Elbow Brace
The Mayo Clinic elbow brace acts as an arm immobilizer for patients after surgery, and also functions as a stretching device to reduce inflammation. By using the control knob, as seen in Figure 8, the user can adjust the static angle of the arm allowing the muscles to stretch in that position and return to a comfortable position when finished.

![Figure 8 - Mayo Clinic Elbow Brace](image)

The control knob can also be unlocked allowing a set range of motion. Combined with hard stops, the brace will only allow the user to move a predetermined range of motion to ensure they do not exceed their medical limitations.
Myomo
Myomo is a physical therapy tool to help teach patients who have lost complete control of their arms (i.e., stroke victims) how to control the muscular impulses that tell the body to move the arm. In Figure 9, the Myomo brace is shown contracted with the sensor on the patient’s triceps giving them the ability to extend.

Figure 9 - Myomo Arm Therapy Device

Changing the placement of the sensor from the triceps to biceps can change the mechanisms function from extending the muscle to contracting the muscle. Inside the brace portion hard stops regulate how far the user’s arm will extend or contract preventing any type of hyperextension injury. This muscular sensor is key in the rehabilitation process.

Interview Information
Information provided by First Lieutenant Brent Kreckman, (6) USMC Pilot, elaborates on what equipment is standard and what kind of performance is desired in the field of combat. Lt. Kreckman states that common situations where a protective structure would be most desired is Combat Engineers, EOD officers (Explosive Ordnance Disposal Officer) and Special Forces units.

The duty of a Combat Engineer is to clear the field of any type of hazards and build the forward operating base. These officers need to be capable of getting up and down quickly and easily. Also, they need to be able to get in close proximity to explosives to disarm them.

EOD officers are simply bomb workers. Their range of motion needs to be uninhibited allowing their hands to be completely free. Any armor used by EOD officers needs to assemble and disassemble quickly and easily.

Special forces must be able to shoulder a rifle using a three point sling and not have any interference while bringing the firearm from a rest to a ready position. Other motions will involve mounting and un-mounting gear, dropping to one’s hand and knees and getting back onto their feet quickly and throwing a grenade overhand.

Infantry soldiers currently carry approximately 150lbs of gear. This can consist of firearms, ammunition, communication equipment, food, and supplies. Soldiers need to maintain the
ability to be mobile at all times. Simple breakdowns in the field can be severely devastating. More so, most infantry equipment is relatively inexpensive so a soldier should be able to drop all unnecessary equipment to allow them to protect themselves if need be. Therefore an armored structure should not be too expensive.

An exo-skeleton should be designed with the user in mind. Enabling them to move freely, carry gear and supplies, maintain and repair easily and jettison the equipment quickly are the most important features a designer should keep in mind for military users. In all, the use of an ergonomic and simple exo-skeleton is widely desired more for personal protection than anything else.
CUSTOMER FEED BACK, FEATURES AND OBJECTIVES

SURVEY ANALYSIS
A survey was conducted to determine the importance of different customer features. A general questionnaire about exoskeletons was given to 10 people who are or were at one time military personnel. The results of the survey dictate the importance of each feature which are listed in Table 1 in the order of importance. The customer importance was recorded on a scale from 1 to 5 with a 5 rating meaning most important. The designer’s multiplier is a value the design team adds to enhance the importance of certain features.

The design multiplier was added to the customer importance because the design team believed it was necessary to enhance the importance of certain criteria.

Table 1 – Customer Features and Survey Results

<table>
<thead>
<tr>
<th>Feature</th>
<th>Customer importance</th>
<th>Designer’s Multiplier</th>
<th>Modified Importance</th>
<th>Relative weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Range of Motion</td>
<td>4.56</td>
<td>1.20</td>
<td>5.47</td>
<td>12%</td>
</tr>
<tr>
<td>Smooth Motion</td>
<td>4.20</td>
<td>1.20</td>
<td>5.04</td>
<td>11%</td>
</tr>
<tr>
<td>Safe for the operator/bystanders</td>
<td>4.80</td>
<td>1.00</td>
<td>4.80</td>
<td>10%</td>
</tr>
<tr>
<td>Be Durable</td>
<td>4.60</td>
<td>1.00</td>
<td>4.60</td>
<td>10%</td>
</tr>
<tr>
<td>Easy to Repair/ Maintain</td>
<td>4.50</td>
<td>1.00</td>
<td>4.50</td>
<td>10%</td>
</tr>
<tr>
<td>Easy to Operate</td>
<td>4.20</td>
<td>1.00</td>
<td>4.20</td>
<td>9%</td>
</tr>
<tr>
<td>Be Light Weight</td>
<td>3.70</td>
<td>1.10</td>
<td>4.07</td>
<td>9%</td>
</tr>
<tr>
<td>Have an ergonomic fit</td>
<td>3.90</td>
<td>1.00</td>
<td>3.90</td>
<td>8%</td>
</tr>
<tr>
<td>Have a Compact Design</td>
<td>3.44</td>
<td>1.00</td>
<td>3.44</td>
<td>7%</td>
</tr>
<tr>
<td>Loudness</td>
<td>3.40</td>
<td>1.00</td>
<td>3.40</td>
<td>7%</td>
</tr>
<tr>
<td>Low Cost</td>
<td>3.00</td>
<td>1.00</td>
<td>3.00</td>
<td>6%</td>
</tr>
</tbody>
</table>

The survey results show that having a full normal range of motion is most important to the potential customers, while having smooth motion, being safe for the operator and bystanders, being easy to repair and maintain, and being durable were next important features. Having a compact design, loudness and low cost are least important. This may be due to the idea that equipment like this would not be used in a stealth situation therefore it would not need to be quiet or have a compact streamline design. Low cost is not a factor to any military personnel because the government will supply all equipment at no cost to user therefore it ultimately does not matter how much it costs.

PRODUCT FEATURES AND OBJECTIVES
The product objectives are derived from the customer features that were included in the survey. These objectives will become the basis on which the prototype will be evaluated. The product objectives are as follows, in order of importance:
Normal Range of Motion (12%)
- Normal ranges of motion will be referenced from cited texts.

Smooth Motion (11%)
- Joints will be lubricated.
- Moving parts will not contact others causing them to bind.

Safe for the operator/bystanders (10%)
- Pinch points will be designed out or the operator will be guarded against them.
- An Emergency Stop will be included.
- Hard safety stops will be included into the joints to prevent hyperextension.

Be Durable (10%)
- Fasteners will be Grade 8 or equivalent.
- Correct materials will be chosen according to the design loads.
- Loctite will be applied to the fasteners to prevent them from backing out.
- A factor of safety agreeing with cited texts.
- All bolts will be tightened to the allowable torque in cited texts.
- Electrical connections will be soldered and then covered with heat wrap if needed.

Easy to Repair/ Maintain (10%)
- All fasteners will be bought and not made.
- Parts will not be welded.
- Sections will be modular.
- Quick connect electronic connectors will be used.

Easy to Operate (9%)
- Approximately 3 hours of training will be enough to qualify someone to be able to use it.
- No more than two people will be needed to assemble and put on the hardware.
- It will be easily controlled through sensors or switches.

Be Light Weight (9%)
- The arm will weigh less than 50 pounds, excluding armor.

Have an ergonomic fit (8%)
- The operator will be protected from coming in contact with the hardware.

Have a Compact Design (7%)
- All drive and control systems will be contained in the skeleton.

Loudness (7%)
- The arm will be no louder than an electric shaver.
Low Cost (6%)

- Easily obtainable materials and fasteners such as steel or aluminum will be used for construction.
DESIGN
This report will contain the design sequence for the Wrist and Elbow portion of the Exo-Skeleton project.

SAFETY FACTOR
The safety factor chosen for the wrist and elbow design was 4. This safety factor corresponds with components under repeated loading (7).

DESIGN RESEARCH
The wrist joint contains three axis of motion: One rotating motion and two bending motions seen in Figure 10 (7). The two bending motions can be either addressed independently or can be combined into one complex joint similar to a ball and socket joint.

For the safety of the operator the wrist will be designed with several hard stops to prevent the operator from moving outside the normal range of motion. These ranges are published in an Occupational Therapy text book (8) as seen in Figure 11.

The wrist deviation is cited at 0-20 degrees off neutral towards the thumb and 0-30 degrees bending away from the thumb. In the wrist design these stops were set at 0-20 degrees for both motions. The wrist flexion motion is 0-80 degrees upwards and the extension motion is
0-70 degrees downward. The rotating action for the wrist is called the supination and pronation and its’ range of motion is 0-80 degrees in both directions. For the elbow, the flexion-extension motion is 0-150 degrees. This is the bending and contracting motion seen in Figure 12 (9). The elbow supination and pronation is handled in the upper section of the arm and will not be discussed in this report. Hyperextension can vary with each individual, therefore, it will not be included in the design of the elbows movement.

\[\text{Figure 12 – Elbow range of motion}\]

The lower elbow joint will consist of only one degree of freedom while the wrist will have three degrees of freedom.

**WRIST ALTERNATIVE DESIGN AND SELECTION**

The primary focus for the wrist design was the rotating motion or the supination and pronation. The first concept was to use a ring design held in place precisely with a threaded locking ring feature (Figure 13 – 14).

\[\text{Figure 14 – Rotating ring with Locking ring feature}\]
\[\text{Figure 13 – Locking ring feature exploded view}\]

This threaded locking ring needs to have very tight tolerances and would require a special tool to tighten into place. In order to capture the wrist and follow the operators movements a contoured outer ring was designed (Figure 15).
This design included one bending motion before the rotating joint and one bending motion after. Having one bending motion before and after seemed to complicate the movement as well as not allow for an easy transition from one motion to the other. The inner and outer ring would also require extremely tight tolerances in order to function properly. This creates a high degree of difficulty in manufacturing as well as assembly would pose a problem in both cost and quality control. Additionally the need for these tight tolerances could create operational issues after the unit has seen wear or been damaged.

This prompted the second iteration to the wrist design utilizing a clasping idea (Figure 16-17). Using a clasp to connect two half rings that capture the rotating rings will allow for easier assembly and disassembly.

The two bending motions of the wrist were moved forward of the rotating joint to allow for a more natural movement and position with the human anatomy. It was decided to combine the deviation, the flexion and the extension motions using a swivel ball joint, seen in Figure 18 and 19. This standard component can be purchased through an online distributor McMaster Carr making manufacturing and production more streamline. The published range
for the swivel ball joints’ deviation motion is 20 degrees on either side (10).

While value is not consistent with the maximum range of motion for the average person, it was decided to be acceptable because it would still prevent the user from harm with its restriction.

To accommodate the ball joint a mount was designed on the front of the wrist rotating assembly as seen in Figure 20. The contoured wrist rotating ring is used to help capture and follow the operators’ motions and give the wrist structure extra support. Capturing the wrist with a form fitting contour ensures that forces are distributed directly into the wrist assembly rather than through the hand.

The hard stops for the flexion and extension motion were built into the ball joint mounting feature using standard dowel pins which will be in double shear to increase its strength (Figure 21). Palm support rods were added to give the operator something to grip while moving the wrist as well as provide a base frame for future advancements.
The future advancements might include a form fitting palm support rod to entrap the fingers, also giving the operator a combat device similar to brass knuckles.

The wrists rotating action has hard stops in the form of pins. These pins are placed so that they stop movement at the body’s’ natural limit. In figure 22, the hand would be inserted through the rotating joint with the palm upwards. There is a total of 160° between the surfaces of these pin stops, allowing for both the 80° supination and 80° pronation. There are two sets of pins mirrored to give each stop the advantage of being in double shear, thus amplifying the strength of the rotating joint.

Figure 22 – Rotating joint

Figure 23 shows the wrist joint at its neutral position while figures 24 and 25 show the wrist joint at the extreme positions.
Using simple dowel pins as the hard stops cuts down on cost and manufacturability. If ever these hard safety stops were to ever break they are available from nearly any fastener manufacturer and distributor making it a widely versatile component in this design.

**ELBOW ALTERNATIVE DESIGN AND SELECTION**

The focus of the elbow design was on its bending motion or its flexion-extension motion. However, this motion had to consider the upper arms elbow rotating joint. These components must function together without interference.

Preliminary designs for the elbow joint consisted of two friction discs that would be fastened together using a shoulder bolt. Shoulder bolts, as seen in Figure 26, are commonly used in rotating, sliding and pin fastening applications.

The clearance between the two friction surfaces can be precisely controlled using shoulder bolts allowing the surfaces to rotate and slide freely. To enhance the movement of the elbow joint the friction surfaces will be “scraped”. This is done by scraping the precision surface with a carbide scraper so that the surface has high points and low points that can vary as much as 0.001 inches. This allows for smooth movement as well as a small cavity for lubricant to sit. The friction plates have support features that extended out to connect the upper elbow and wrist rotating joints. Figure 27 shows the surface plates and the support.
arms that extend away from them.

Figure 27 – Elbow first iteration

This concept would have support arms extending to the wrist assembly on either side of the forearm. In the opposite direction, the support arms would extend to the upper arm rotating joint. In this iteration the upper arm rotating joint is located close to the elbow joint as seen in figure 28.

Figure 28 – Elbow assembly first iteration

Designing the upper arm rotating ring this close to the elbow joint would cause interference with the operators’ arm. The next iteration design (Figure 29) consists of the upper support arms extended further towards the shoulder and hard stops included around the friction surfaces to encompass the operators’ range of movement.

Figure 29 – Elbow Assembly Second iteration
The cross sectional area of the hard stops was increased, to allow more force to be absorbed before failure as seen in Figure 30.

Designing the hard stops on the outer portion of the arm supports eliminated any possible pinch points where the operator could be injured.

When designing for a loading condition it was determined that there needed to be a cross member connecting the support arms. These cross members or “support brackets” were designed to span around the operator’s arm attaching to either side. Not only would this create a more stable structure but it would also give the operator more support around the forearm and elbow for movement, following the operator more closely. Several iterations (Figures 31-34) of the support brackets were designed, each increasing the structural integrity.
Enhancing the shape of the supports helped distribute forces as they were applied in specific loading conditions.
LOADING CONDITIONS, DESIGN ANALYSIS AND MATERIAL SELECTION

It is difficult to precisely estimate what type of loading conditions any working system will encounter in the field of combat. The following are examples of loading conditions for the worst case scenario thought to occur in a hostile environment. It was decided that these situations would not exceed 150 pounds in any given direction.

Load Condition 1
The first load condition was performed with the forearm region of the arm. This condition experienced forces axially through the wrist area with the elbow being restrained (Figure 35). This test was performed with several variations (Figure 36 – 38) to the arm assembly to demonstrate how the design prospered with each design iteration as well as with the selection of material.
The analysis of each iteration is shown below in Figures 39-43. They depict the maximum stress exerted on the part, the maximum deflection and the safety factor.

Figure 39 – Design 1 Analysis

Frame Material: 4340 or 8620 Steel
Max Stress: 193 ksi
Max Deflection: 0.351 in
SF: 0.35

Figure 40 – Design 2 Analysis with Aluminum Supports

Frame Material: 4340 Steel
Support Material: Alum 7075-T6
Max Stress: 112 ksi
Max Deflection: 0.148 in
SF: 1.1

Figure 41 – Design 3 Analysis with Aluminum Supports

Frame Material: 4340 Steel
Support Material: Alum 7075-T6
Max Stress: 34.4 ksi
Max Deflection: 0.025 in
SF: 2.1
Load Condition 2
Analysis of the wrists’ swivel ball joint mounting feature includes a stress analysis of the three major possibilities for component failure. These three failure modes include the swivel joint moving in either deviation motions (Figures 44 and 45), a double tear out caused by pulling forces on the swivel ball joint mount and shearing forces on all hard stops in the wrist assembly.
Load Condition 3

The double tear out was calculated using the Force/Area formula. Assumptions were made that there are two ball joint mounts each having double tear out. Therefore there is a total of four cross sectional areas that will be considered when applying the forces. The calculations are shown in Table 2. The total stress seen by this loading condition is 4266.6 psi, and the safety factor for this component in this configuration is 58.96.

**Table 2 – Stress Calculation for the Ball Joint Mount Double Tear Out**

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>$F$</td>
<td>150</td>
<td>lbf</td>
</tr>
<tr>
<td>Diameter</td>
<td>$d$</td>
<td>0.1875</td>
<td>in</td>
</tr>
<tr>
<td>Tear Out Thickness</td>
<td>$t$</td>
<td>0.09375</td>
<td>in</td>
</tr>
<tr>
<td>Width</td>
<td>$w$</td>
<td>0.09375</td>
<td>in</td>
</tr>
<tr>
<td>Number of Tear Outs</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Yield Strength</td>
<td>$\sigma_{ys}$</td>
<td>251600</td>
<td>psi</td>
</tr>
<tr>
<td>Total Tear Out Area</td>
<td></td>
<td>0.035156</td>
<td>in²</td>
</tr>
<tr>
<td>Stress</td>
<td>$\sigma$</td>
<td>4266.667</td>
<td>psi</td>
</tr>
<tr>
<td>Safety Factor</td>
<td></td>
<td>58.96875</td>
<td></td>
</tr>
</tbody>
</table>

**Load Condition 4**

The wrists’ supination and pronation hard stops are consisted of standard dowel pins which have a published loading capacity of 4100 lbs in the double shear configuration (10). When the wrist rotates, two pins come into contact with hard stops simultaneously in single shear. This action will simulate the double shear condition for one pin diameter. Table 3 shows the force calculation.

**Table 3 – Rotating Joint Hard Stop Loading Conditions**

<table>
<thead>
<tr>
<th>Diameter (in)</th>
<th>0.156 in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Shearing Force</td>
<td>4100 lbf</td>
</tr>
<tr>
<td>Applied Force (lbf)</td>
<td>150 lbf</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>27.3</td>
</tr>
</tbody>
</table>
Load Condition 5
The hard stops in the ball joint mount are the same style pin. However, this loading simulation would be reduced by half because there are two ball joint mounts and they are both loaded in double shear. Force calculations are shown in Table 4 below.

Table 4 – Ball Joint Mount Hard Stop Loading Conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (in)</td>
<td>0.156 in</td>
</tr>
<tr>
<td>Allowable Shearing Force</td>
<td>4100 lbF</td>
</tr>
<tr>
<td>Applied Force (lbF)</td>
<td>75 lbF</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>54.7</td>
</tr>
</tbody>
</table>

Load Condition 6
When considering the elbows flexion-extension motion, the design must consider the weakest loading configuration. When the arm extends outward towards hyper-extension, as seen in Figure 48, the hard stops meet with a surface area of 0.177 in² depicted in Figure 49.

When the arm contracts bringing the wrist towards the body, as seen in Figure 50, the hard stop meets with a surface area of 0.089 in² depicted in Figure 51.
Because the stresses are more concentrated into a smaller area loading condition 6b will be assumed as the weakest configuration.

To calculate the forces acting on the hard stop it will be assumed that the lower arm support will act as a moment arm rotating about the shoulder bolt. The force diagram is shown in Figure 52.

To find the force acting on the hard stop the sum of the moments about point C was set equal to zero.

\[
\sum M_C = 0 = -75 \text{lbf}(11.313\text{in}) + F_B(0.914\text{in})
\]

\[
\frac{-75 \text{lbf}(11.313\text{in})}{0.914\text{in}} = F_B
\]

\[
F_B = 928.9\text{lbf}
\]

To find the force acting on the shoulder bolt at point C the sum of the forces was set equal to zero.
The stress values between the hard stop and the bolt were compared to determine which was higher.

The cross-sectional area of the bolt in Figure 53 is 0.0491 inches.

\[
\sum F_y = 0 = 75 \text{lbf} - 928.9 \text{lbf} + F_C \\
928.9 \text{lbf} - 75 \text{lbf} = F_C \\
F_C = 853.9 \text{lbf}
\]

\[
\sigma_{b\text{o\text{l}\text{t}}} = \frac{F}{A}
\]

\[
\sigma_{b\text{o\text{l}\text{t}}} = \frac{853.9}{0.0491 \text{in}^2}
\]

\[
\sigma_{b\text{o\text{l}\text{t}}} = 17,064.3 \text{psi}
\]

The cross-sectional areas likely to be effected by the forces applied on the hard stops are shown in Figures 54 and 55. It is more likely for the elbow upper arm support to shear first due to its smaller Cross-sectional area of 0.143in\(^2\).

\begin{itemize}
  \item Figure 54 – Load Condition 6b Cross-Sectional Area of Upper Arm Support
  \item Figure 55 – Load Condition 6b Cross-Sectional Area of Lower Arm Support
\end{itemize}
Stresses acting on the upper arm support hard stops are calculated by using the equation below.

\[ \sigma_{stop} = \frac{F}{A} \]

\[ \sigma_{stop} = \frac{928.9\text{lbf}}{.143\text{in}^2} \]

\[ \sigma_{stop} = 6495.8\text{psi} \]

A comparison between the two stresses shows that the shear stresses at the bolt are higher therefore it is the worst case scenario. The minimum tensile strength is 144,000 psi (10). The shear strength of the bolt is 57% of the tensile strength which calculates out to approximately 82,080 psi. The safety factor is calculated using the equation below.

\[ SF = \frac{\text{Maximum Stress}}{\text{Applied Stress}} \]

\[ SF = \frac{82,080\text{ psi}}{17064.3\text{ psi}} \]

\[ SF = 4.72 \]

The strength of the elbows’ shoulder bolt has a safety factor of 4.72 when a 150lb load is applied to the wrist causing the elbow to bend in a flexion motion and coming to rest against the hard stops.

**Load Condition 7**

The final loading condition is applying a pulling force of 150lbs to the wrist directed outwards as shown in Figure 56.
There are two possible points where the maximum stress can occur. The first is a shearing stress in the elbow shoulder bolts and the second is in the flat head bolts that connect the lower arm support to the wrist rotating ring. The stresses in the elbow will be distributed among two shoulder bolts dividing the load in half yielding a 75 lb force. The stresses in the wrist will be distributed between four flat head bolts dividing the load by four yielding a 37.5 lb force. The equations below compare the stresses.

\[
\sigma_{\text{Shoulder Bolt}} = \frac{F}{A} = \frac{75 \text{ lbf}}{0.0491 \text{ in}^2} = 1527.9 \text{ psi}
\]

\[
\sigma_{\text{Flat Head Bolt}} = \frac{F}{A} = \frac{37.5 \text{ lbf}}{0.0133 \text{ in}^2} = 2829.6 \text{ psi}
\]

After comparison, the 8-36 flat head bolt, with a minor diameter of 0.1299 inches (12), takes more stress therefore it is the weakest member in this loading condition. The flat head bolts have a minimum tensile strength of 144,000 psi (10). The shear strength is calculated to be 57% of the tensile strength at approximately 82,080 psi. The equation below calculates the safety factor at 29.

\[
SF = \frac{\text{Maximum Stress}}{\text{Applied Stress}}
\]

\[
SF = \frac{82,080 \text{ psi}}{2829.6 \text{ psi}} = 29
\]

Table 5 shows the list of loading conditions and their corresponding safety factors.

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>6.11</td>
</tr>
<tr>
<td>3</td>
<td>58.97</td>
</tr>
<tr>
<td>4</td>
<td>27.3</td>
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<tr>
<td>5</td>
<td>54.7</td>
</tr>
<tr>
<td>6b</td>
<td>4.72</td>
</tr>
<tr>
<td>7</td>
<td>29</td>
</tr>
</tbody>
</table>
The overall worst case scenario is loading condition 6a and its corresponding safety factor of 4.72. This safety factor meets the set design parameters of a safety factor of 4 or higher for repeated loading.

**Material selection**

Material selection was primarily based on the analysis of the forearm section previously mentioned in Figures 39-43. Preliminary materials selected for this design project were 8620 steel and 7075-T6 aluminum. 8620 is a high ware resistant steel alloy commonly used for gears, industrial clutch plates, backhoe bucket teeth and many other high friction parts. Aluminum 7075-T6 is an aircraft grade aluminum that has a 73,000 psi (13). Preliminary material consideration was to use 8620 steel for all moving parts and 7075-T6 aluminum for all supporting parts. During the initial analysis it was determined that the concept using these materials would not withstand the stressed applied. The material for moving components was changed to 4340 steel for all moving parts. While this performed better in the analysis, using 4340 steel for the moving parts did not yield an acceptable safety factor. The next step was using 4340 steel for every component. Once again the safety factor increased but was still below the acceptable range. Finally a 4140 heat treated steel alloy was used for all the components. 4140 is a tough steel alloy with a medium machinability rating. It is also capable of being heat treated to a very high strength. This change yielded an acceptable safety factor of 10.6, well above the necessary rating of 4. Final material selection for all components, moving and supporting, is 4140 steel hardened, normalized at 1600°F, reheated to 1550°F, oil quenched and tempered at 400°F. This hardened and tempered alloy will have a yield strength of 251,600 psi.

**Motor Selection**

A motor is needed to actuate two of the degrees of freedom: Shoulders’ abduction and adduction motion and elbows’ flexion and extension motion. The total arm weighs approximately 14.5 lbm. With the center of gravity approximately 10.7 inches from the fulcrum, 156 in*lbs of torque is needed to actuate the shoulders’ abduction and adduction motion. This is considered the worst case senario due to the fact that this actuation needs to lift the entire weight of the arm where as the elbows’ flexion and extension motions only actuate the weight of the forearm.

The current market for small sized, high torque motors does not suit our budget. Any motor that is rated for this torque is either too large or out of the budget range for this project.

Using a pulley system, the needed torque can be reduced. Figure 57 shows the reduction rate for the pulley system used for this actuation.
With the weight of the arm reduced to one third the actual torque needed to actuate the arm is 52 in*lbs. This equates to approximately 832 in*oz, which is the common torque unit for a small electric motor. After researching, Dynamixel RX-64 motor was selected. This motor has a torque rating of 888in*oz at 18volts. This motors’ torque rating exceeds the needed torque of 832in*oz. The motor will be mounted in a central location to both actuated motions as seen in Figure 58.

**LUBRICATION**
Moving components will be lubricated with either a dry lubricant such as graphite or a wet lubricant such as lithium grease. Possible candidate for wet lubricant is AGS® White Lithium Grease (WL-1H).
SURFACE TREATMENT
All fabricated parts will be finished with black oxide surface treatment. This will be done for the following reasons (14):

- **No dimensional changes**: The as-formed dimensions do not change (as they do when plated or painted). Black oxide is a coloring of the base metal, no metal is removed or deposited.
- **The finish will not chip, peel, flake, or rub off**: Black oxide can only be removed by mechanically or chemically removing the finish itself.
- **Reduces light glare (reflection)**: Black oxide makes an excellent finished surface for moving parts such as hand tools and machine parts. The reduction in reflectivity reduces eye fatigue and is less distracting.
- **Can be coated for additional protection**: Black oxide finishes with supplementary treatments ("after-finishes") improve the appearance, abrasion resistance, and corrosion resistance of the part to which they are applied. The normal after-finishes are Oil, Wax, Lacquer, and Chromic Seals. The part configuration and the end-use will help to determine which after-finish to specify.
- **Improved lubrication characteristics**: Black oxidized parts have improved lubricity and anti-galling characteristics due to the after-finish (oil or wax) resulting in smoother running, mating parts.
- **Color change resistant to temperature**: Black oxide finishes can be exposed to a temperature of 900 degrees F. (482 degrees C.) before the color begins to change.
- **No hydrogen embrittlement**: The black oxide process does not require an acid activation nor is it an electro-process; therefore, hydrogen embrittlement is not a factor. If the parts are scaled or rusty and an acid pickle is required, any hydrogen that may have evolved will quickly dissipate in the black oxide tank (running temp. 285 degrees F). Any remaining hydrogen will be completely dissipated within 48 hours after processing.
- **No white corrosion**: The finished part does not have a "white-corrosion" state as some electro-plated parts exhibit over time. This makes black oxide an excellent finish for parts used internally on electronic components. The small white corrosive flecks are conductive and may cause an electrical short.
## Bill of Materials

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
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<td>Wrist Rotating Joint Forearm Ring V3</td>
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</tbody>
</table>
FABRICATION
The fabrication process consisted of using several different types of machine tools to remove metal and shape the raw material into the final designs.

MATERIAL
As stated previously in the design section, the material being used for this exo-skeleton is 4140 Heat Treated and Tempered. Contrary to many beliefs is if in fact extremely difficult to machine material that has been hardened in large quantities. Certain features must be performed after hardening, however it is strongly recommended that as much of the machining is performed prior to the heat-treating. For this reason, the material that was purchased was either 4140 Annealed or Pre-Heat Treat. 4140 in the annealed state is simply cold rolled into the raw material. The majority of the flat stock used for this project was 4140 Annealed. 4140 Pre-Heat Treat was chosen for many of the round parts due to its greater stability. This material is often hot rolled and is kept at a certain temperature for a period of time to eliminate some of the internal stresses that can be formed in the rolling process. 4140 typically has a tendency of warping during machining processes due to the stresses applied from the cutting tool or holding fixture. More about this will be covered later in the report.

PARTS – WRIST ASSEMBLY
The wrist components were fabricated using both manual machining methods. The most complicated machining processes in this project occurred in the wrist joint. Beginning at the furthest out point, the palm support features were made from several pieces of round stock. Tongue and groove features were machined using a manual vertical mill and the same time the holes were drilled and reamed for the hinge pins. The threaded ends of the round stock were turned down on a manual lathe to the major diameter of the thread and finally, using a die handles the external threads were put on by hand, aligning the features using the tailstock of the lathe. Figure 60-65 show some of the machining performed on these components.
The next component in the system is the Wrist Ball Joint Mount. This was machined out of a piece of 4140 annealed bar stock. These components were machined square as one long piece and then cut into two pieces. The term machined square simply means that all the sides are now parallel and perpendicular with each other. This is critical when machining precision parts because without square surfaces there is no accurate way to locate datums and machine important features. The easiest method for fabricating this part was to put the hole features in first using the datums in the print, and finally machining the slot to size. This ensured the hole locations were accurate because there was enough of the part to hold onto to fixture the part in the vice securely. Figures 67-71 show the fabrication of these parts. Figure 72 shows the fabricator using gage blocks to measure the width of the slot.
Figure 67 – Ball joint mount blanks

Figure 68 – Ball joint mount roughing slot

Figure 69 – Ball joint mounts with holes

Figure 70 – Ball joint mount finishing slot

Figure 71 – Ball joint mount roughed slot

Figure 72 – Ball joint mount measuring
These pieces are assembled into a wrist-palm assembly shown in Figures 73-76. This assembly was fastened together using mostly pins. These pins held each component together due to the press fit and slip fit call outs on all of the holes.

Figure 73 – Ball joint moint and ball joint rod end

Figure 74 – Inserting Ball joint into ball joint mount

Figure 75 – Swivel action of ball joint

Figure 76 – Wrist – Palm assembly
The rotating wrist pieces were fabricated with both CNC and manual lathes as well as a CNC vertical mill. The lower wrist rotating ring was turned on a manual mill for the outer dimensions as well as for a hole that was close to the final dimension of the wrist cut out. The holes and wrist cut out was done in a later operation in the vertical mill using a disposable fixture plate. A disposable fixture plate is simply a flat piece of metal in which you mount the part to be machined onto. During the machining process the machine will cut into the disposable fixture plate. This is a cheap and efficient way to hold a part for machining and ensure good dimensions. Some of these fabrication techniques can be seen in Figures 77-81.

Figure 77 – Lower rotating ring on manual lathe

Figure 78 – Lower rotating ring profile

Figure 79 – Proto-Trak vertical milling system

Figure 80 – Lower rotating ring on disposable fixture before machining
The upper rotating ring was fabricated using a Mori Seiki CNC lathe with live tooling. Using this machine was the easiest way to machine all the critical features in this part without tedious gaging and setup work. This Mori Seiki lathe had a restriction to the movement of the live tooling so one secondary set up was required on the Haas Tool Room Mill to cut down the features to mount to the elbow components. The Mori Seiki lathe was also used to fabricate the wrist clamp rings These fabrication steps can be seen in Figure 82-88.
The wrist clamping mechanism included the clamp rings, clamping lever and wire clasp which was simply stainless steel welding wire bent into the correct shape using a rough fixture seen in Figure 88. The clamp rings are seen above in Figure 84 after the first machining operation. After the turning operation these rings were drilled and scribed to be cut on a band saw. Finally, these now half rings, are filed and shaped to fit around the two wrist rotating rings. Figures 87 – 92 show these components as they were fabricated.
Figure 87 – Clasp Lever fitting on clamping ring

Figure 88 – Wire Clasp fixture

Figure 89 – Bent wire clasp

Figure 90 – Clasp assembly

Figure 91 – Fitting the Clamp half-rings

Figure 92 – Completed wrist rotating assembly
PARTS – ELBOW ASSEMBLY
The elbow components were fabricated using various milling and grinding operations. The two components that make up the elbow joint had several operations before they were finish machined using disposable fixture plates. These preliminary operations included grinding, drilling, reaming and tapping using CNC controls to locate the holes precisely. The benefit to machining all the holes in a flat part before milling out the shape is that the holes can be used for both location and fixtureing. The parts were precision ground square to prepare the surfaces for mating and rubbing. This precision ground surfaces provided true mounting surfaces for fixturing. Mentioned before, warping due to internal stresses caused by machining is a serious problem when working with 4140 steel. These parts are substantially longer than wide so there is a great risk of warping due to machining. This proved to be true when these parts were removed from the disposable fixture. Because the parts were fastened down to the disposable fixture securely any critical feature was machined in that flat state. The solution to fix warpage in each machined part was to simply place the part in a press and bend against the warped curve. These parts were left in the press to allow the metal to come to rest in that flat position. The longer parts needed to be pressed further past the neutral position so they could return to an equilibrium shape. Some of these fabrication pictures are shown in Figures 93-98.
Parts – Sheet Metal and Motors

There is sheet metal used as structural supports spanning from one side of the arm to the other. This support aids in the distribution of a load as well as provide a suitable surface to mount armor in the future. In this project it was mandatory to include two motors to actuate two degrees of freedom. The motor mounts were made of sheet metal as well. Figure 99 shows the motor mount which was cut using a CNC plasma cutter while Figure 100 shows a 0.250 inch thick section of sheet metal that was cut using a water-jet cutter and bent using a brake press.

In order to actuate the arm in the manor described in the design portion a spool was fabricated to go on the motor ends. Figure 101 and Figure 102 show this component.
ASSEMBLY

The assembly of the arm is designed to be modular. The entire arm composed of a total of three sub-assemblies when the user goes to mount it to their person. All components had proper tolerances so every part fit together with very little fitting at assembly required. The three sub-assemblies that compose the final assembly are the shoulder assembly, the lower arm assembly and the wrist assembly. These three modular components attach together using the clamping rings and clasp system. Figures 103-108 show the arm assembled, it being used on an operator, and some of the ranges of motion.
DESIGN ALTERATIONS

A few design modifications were made after the design portion was finished due to availability and functionality. These changes mainly occurred in the shoulder area with the motor assembly. The motor previously selected were unavailable to the team therefore the Hennkwell DC planetary gear brush motor was selected in its stead. This motor proved to be less costly and require less controller equipment. It is also stronger and performed the necessary actuation without the use of a pulley amplification system. Figure 109 shows a diagram of the motor and previously mentioned Figure 100 shows the motors mounted to the sheet metal.
TESTING

Testing this product was viewed as a success by the design team. This arm exo-skeleton did everything that the design team expected and more. This section of the report will list and describe how the product succeeded. Testing parameters are as follows:

- Have the ability to throw a baseball.
- Measure ranges of motion.

An operator was successfully able to throw a baseball using a normal range of motion with little stress on his own body.

The joints extreme positions were measured to prove if the arm in fact maintained a full range of motion. These measurements are listed in Table 6.

Table 6 – Range of Motion

<table>
<thead>
<tr>
<th>Movement</th>
<th>From Nutral Plane to End Point (deg)</th>
<th>Designed Total Motion (deg)</th>
<th>Cited Total motion (deg)</th>
<th>% Reduction in Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Flexion</td>
<td>0-115</td>
<td>126</td>
<td>240</td>
<td>-47.5%</td>
</tr>
<tr>
<td>Shoulder Extension</td>
<td>0-11</td>
<td>116</td>
<td>180</td>
<td>-35.6%</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>0-116</td>
<td>116</td>
<td>180</td>
<td>-35.6%</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
<td>0-90</td>
<td>90</td>
<td>135</td>
<td>-33.3%</td>
</tr>
<tr>
<td>Shoulder Horizontal Adduction</td>
<td>0</td>
<td>0</td>
<td>135</td>
<td>-33.3%</td>
</tr>
<tr>
<td>Shoulder Internal Rotation</td>
<td>0-70</td>
<td>110</td>
<td>110</td>
<td>0.0%</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td>0-90</td>
<td>140</td>
<td>150</td>
<td>-6.7%</td>
</tr>
<tr>
<td>Elbow Flexion and Extension</td>
<td>0-140</td>
<td>126.38</td>
<td>150</td>
<td>-15.7%</td>
</tr>
<tr>
<td>Wrist Flexion</td>
<td>0-80</td>
<td>126.38</td>
<td>150</td>
<td>-15.7%</td>
</tr>
<tr>
<td>Wrist Extension</td>
<td>0-70</td>
<td>126.38</td>
<td>150</td>
<td>-15.7%</td>
</tr>
<tr>
<td>Wrist Ulnar Deviation</td>
<td>0-30</td>
<td>22.62</td>
<td>50</td>
<td>-54.8%</td>
</tr>
<tr>
<td>Wrist Radial Deviation</td>
<td>0-20</td>
<td>165</td>
<td>160</td>
<td>3.1%</td>
</tr>
<tr>
<td>Wrist Pronation</td>
<td>0-80</td>
<td>165</td>
<td>160</td>
<td>3.1%</td>
</tr>
</tbody>
</table>

Measuring some of the ranges of motion can be shown in Figures 110-111

Figure 110 – Elbow Flexion
Figure 111 – Elbow Extension

Though there is some reduction in range of movement the design team believes that this is due to interferences with clamps and improper deburring of some parts. These ranges of motion can be increased with more design time and research and development.
• Weigh complete assembly on a scale.
The entire assembly weighs just under 15 pounds which is far below the design criteria of 50 pounds
• Time putting on and taking off.
The arm required two people, including the operator, mount onto the operator in a timely manor. However, it is certainly possible for the operator to assemble the arm himself in a slightly longer time frame.
• Time learning how to operate the system.
The design team had another student from the University of Cincinnati wear the arm and attempt to move around with it. The operator who had never used this device before was able to move freely and with a high range of motion without any instruction from the design team.
• Torque bolts with a torque wrench.
All bolts were torque down the a specification listed in Table 7. All values are in foot – pounds.

<table>
<thead>
<tr>
<th>Table 7 – Torque Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bolt Dia.</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1/4</td>
</tr>
<tr>
<td>5/16</td>
</tr>
<tr>
<td>5/16</td>
</tr>
<tr>
<td>3/8</td>
</tr>
<tr>
<td>3/8</td>
</tr>
<tr>
<td>7/16</td>
</tr>
<tr>
<td>7/16</td>
</tr>
<tr>
<td>1/2</td>
</tr>
<tr>
<td>1/2</td>
</tr>
<tr>
<td>9/16</td>
</tr>
<tr>
<td>5/8</td>
</tr>
<tr>
<td>5/8</td>
</tr>
<tr>
<td>3/4</td>
</tr>
<tr>
<td>3/4</td>
</tr>
<tr>
<td>7/8</td>
</tr>
<tr>
<td>7/8</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

Proper torque spec varies depending on the material, bolt grade or if lubrication is used such as oil, wax, or anti-seize. Always go to the manufacturer for proper torque specifications. The chart above is an approximate estimate of torque values and have not been validated for accuracy. The numbers above have been compiled from various machine builder specs and other resources.

• Measure sound level.
The sound level without the motors was very low and with the electric motors actuating the arm it did not become louder than an electric razor.
• Joints are lubricated.
All joints were lubricated with the white lithium grease specified in the design portion of this report.
SCHEDULE AND BUDGET

SCHEDULE
The full project schedule can be found in Appendix E. The blue and red dates represent the proposed date and the orange dates represent the date the event was completed. Key milestone dates are seen below in Table 8, these are the dates the event actually took place or was completed. The timeline spans from November 23, 2011 to June 8, 2012, just over 5 months.

Table 8 – Key Milestone Dates

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proof of Design Agreement</td>
<td>23-Nov</td>
</tr>
<tr>
<td>Initial Modeling</td>
<td>7-Jan</td>
</tr>
<tr>
<td>Design Freeze</td>
<td>4-Feb</td>
</tr>
<tr>
<td>Final Modeling</td>
<td>21-Feb</td>
</tr>
<tr>
<td>Material Purchase</td>
<td>12-Apr</td>
</tr>
<tr>
<td>Design Oral Presentation</td>
<td>28-Feb</td>
</tr>
<tr>
<td>Design Report</td>
<td>6-Mar</td>
</tr>
<tr>
<td>Fabrication</td>
<td>17-May</td>
</tr>
<tr>
<td>Assembly</td>
<td>17-May</td>
</tr>
<tr>
<td>Field Testing</td>
<td>17-May</td>
</tr>
<tr>
<td>Final Tuning</td>
<td>17-May</td>
</tr>
<tr>
<td>Faculty Demo</td>
<td>17-May</td>
</tr>
<tr>
<td>Final Oral Presentation</td>
<td>24-May</td>
</tr>
<tr>
<td>Final Report</td>
<td>8-Jun</td>
</tr>
</tbody>
</table>
**BUDGET**

The budget began as a compilation of estimated costs for materials, electronics, motors, wires, hardware and services. After the design phase the design team was able to adjust some of the forecasted costs taking into consideration manufacturing methods, intended machine use, motor size and number of fasteners. The final cost came out to be substantially less than the original proposal as well as under the adjusted proposal. The budget, seen in Table 9, consists of materials for fabricating, assembling and testing the prototype.

The prototype was paid for using a generous gift by the Work Force Development Agency.

<table>
<thead>
<tr>
<th>Item</th>
<th>Forecasted Cost</th>
<th>Adjusted Cost</th>
<th>Actual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Trip</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
</tr>
<tr>
<td>Batteries</td>
<td>$400.00</td>
<td>$300.00</td>
<td>$307.28</td>
</tr>
<tr>
<td>Control Electronics</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
<td>$538.48</td>
</tr>
<tr>
<td>Mounting Brackets</td>
<td>$200.00</td>
<td>$150.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Wires</td>
<td>$200.00</td>
<td>$200.00</td>
<td>$66.18</td>
</tr>
<tr>
<td>Motors (2)</td>
<td>$1,600.00</td>
<td>$1,000.00</td>
<td>$107.98</td>
</tr>
<tr>
<td><strong>SUB TOTAL</strong></td>
<td><strong>$5,400.00</strong></td>
<td><strong>$4,650.00</strong></td>
<td><strong>$2,519.92</strong></td>
</tr>
<tr>
<td>Aluminum Plate</td>
<td>$1,000.00</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Steel Round and Plate</td>
<td>$800.00</td>
<td>$1,200.00</td>
<td>$333.96</td>
</tr>
<tr>
<td>Bolts and Fasteners</td>
<td>$400.00</td>
<td>$300.00</td>
<td>$159.84</td>
</tr>
<tr>
<td>Consumable Tooling</td>
<td>$500.00</td>
<td>$400.00</td>
<td>$64.03</td>
</tr>
<tr>
<td>Machine Time</td>
<td>$2,500.00</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Heat Treating</td>
<td>$400.00</td>
<td>$200.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Mounting Apparatus</td>
<td>$250.00</td>
<td>$250.00</td>
<td>$41.63</td>
</tr>
<tr>
<td><strong>SUB TOTAL</strong></td>
<td><strong>$5,850.00</strong></td>
<td><strong>$2,350.00</strong></td>
<td><strong>$599.46</strong></td>
</tr>
<tr>
<td><strong>GRAND TOTAL</strong></td>
<td><strong>$11,250.00</strong></td>
<td><strong>$7,000.00</strong></td>
<td><strong>$3,119.38</strong></td>
</tr>
</tbody>
</table>
CONCLUSION

In conclusion this project is deemed a success. It succeeded in demonstrating that you can create an exo-skeleton system that can completely surround an operator while maintaining a full range of motion. Though some of the ranges did not completely meet the cited text, with more research and development this arm can maintain those values.

Future advancements might include further development of the shoulder to increase range of motion, reduction of part thicknesses and factors of safety to decrease the weight, and perfecting manufacturability of parts to decrease the total cost of the project.

If this project were to continue, it should be expanded into a three person team to develop the entire suit. This suit timeline is proposed at five years for a working prototype. Additional armor should be considered by a separate team utilizing clad technology to maintain a favorable strength to weight ratio.

Cost for an initial working prototype of the entire suit is estimated at $1,250,000 USD, using three team members for five years including a rough estimate for materials and tooling.
REFERENCES


This impressive breakthrough in robotics technology is being developed by Steve Jacobsen and the engineers at Sarcos; a robotics company that he founded in 1983 and was purchased by Raytheon. The engineers at Sarcos realized that this exoskeleton would require the ability to mimic the soldiers movements perfectly in order for it to be successful. Therefore, they created flexible joints so that it can adapt to the versatile movements of the human wearing it; and made it capable of performing fluid, precise tasks. The major benefits for the soldier wearing the suit is that it will make the subject faster, stronger and more resistant to fatigue. In some tests the XOS was used to lift 200 pounds repetitively for 500 repetitions before the user stopped; it should be noted that the reason for stopping was out of boredom and not due to fatigue.

The major hurdle for Sarcos is that they need to develop a continuous power source that will allow the XOS to function for 4 to 24 hours. Sarcos predicts that the first versions will be used for heavy work rather than combat until a solution to this problem can be negotiated. This type of technology makes the sci-fi world of RoboCop more realistic than we previously imagined.
Specific stats on the Trojan are as follows: 90% flexibility, 95% body coverage. The Trojan allows the wearer to drive vehicles, run full-tilt, climb stairs and conduct dive roll manoeuvres. The Trojan weighs a mere 30 pounds without the Trojan shield. The Trojan incorporates 16 different electronic functions and prototypes impregnated into its exoskeleton. Some of the Trojans key features are a laser tracking system, 5 L.E.D. light spectrums, a voice recorder, a voice activated pedometer, a digital electronic compass, built in compartments for salt tablets and morphine pills, a digital thermometer, a built in intake cooling fan which runs on solar power, a throwing and knife, a medical emergency light transponder and much more.

http://christianburns.wordpress.com/2007/02/19/trojan-suit-full-body-armor-failed-to-sell-on-ebay/

7/15/11 Trojan Suit Armor made by Troy Hurtubis
http://www.metacafe.com/watch/528600/the_trojan_suit/

Never been tested in the field
Too many gizmos
Cheap to produce
Light weight
Not powered
Covers most of the body
Near full range of motion
Durable
Not low profile
Somewhat streamlined
One man assembly
No hard limit

Appendix A2
"Robot Suit HAL" is a cyborg-type robot that can expand and improve physical capability.

When a person attempts to move, nerve signals are sent from the brain to the muscles via motoneuron, moving the musculoskeletal system as a consequence. At this moment, very weak biosignals can be detected on the surface of the skin. "HAL" catches these signals through a sensor attached on the skin of the wearer. Based on the signals obtained, the power unit is controlled to move the joint unitedly with the wearer's muscle movement, enabling to support the wearer's daily activities. This is what we call a voluntary control system that provides movement interpreting the wearer's intention from the biosignals in advance of the actual movement. Not only a voluntary control system "HAL" has, but also a robotic autonomous control system that provides human-like movement based on a robotic system which integrally work together with the autonomous control system. "HAL" is the world's first cyborg-type robot controlled by this unique Hybrid System.

"HAL" is expected to be applied in various fields such as rehabilitation support and physical training support in medical field, ADL support for disabled people, heavy labour support at factories, and rescue support at disaster sites, as well as in the entertainment field.

**HAL-8 Type-8 Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
<td>wearable robot</td>
</tr>
<tr>
<td></td>
<td>Height 1,600mm</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Full Body Type approx. 23kg</td>
</tr>
<tr>
<td></td>
<td>(Lower body approx. 15kg)</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>Battery Drive</td>
</tr>
<tr>
<td></td>
<td>Charged battery( AC100V)</td>
</tr>
<tr>
<td><strong>Continuous operating time</strong></td>
<td>Approximately 2 hours 40 minutes</td>
</tr>
<tr>
<td><strong>Motions</strong></td>
<td>Daily Activities (standing up from a chair, walking, climbing up and down stairs)</td>
</tr>
<tr>
<td></td>
<td>Hold and lift heavy objects and more...</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td>Hybrid Control System</td>
</tr>
<tr>
<td><strong>Working Environment</strong></td>
<td>Indoor and outdoor</td>
</tr>
</tbody>
</table>

- Light weight
- Near full range of motion
- Overly powered
- Expensive
- Little operator protection
- Not designed for combat
- Designed for rehab
- Easy operation
- Operating life: mediocre
- Fluid motion
- Ergonomic
- Streamline designed
- Takes load from operator


HAL Suit Cyberdyne
Berkeley Bionics, a designer and manufacturer of exoskeletons for augment human strength and endurance, has introduced a device that increases its wearer’s strength while at the same time decreasing the “metabolic cost of walking.” The demonstrated exoskeleton is comprised of two powered anthropomorphic legs, a power unit, small on-board microcomputer, and a backpack-like frame on which a variety of heavy loads can be mounted. Such a system allows the user to carry loads of up to 150 pounds with minimal physical effort, over any type of terrain for extended periods of time. According to the company, the wearer simply doesn’t feel the backpack’s weight, as the exoskeleton moves in accordance with the user movements, minimizing interaction force between the two.

http://thefutureofthings.com/video/6647/artificial-strength.html 7/15/11
Berkeley Bionics,
Eythor Bender of Berkeley Bionics brings onstage two amazing exoskeletons, HULC and eLEGS -- robotic add-ons that could one day allow a human to carry 200 pounds without tiring, or allow a wheelchair user to stand and walk. It's a powerful onstage demo, with implications for human potential of all kinds.

http://www.ted.com/talks/eythor_bender_demos_human_exoskeletons.html
7/15/11 TED Talks HULC and eLEGS

Near full range of walking motion
Expensive
Little operator protection
Not designed for combat
Designed For rehab
Easy operation
Operating life: mediocre
Fluid motion
Ergonomic
2 person use
Takes load from operator
Dean Kamen's "Luke arm"—a prosthesis named for the remarkably lifelike prosthetic worn by Luke Skywalker in Star Wars—came to the end of its two-year funding last month. Its fate now rests in the hands of the Defense Advanced Research Projects Agency (DARPA), which funded the project. If DARPA gives the project the green light—and some greenbacks—the state-of-the-art bionic arm will go into clinical trials. If all goes well, and the U.S. Food and Drug Administration gives its approval, returning veterans could be wearing the new artificial limb by next year.

The Luke arm grew out of DARPA’s Revolutionizing Prosthetics program, which was created in 2005 to fund the development of two arms. The first initiative, the four-year, US $30.4 million Revolutionizing Prosthetics contract, to be completed in 2009, led by Johns Hopkins Applied Physics Laboratory in Laurel, Md., seeks a fully functioning, neurally controlled prosthetic arm using technology that is still experimental. The latter, awarded to Deka Research and Development Corp., Kamen’s New Hampshire–based medical products company (perhaps best known for the Segway), is a two-year $18.1 million 2007 effort to give amputees an advanced prosthesis that could be available immediately "for people who want to literally strap it on and go." Kamen’s team designed the Deka arm to be controlled with noninvasive measures, using an interface a bit like a joystick.

http://spectrum.ieee.org/bio
medical/bionics/dean-
kamens-luke-arm-
prosthesis-readies-for-
clinical-trials 7/18/11
Luke arm, Dean Kamen’s

Near full range of motion
Expensive
Not designed for combat
Designed For amputees
Not easy operation
Operating life: mediocre
Non fluid motion
Looks humanoid
Not exoskeleton
A pneumatic cylinder fed with compressed-air, combined with a transmission lever system, provides balance to the load weight applied.
The cylinder force is controlled through two pneumatic circuits purposely arranged: the first one always keeps the weight system balanced; the second one provides to always keep the weight load balanced.
The operator can change the load level applying a minimum force on the gripping tool or directly on the load.

Technical characteristics of pneumatic Manipulators
Partner PS

Max weight capacity 250 Kg
Max working radius: 3400 mm
Max vertical lifting speed: 0,5 meters/second
Constant 360° rotation on the column and tooling axis
Vertical lift: 1900 mm
Control system: solely pneumatic
Supply: filtrated compressed-air (40 µm), not lubricated
Working pressure: 0.7 ÷ 0.8 Mpa
Working temperature: from +0° to +45° C
Noise level: <70 dB
Consumption: from 30 Nl ÷ 150 Nl per working cycle
The explosion-proof execution is possible according to ATEX Standard

Not exoskeleton
Limited field of motion
Good range of motion
Fluid motion
Takes load from operator
Lifts heavy loads
Easy to use
Material handling uses
Durable
Operated by one person
Hard safety limits
Expensive

http://www.dalmec.com/ing/manipulators/Industrial_manipulators_Partner_PS.html 7/18/11 Google search: Industrial Manipulator
The Mayo Clinic Elbow Brace, featuring an innovative control knob and adjustable hinge, provides exceptional stability and comfort while allowing for immobilization, static stretch or free motion option of the elbow.

The sturdy metal uprights provide stability, while the straps with aircells securely hold the brace in position which ensures patient comfort and avoid pressure points.

**The Mayo Clinic Elbow Brace Features:**

- Lock/unlock mechanism enables a rapid switch between immobilization, static stretch, and free ROM
- Calibrated control knob is easy to read and assists in monitoring therapy progress
- Repositionable hinge stops control ROM
- Universal design can be applied to right or left arm
- Size adjustment feature accommodates varying humeral/radial circumferences
- Includes Arm Sling for patient comfort
- Optional ARC™ Forearm Rotational Brace controls pronation/supination (sold separately)

---


Google search: Arm Brace

Not exoskeleton
Hard safety limits
Smooth motion
Not designed for combat
Designed for rehab
Low power consumption
Low profile
Streamline designed
One person use
Ergonomic
Expensive
Myomo® is a new generation medical device company that has combined innovative robotics technology with leading rehabilitation expertise to revolutionize stroke therapy. Myomo’s technology was originally developed at Massachusetts Institute of Technology (MIT) in collaboration with medical experts affiliated with Harvard Medical School. Its rehabilitation professionals have been trained at the best hospitals in the country including, Rehabilitation Institute of Chicago (RIC), New York University (NYU) and UPMC.

Patented EMG (electromyography) control software continuously monitors and senses, but does not stimulate, the affected muscles. The patient self-initiates and achieves natural movement patterns by their own muscular signals that indicate intention to move. The system senses even a very weak EMG muscle signal and then processes data to a motor on the device that enables desired motion. This processing occurs so quickly that it is not apparent to the patient. Importantly, EMG-driven robotics requires that patients are actively engaged throughout the therapy session; if they stop, the device stops. No electrical stimulation or invasive procedures are employed.

http://www.myomo.com/  7/18/11 Google search: MYOMO

Not exoskeleton
Hard safety limits
Not designed for combat
Designed for rehab
Low power consumption
One person use
Ergonomic
Expensive
Uses operators brain signals to control.

Appendix A9
Interview with customer, August 4, 2011  
First Lieutenant Brent Kreckman USMC Pilot 7157 Pine Blossom Rd. Milton Florida 32570 (937) 631-8994

Power source needs to be cheap  
Infantry less prone to have a full suit  
(Person) Needs to be mobile all the time  
Needs to be low profile  
Carries 150 lbs. Guns, food, supplies, ammo, armor (20-40lbs),  
Could drop it if needed (disposable, cheap)

Combat engineers: mine clearing, building Forward Operating Base  
Motion common for combat engineers: getting up and down a lot, overall small size, to get closer to disarm explosives,  
Bomb workers: needs fast motion, normal range of motion, easy and fast assembly of suit, suit needs little maintenance must be simple, make sure it doesn’t make the user excessively large, hands completely free with full range of motion,  
Armor now is very restrictive, hard to move with current armor, hard to throw a grenade.

Be able to hold a M16/M4 (collapsible but stock) rifle, may have a three point sling.  
Arms to bring the rifle up to shoot and aim. Keep the butt stock against the armpit/shoulder.  
Elbows and knees see the most ware and tare from getting up and down.
APPENDIX B - SURVEY

Assisted Robotic Exo-Skeleton (A.R.E.S.)
CUSTOMER SURVEY

The project is to develop a portion of an external skeletal structure in which to later mount armor to. This proof of concept design will focus on protecting the arm of an operator in hostile environments, not give it super strength. By answering these questions below you will help determine the relative importance of each feature.

How important is each feature to you for the design of an exo-skeleton?
Please circle the appropriate answer. 1 = low importance  5 = high importance

<table>
<thead>
<tr>
<th>Feature</th>
<th>1</th>
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<th>3</th>
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<td>3</td>
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<td>5(1)</td>
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</tbody>
</table>

If you would like to donate or have any questions, please contact Nick Plataniotis or Frank Ricciardi for further information. Any contribution would be greatly appreciated.

Nick Plataniotis – platanna@mail.uc.edu
Frank Ricciardi – ricciafn@mail.uc.edu

Thank you for your time.
## APPENDIX C - QFD

<table>
<thead>
<tr>
<th>Feature</th>
<th>Force to change directions (in-lbs)</th>
<th>Range of Motion (deg.)</th>
<th>Safety Factor (#)</th>
<th>Weight (lb)</th>
<th>Sensors or switches (y/n)</th>
<th>Training Time (hrs.)</th>
<th>Modular Assembly (y/n)</th>
<th>Cost ($)</th>
<th>Drive system Contained (y/n)</th>
<th>Assembly/ Maintenance (# of people)</th>
<th>Cost to Operator Protected (y/n)</th>
<th>Operator Protected (y/n)</th>
<th>Decibel level (db)</th>
<th>Customer Importance</th>
<th>Designer’s Multiplier</th>
<th>Modified Importance</th>
<th>Relative weight</th>
<th>Relative weight %</th>
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</table>

Frank Ricciardi Nick Plataniotis (A.R.E.S.) Assisted Robotic Exo-Skeleton (arm) 9 = Strong 3 = Moderate 1 = Weak

Appendix C1
Product Objectives

Assisted Robotic Exo-Skeleton (A.R.E.S.)

The following is a list of product objectives and how they will be obtained or measured to ensure that the goal of the project was met. The product objectives will focus on a portion of an exo-skeleton suit. We are focusing on the right arm. The project is to design an adequate skeletal structure to protect the operator. The prototype arm will not be customizable and will be designed for a specific individual. The arm will not have power enhancing features, but it will be motorized enough to hold its own weight including estimated armor weight.

Normal Range of Motion (11%)
- Normal ranges of motion will be referenced from cited texts.

Smooth Motion (10%)
- Joints will be lubricated.
- Moving parts will not contact others causing them to bind.

Easy to Repair/ Maintain (10%)
- All fasteners will be bought and not made.
- Parts will not be welded.
- Sections will be modular.
- Quick connect electronic connectors will be used.

Safe for the operator/bystanders (10%)
- Pinch points will be designed out or the operator will be guarded against them.
- An Emergency Stop will be included.
- Hard safety stops will be included into the joints to prevent hyperextension.

Be Durable (10%)
- Fasteners will be Grade 8 or equivalent.
- Correct materials will be chosen according to the design loads.
- Loctite will be applied to the fasteners to prevent them from backing out.
- A factor of safety agreeing with cited texts.
- All bolts will be tightened to the allowable torque in cited texts.
- Electrical connections will be soldered and then covered with heat wrap if needed.

Be Light Weight (9%)
- The arm will weigh less than 50 pounds, excluding armor.

Easy to Operate (9%)
• Approximately 3 hours of training will be enough to qualify someone to be able to use it.
• No more than two people will be needed to assemble and put on the hardware.
• It will be easily controlled through sensors or switches.

**Have an ergonomic fit (9%)**
• The operator will be protected from coming in contact with the hardware.

**Loudness (8%)**
• The arm will be no louder than an electric shaver.

**Have a Compact Design (8%)**
• All drive and control systems will be contained in the skeleton.

**Low Cost (6%)**
• Easily obtainable materials and fasteners such as steel or aluminum will be used for construction.
## APPENDIX E - SCHEDULE

### Tasks

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<th>Task</th>
<th>Start Date</th>
<th>End Date</th>
<th>Duration</th>
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<td>Proof of Design to Advisor</td>
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<td>Concept Sketches to Advisor</td>
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<td>Initial Solid Modeling</td>
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<td>Assemble</td>
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## APPENDIX F – BUDGET

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### APPENDIX G – BILL OF MATERIALS

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NOTE: WaterJet

8X ø .177

3.750
3.438
3.063
2.750

1.000
.688
.313
0

2.50 1.250 2.200 3.200 4.851 5.851 6.802 7.802 8.052

R.25 TYP

.250
Appendix H7

Cut as Ring
Perform Cutout on Mill

DETAIL B
SCALE 2 : 1

DETAIL A
SCALE 2 : 1

1/16 Drill
Cut out by hand

R2.657
2.488
0.790

R2.533
2.592
0.125

0.210

0.210

0.125

0.500 ±0.002

+0.002

0.250

0.000

0.063
Reamed

0.125

R0.13
O.K. by hand

Material

NOTE: DRAWN TO SCALE OF 2:1
2X Ø .156 THRU
Reamed 180° Apart

4X Ø .136 THRU
8-36 UNF

.188 Centered
NOTE: WaterJet
2X Ø0.063 THRU
Reamed or Roll Pinned

0.043
0.325
0.200
0.025

Appendix H25
Appendix H26