2012

Impact tactor design and research for creating consequence in virtual military training

David Prater
Iowa State University

Recommended Citation

Prater, David, "Impact tactor design and research for creating consequence in virtual military training" (2012). *Graduate Theses and Dissertations*. 12896.
http://lib.dr.iastate.edu/etd/12896

Impact tactor design and research for creating consequence in virtual military training

by

David A. Prater

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Human Computer Interaction

Program of Study Committee:
Stephen Gilbert, Co-major Professor
James Oliver, Co-major Professor
Eliot Winer

Iowa State University

Ames, Iowa

2012

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

ABSTRACT

Current force-on-force military training simulators lack one major quality that is needed to impart a lasting impression on soldiers: the consequence of getting shot. This thesis presents one such solution to providing that necessary feedback in the form of a Tactical Tactile Training Vest (T3V) design and prototype. The T3V is equipped with torso-based haptic tactors, meant to be used in a mixed-reality training simulator as a feedback device and research platform for further work.

The tactile vest is equipped to provide an impact sensation intended to be a surprising disincentive. Assuming that a “surprise” is made up of an intense stimulus over a duration of time, it is assumed that a surprising physical hit can be classified as an impact—a force over a duration of time. Where other researchers specified a time duration needed for a “surprising” stimulus, this research presents a novel tactor capable of adjustable force with an expectation that a higher impact will yield a higher quality of attention grabbing disincentive.

With the use of a device like this, the teaching model for state-of-the art virtual reality training facilities can be changed from an outdated corrective feedback training approach to a consequential feedback model, whereby trainees are forced to consider why an action is important, instead of just how and when to perform an action. The results of this research outlines the design and testing of the specific impact tactors and controlling systems designed for this application and outlines the best parameters for safe and effective operation.

CHAPTER 1. OVERVIEW

Introduction

The more mistakes a soldier can make during training, the less likely he or she will make them when it counts. By this philosophy, in order for troops to come home safely, they must be (virtually) shot in training. This thesis is focused on designing a tactile vest to be used in a mixed-reality military training simulator, employing a specially designed impact tactor which is able to provide a strong disincentive—an indicator that the trainee has just been shot. The need for the technology as well as specific design of the impact tactor and garment, are all discussed in detail below.

LVC Training/the Veldt

The new paradigm in military training is in mixed-reality virtual environments, where trainees can work in conjunction with, or fight against live, virtual, or constructive (LVC) entities, where “virtual” refers to avatars controlled directly by other people, and “constructive” entities are those that are controlled by artificial intelligence. This model is called LVC training (Karr, Reece, & Franceschini, 1997). In an effort to advance (LVC) military training, and partnering with the United States Army Research, Development and Engineering Command (RDECOM), Iowa State University’s Virtual Reality Applications Center (VRAC) developed “The Veldt”, a mixed-reality combat tactics and military engagement trainer (Newendorp et al., 2011; Pollock, Winer, Gilbert, & De La Cruz, 2012). Participants work their way through different scenarios, toting mock M4 rifles, and are tracked optically in three dimensions. The scenarios were designed for dismounted troops who routinely monitor checkpoints or clear rooms in close quarter alleyways, or are otherwise on foot and in the line of fire. Staying true to the title of LVC training, the Veldt makes it possible for participants to engage live, virtual, or constructive targets. Similarly a trainee can also work cooperatively with live, virtual or constructive entities.

The Veldt was designed to be reconfigurable for a multitude of different combat missions, so that in 20 minutes time, the scenario can be changed from a tight Iraqi alley to an open Afghan street scene. The advantage of the Veldt is in the use of artificial intelligence and digitally represented entities. Normally, in military exercises, live role players are dressed up to represent enemy fighters or civilian bystanders. By allowing those characters to be represented digitally, both time and money can be saved in running a training exercise, and scenarios can be highly customized, teaching more than just combat.

Since the Veldt and other types of military training simulators are ultimately trying to teach specific lessons, it is important to define the type of learning model for the exercises. Trainees can either be taught with corrective feedback, or consequential feedback. In terms of military training, corrective feedback would be an After Action Report (AAR), in which a commanding officer would break down what happened during an exercise, and identify what could be done differently. Consequential feedback is a more exploratory approach to teaching and allows mistakes to happen (Smith & Ntuen, 1999). For instance in training, a soldier could be allowed to be shot, but must be able to reflect on his or her own mistakes, and must also be allowed the time to re-practice what was learned from the original mistake. “The aspects of immediate feedback plus the consequence of a bit of pain when you make a mistake combine to equal something in force on force training that no other tool can provide. It is one thing to play laser tag and have your buzzer go off. It is another to get smacked by something that gets your attention.” (Johnson, n.d.)

Training Model

The consequential feedback teaching model takes more time per trainee, but those who learn in this way are more likely to think conceptually about what the right approach is (Smith & Ntuen, 1999), which I would argue does a better job at teaching right and ethical decisions, which is a critical trait that our deployed soldiers need to have.

This consequential feedback model is the seed of this thesis. Participants training in the Veldt needed to know if and when they are shot, otherwise they would not get the immediate feedback that is necessary for retaining lessons learned (Dihoff, Brosvic, Epstein, & Cook, 2010), especially in the high-stresses of tactical training.

The Tactical Tactile Training Vest

The Tactical Tactile Training Vest (T3V) designed for the Veldt started as a “you’ve been hit” indicator and was later expanded to be adaptable for other types of experiments in the Veldt, both combat-oriented and otherwise.

Three different systems were designed for the T3V, to work in harmony to further immerse the trainee in the mixed-reality environment: 1) Impact tactors to indicate whether a soldier has been shot or otherwise received bodily harm, along with the direction of fire; 2) an array of vibration motors in a band around the trainee's midsection; and 3) an array of four speakers located in front, back and on each shoulder on the T3V, providing personalized 3-dimensional sound. Paired with the 3D sound in the Veldt, the speakers can be used to provide tactical information like where a sniper shot originated, or immersive cues like the sounds of a virtual car driving through a real space, which is intrinsically different for each participant. The band of vibration motors are not meant to simulate a real stimulus, but are meant to be able to provide spatial cues that are intrinsically lost in a mixed or virtual reality environment, like one's sense of direction. This thesis discusses the vision for the T3V and the integration of the three different systems, but the primary research focuses on the dynamics of the impact tactor in an effort to increase the force with which the tactor transfers to the body of the trainee.

Structure

Following the introduction of this thesis, prior research is discussed in *Chapter 2: Review of Literature*. *Chapter 3: Methods and Procedures* will outline and discuss the different tactor designs, prototypes and supporting systems and the equipment that was used to carry out the impact tactor tests. The results of the testing are presented in *Chapter 4: Results*, and the discussion of results is found in *Chapter 5: Summary and Discussion*. The test plan and data can be found in the Appendices.

CHAPTER 2. REVIEW OF LITERATURE

Introduction

The basic goal of this thesis is aimed at training today's warfighter more effectively, and with fewer resources. Effective training however, does not just refer to training for combat situations, but also for preparing a soldier for the lifestyle of war, and also re-integrating that soldier back into society after active duty.

Training in Virtual Reality

Virtual reality training has recently become a part of many soldiers' training regimen (Hickey, 2007; Wilson, 2008). Virtual reality exposure therapy has even been shown to reduce post traumatic stress disorder (PTSD) symptoms in soldiers returning from the front lines of war (Gerardi, Rothbaum, Ressler, Heekin, & Rizzo, 2008; Wilson, 2008), and it is theorized that a high level of immersion and a strong illusion of presence in a virtual reality environment contributes to the success of this therapy. Immersion is defined as "…the number of the users' senses that are provided with input and the degree to which inputs from the physical environment are 'shut out'"(Lombard & Ditton, 1997). With regard to a mixed-reality environment however, I would re-phrase the last part of Lombard's sentence by saying that immersion is the number of the users' senses that are provided with input and the degree to which inputs from the physical environment *pertain* to the virtual world. Similarly, Schuemie paraphrases Lombard's quote as: "presence as… …immersion, the extent to which the senses are engaged by the mediated environment…"(Schuemie, Van Der Straaten, Krijn, & Van Der Mast, 2001).

In November 2007, a high-tech mixed-reality immersive military training simulator, the Infantry Immersion Trainer (IIT) was launched at the Marine Corps Base Camp Pendleton, California (Babb, n.d.). Two years after the launch of the IIT, the Public Broadcast Service aired a show on *Dateline* about virtual training, highlighting the IIT. Indirectly identifying both the reasoning for the Veldt and for the T3V are two different quotes taken from one of the *Dateline* videos posted by PBS on their website. At 1:35 minutes into the video, Tom Buscemi, the director of the First Marine Expeditionary Force Simulation Center is speaking about Camp Pendleton's IIT, saying, "We want to inoculate the Marine with the sights, sounds, smells and chaos of close-quarters battle, so that his first firefight, or his next firefight is no worse than his last simulation."("Waging War - Immersion Training | Digital Nation | FRONTLINE | PBS," n.d.) 3:23 minutes into the same video, young Marine remarks, "Ultimately, you know that nobody's going to shoot back at you in there" (meaning inside of the IIT.)

The IIT may look, sound, and it may even smell like an Afghan or Iraqi village, but according to Lombard's explanation of presence and the account from the young Marine in the *Dateline* video, the IIT is lacking in stimulating certain important senses and the ability to make soldiers feel physically threatened. Soldiers can feel objects in the mixed reality space and there is certainly a tactile feedback coming from moving through a real environment or kicking in a door, but the lack of consequential tactile feedback, beyond just an After Action Report (AAR) style corrective feedback in a mixed-reality training facility is truly necessary to make the most out of the training.

The Consequential Training Model

In order to compare the T3V to previous approaches, it is necessary to understand the consequential training model. It is partly because of this supported training model that makes the T3V unique. In the realm of a virtual or mixed reality military training simulator, consequential training could be defined as allowing a trainee to be virtually shot or wounded, where corrective feedback would tell a trainee for example, not to stand in the middle of the street, but to take cover in a tactical stance. Consequential training actually takes more time, and more mistakes are made by each participant than by using a corrective feedback training strategy (Smith & Ntuen, 1999), and previous research argued that a learning approach should be designed to prevent errors, in order to increase positive reinforcement in learning (Skinner, 1953). However, training with error management instructions has been proven to yield a higher performance than both training without the ability to make errors at all, or training without error management instructions (Heimbeck, Frese, Sonnentag, & Keith, 2003). Here, error management instructions were defined as encouragement to make mistakes and learn from them. Participants who were guided by step-by-step instructions, avoiding the possibility for mistakes often completed tasks in less time, which agrees with Smith and Ntuen's research, but this was because “time-consuming errors did not occur as in the other two groups” (Heimbeck et al., 2003). Thus, a trainee must be able to make mistakes, but it must also be made clear to the trainee that errors are to be learned from. For example, a trainee should be allowed to be virtually shot, or wounded, to engrain the need for cover or taking a tactical stance. Similarly though, more time should be allotted for each trainee to make the mistakes necessary to adequately learn the lessons at hand.

This thesis focuses on a device that is meant to escalate a corrective feedback-based mixed reality military training simulator to a consequential feedback learning model. This consequential feedback is the sense of being shot, portrayed by impact tactors mounted on a tactile vest. Beyond this initial scope though, the T3V was recognized as a possible research platform for other types of tactors. For this reason, the T3V was also equipped with a band of vibrotactile motors for future studies such as for a navigational aid and wayfinding. Future topics of study are discussed further in Chapter 5.

Simulated Return Fire

There are several different types of simulated return-fire systems being developed and tested for different purposes including military, police and entertainment. Some systems use actual projectiles (Johnson, n.d.; “Patent US5980254 - Electronically controlled weapons range with return fire - Google Patents,” n.d., “Waging War - Immersion Training | Digital Nation | FRONTLINE | PBS,” n.d.) and others use locally worn tactors (Corley, 2010; “Threat-Fire^{TM} | Virtra,” n.d., “TN Games,” n.d.). The Veldt at Iowa State University was designed to be used with virtual firepower instead of actual projectiles in order to preserve the expensive equipment required to run the scenarios however, when the training situation permits, Simunition® can also be a desirable option (Johnson, n.d.). What virtual training inherently can provide over Simunition® though is recorded and reviewable four dimensional data for after action reviews.

The Threat-Fire™ designed by Virtra actually delivers an electric shock to the participant (“Threat-Fire^{TM} | Virtra,” n.d.). However effective this system may be, this concept was not pursued because of the perceived detrimental impacts this could have to physiological testing equipment. The Threat-Fire™ however, also operates in a vibration-mode, as well as other tactile vests described below. Aimed at increasing the stress level of simulated return-fire though, a vibratory feedback was ruled out since it was expected that the message communicated by a vibration would not portray the urgency or magnitude of an event like being shot. “It is one thing to play laser tag and have your buzzer go off. It is another to get smacked by something that gets your attention.” (Johnson, n.d.) Thus, the simulated return fire for an environment like the Veldt requires a physical impact form of feedback.

Tactile Vests

Similar tactile vests have been constructed, but none quite like the Tactical Tactile Training Vest (T3V), which is the prototype tactile vest that was built for this thesis and is discussed herein. Many different torso-based tactile garments have been developed both commercially and for research. Some of those similar garments are: the “3RD Space Vest” from TN Games(“TN Games,” n.d.), the “Tactile Gaming Vest” (TGV) designed by students at the University of Pennsylvania (Corley, 2010), and different tactile feedback vests designed by researchers at the University of California, Los Angeles Center for Advanced Surgical and Interventional Technology (Wu et al., 2010), researchers at Massachusetts Institute of Technology (MIT) (L.A. Jones, Lockyer, & Piateski, 2006), and the University of Michigan (U Mich), Ann Arbor (Beom-Chan Lee, Shu Chen, & Sienko, 2011). See Table 1. Comparison of tactile garments for a comparison of the tactors used in these vests.

The 3RD Space Vest (“TN Games,” n.d.) and the Tactile Gaming Vest (personal communication, February 3, 2011) are focused on gaming and entertainment in purely virtual first-person type computer games. Both the tactile feedback vest from UCLA and the tactile band from the University of Michigan were developed purely for research for patients with vestibular disorders (Beom-Chan Lee et al., 2011; Wu et al., 2010), and the pattern recognition tactile array from MIT was designed to be a navigation aid (L.A. Jones et al., 2006). Many of these tactile garments employ some of the same style vibrotactile motors in some way. The TGV uses solenoid-driven impact tactors to induce a disincentive.

The TGV also used a peltier element as a unique type of tactor in an effort to induce a sensory illusion of burning, by creating regions of hot and cold side-by-side (personal communication, February 3, 2011) however, the time delay of the element was too great and did not create enough of a sensation to be recommended.

Table 1. Comparison of tactile garments

Type of Tactor	T3V	TGV	3RD Space Vest	UCLA tactile vest	MIT tactile band	U Mich tactile band
Vibrotactile Motors	X	X			X	X
Electromagnetic Impact Tactor	X	X				
Pneumatic Tactor			X	X		
Peltier Element		X				

It is worth noting that although the T3V does include tactors that could be used to indicate spatial cues with vibration, the primary intent of the vest is impact simulation, and thus this review of previous work focuses primarily on other systems with a similar goal. However, there is a long history of vibrotactile displays that were designed primarily for navigation (L.A. Jones et al., 2006; Lynette A. Jones & Sarter, 2008; Marston, Loomis, Klatzky, & Golledge, 2007; Wu et al., 2010).

In 2007, a patent was filed in 2007 for a “Tactile Wearable Gaming Device” which describes two 4x4 grids of pneumatic impact tactors affixed to the front and back of a vest. Named first on the list of inventors is Mark Ombrellaro, the President and CEO of TN Games (Ombrellaro, Soto, Morris, Kelly, & Ombrellaro, n.d.; “TN Games | News | Bullet-proof: GameZone chats with TN Games’ Mark Ombrellaro,” n.d.) This concept, uses inflating balloon-type tactors, dissimilar to the novel impact tactors described here.

The intent of the T3V is to be used in a physically demanding and high-stress military training simulator. The 3rd Space Vest is low profile, but is not readily portable and leaves the user wanting more of a punch (personal communication, February 3, 2011).

In the 1980s, the United States Military introduced the Multiple Integrated Laser Engagement System (MILES), which is a system worn by soldiers and affixed to weapons to either transmit or receive infrared “bullets,” acting as signals to a system that, during a training exercise, indicate whether or not a soldier has been hit. Actual firearms were used, but with blank cartridges, adding to the realism of the exercise, however the exercises required large training sites and the MILES system was only usable with live combatants in force-on-force operations (it was later expanded to include sensors on vehicles to simulate vehicle health.) The feedback of the MILES system has had several iterations, but mainly uses a high-pitched buzzing noise meant as an irritant. Earlier versions required a hit trainee to lie on his or her back to deactivate the noise. Current versions require a special key which is worn by trainees on their gear, and if hit, the key is inserted into the emitter attached to the muzzle of the trainee's weapon, stopping the sound and "disabling" the weapon. Also often used with the MILES gear were "condition cards" which were handed out by exercise observer/controllers. Condition cards were handed out to simulate different types of injuries (LaBarge, n.d.).

MILES is still used today, but is to be replaced in 2012 by a new system with much more functionality, the Instrumented-Tactical Engagement Simulation System (I-TESS) II. According to defensenews.com, the I-TESS II will be able to differentiate between wounding hits and kills, where MILES could only automatically communicate a "kill" if hit. The I-TESS system is also expected to provide real-time data for immediate After Action Review (AAR), like the T3V would also support, but what I-TESS may be missing is both the ease of integration into virtual or mixed reality training environments, and a physical disincentive appropriate to the exercise.

The disincentive of the impact tactor designed in the T3V is what sets it apart from all other training vests, including the high mobility of the entire system. With its low profile design, the T3V can be worn in a high-activity training scenario like the MILES system, but picking up where MILES left off, the T3V is designed to give startling feedback, instead of just annoying. Also unique to this research is the focus on the force of the impact sensation. An impact is defined as a force over a duration of time. The researchers at UPenn defined an appropriate duration to induce this sensation, and this research defines a system capable of varying the force. This physical sensation is a small detail, but is necessary to increase the stress of virtual and mixed reality training simulators to prepare warfighters for actual engagement.

CHAPTER 3. METHODS AND PROCEDURES

The scope of this thesis is to develop a modular design for a tactile vest used in a mixed-reality military training simulator. For this design, an impact tactor needed to be identified or otherwise designed to be able to induce a “surprising” sensation to the trainee. Since the VRAC’s Veldt is meant to be a research platform, it is also expected that the Tactical Tactile Training Vest also be a platform for research. To foster future research with the T3V, other types of tactors may also be necessary. These supplementary tactors could be used to test tactile or otherwise non-visual approaches to wayfinding or threat recognition under the stress of a military combat simulator, or simply to increase the sense of immersion of the Veldt.

Introduction

The approach taken to create the T3V was to identify, design and build the individual tactors, test them, and then integrate them into the vest. The majority of the time spent was in developing the impact tactor since the initial purpose of the vest was to indicate whether or not a trainee had been “shot.” Further effort was spent outlining the possible future uses for the T3V and what features would make the device more flexible for future research.

The Tactical Tactile Training Vest

Platform

Showcased at the 2010 I/ITSEC conference in Orlando, Florida was one of Qinetiq's © prototype tactile garment, using an array of vibrotactile motors built into an Under Armour© shirt. While a form-fitting shirt is a good platform in which to imbed vibrating tactors, it would not be a suitable platform on which to mount other larger haptic devices, such as impact tactors or large circuit boards. For this reason, the tactile vest was built into a larger platform—a tactical vest, similar to what soldiers wear as tactical protection, otherwise known as a plate carrier or bullet-proof vest. A plate carrier is meant to be worn snug and close to the skin, and is meant to be robust and be able to carry an array of different types of gear from rifle magazines to radios to hydration equipment and medical kits. Instead of an actual plate carrier, a

Figure 1: The T3V and wooden insert with a mounted impact tactor

less expensive mock plate carrier was used. 3/8” sheets of plywood were cut to the correct size and shape to be inserted into the vest on the front and back. It was on these plates that the impact tactors were mounted.

Impact tactor

The impact tactor was designed from the ground up for the T3V. The 3RD Space Vest from TN Games and the Tactile Gaming Vest designed by students at the University of Pennsylvania use pneumatic bladders or solenoids as impact tactors, respectively. For a military application however, a new design was needed: a design that was portable, low-profile, and one that delivered an immediate and succinct feedback that a soldier would immediately recognize. The eight air bags (four in front, four in back) in the 3RD Space Vest are low profile and cover a large area of the torso, but there are some drawbacks: The air compressor needed to power the vest is loud (Kuchenbecker, personal communication, February 3, 2011), and is not readily portable. The housing requirements are also restrictive to this type of tactor driver because of the constant need to draw in air.

The Tactile Gaming Vest at the University of Pennsylvania was created for augmenting movies and theme park type rides. After having tested the 3RD Space Vest, researchers Dr. Katherine Kuchenbecker and Saurabh Palan wanted a better quality of sensation, and didn’t want it to be so loud and cumbersome. They also never wanted to induce pain. The researchers at the University of Pennsylvania also distinguished between an “impact,” and a “poke.” If an impact lasts too long, it will feel more like a “finger poke,” so in order to make the sensation feel more like an impact, Kuchenbecker recommended that the impact duration be kept within 100-200 milliseconds (Personal communication, February 3, 2011).

Like the TGV, this research is not meant to develop a tactor that induces pain or causes contusions, but rather induces a “surprise.” Using a similar approach to the University of Pennsylvania’s TGV, a “surprise” is defined as an impact duration between 100 and 200 milliseconds, so that there is differentiation between a succinct impact and “slowly” increasing and decreasing “poke.”

Avoiding contusions is also important in preserving the livelihood of participants. Excessive energy density of the impact is limited at 10 kilojoules/m^2 (Desmoulin & Anderson, 2011). The research done by Desmoulin and Anderson outline preliminary data for the impact requirement needed to cause bruising in live humans. Since their research was aimed at locating the threshold for where contusions are created, the lower bound of their impactor energy density (approximately 13,000 Joules/meter^2 is carried over as this impact tactor’s upper bound. The energy and energy density of the impact was tested as described below, but the duration of the actual impact was not tested and is left as an exercise for future work.

The T3V impact tactor was designed to be low-profile and hit hard enough to startle the user, but also not to induce pain. Several ideas for impact tactors were entertained, such as solenoids, acoustics, bone conducting elements, Gaussian accelerators, expanding artificial muscles or other materials that constrict/expand with current. The solenoid was initially pursued because of its fast response time, while a vibration-based impact tactor (like a speaker or bone conducting element) was assumed to require a longer actuation time to be noticed by the user, similar to how the Peltier element performed on the TGV, which didn't seem to be able to portray the urgency that was required of the "you've been shot" impact tactor. It is for this reason also, that vibrotactile motors were not used to portray the message "you've just been hit by a virtual bullet."

While defining the best impact tactor for this application, four different impact tactor prototypes were chosen or created and qualitatively tested. Quantitative testing was performed on the final prototype tactor. The design parameters used to evaluate the prototypes are outlined in Table 2.

Table 2. Impact tactor design parameters

Importance	Parameter	Definition	Metric
High	Quality of Sensation	How startling and attention grabbing is the impact?	Qualitative (Great-Poor)
	Low Profile	How protrusive is the tactor if mounted in the vest?	Profile Clearance (mm)
	Customizability	How readily customizable is the profile or quality of sensation?	Qualitative (Highly-Not at all)
	Repeatability	How repeatable is the impact?	Recovery time (seconds)
Low	Consumer Off-The-Shelf	Can the tactor and mount be readily purchased?	Yes/No

The quality of the sensation was most important compared to all other parameters because even if there was only tactor on a vest and it can only be repeated every minute, for instance, the message would still be clear that “you’ve just been hit.” Second most important was the physical envelope of the tactor and its ability to be transportable, ruggedized and kept low-profile in order to be unobtrusive during training exercises.

Impact tactor prototype 1

The first prototype created for the impact tactor was a simple consumer off-the-shelf (COTS) push-style solenoid, directed at the skin of the user. This was modeled after the impact tactor of the TGV. This tactor had a relatively poor quality of sensation, but was had a low profile as

Figure 2: Small push solenoid

seen in

Figure 2 (28mm, un-energized) and was not customizable. The reason this prototype was discarded was because of the qualitative weakness of the impact.

Impact tactor prototype 2

The second prototype was based off of the first, in that it also used a COTS solenoid, but was a much larger solenoid. The quality of sensation was qualitatively better than prototype 1, but it had a very large envelope (58mm un-energized) as seen in Figure 3. It was assumed that a vest worn in a high-activity scenario with impact tactors that protruded so far from the mounting surface of the vest would be too obtrusive. Additionally, it was feared that the tactor could be damaged if a trainee bumped up against a wall while working through a scenario, which was enough of a reason to explore other prototypes.

Figure 3: Large push solenoid

Impact tactor prototype 3

The third prototype was an exploratory proof of concept based off of a Gaussian accelerator. A Gaussian accelerator is made up of at least three ferric ball bearings and high power magnets as seen in Figure 4. The basic principle of a Gaussian accelerator is that as the ball on the left approaches the magnets, it is accelerated towards the magnet because of the magnetic attraction. As the first ball impacts the magnet, the momentum is transferred through the magnet and intermediate balls, and into the ball on the far right. Partially separated from the magnetic field the last ball is able to escape the magnetic field with a high amount of energy that was accumulated by the first ball when it was accelerating toward the magnet. The mathematical principles of this model are left out as this was only a creative proof of concept. The theory of the Gaussian accelerator as an impact tactor was that the trainee would be impacted by the momentum of the last ball. This concept was thrown out because it is unrepeatable without having to manually reset the system. It took considerable force to pry the first ball off of the magnet, and to keep it from

Figure 4: Gaussian Accelerator

Figure 5: Gaussian accelerator, chipped magnets

accidentally accelerating towards the magnet. After several dozen tests of the prototype, the magnets also started to chip and break apart from the impacts of the ball bearings (Figure 5). Other concerns arose as to how the system would even be mounted in a contained unit on the vest since the horizontal orientation of the system is critical to its functionality.

Impact tactor prototype 4

The fourth prototype is a unique approach compared to the previous prototypes and all of the other impact tactors used on other tactile garments researched and discussed earlier. This tactor was based off of rail gun-type electromagnetic projectile launchers (EMPLs). These devices share the same physical principle as a solenoid, being made up of a coil of wire that, when a high voltage signal is sent through it, induces a magnetic field which accelerates a ferric projectile.

One difference between a solenoid and an EMPL however, is the power requirement. A solenoid can operate with a power source of just a few volts, but an EMPL (according to its intended use) needs anywhere from tens of volts to several thousands, applied very quickly—most effectively from a bank of capacitors. The design tradeoff however, is that the physical form of the electromagnetic projectile launcher can be tailored to the application and if certain design parameters of the coil are changed (i.e. number of turns, gauge of wire used) the power output of the tactor can be fine tuned to deliver a much harder punch. Other factors like voltage input and firing duration were also explored in an effort to increase the actual energy carried by the projectile.

Figure 6: Side-by-side comparison of EMPL coils

One major downside of the EMPL is the time it takes to charge the capacitors. With the power source, capacitor bank and boost converter described in the following sections, it took about 25 seconds to charge the capacitor bank up to the 350 volt limit. The design was still pursued however, because of the high quality of impact that was delivered to the skin, even through multiple layers of clothing.

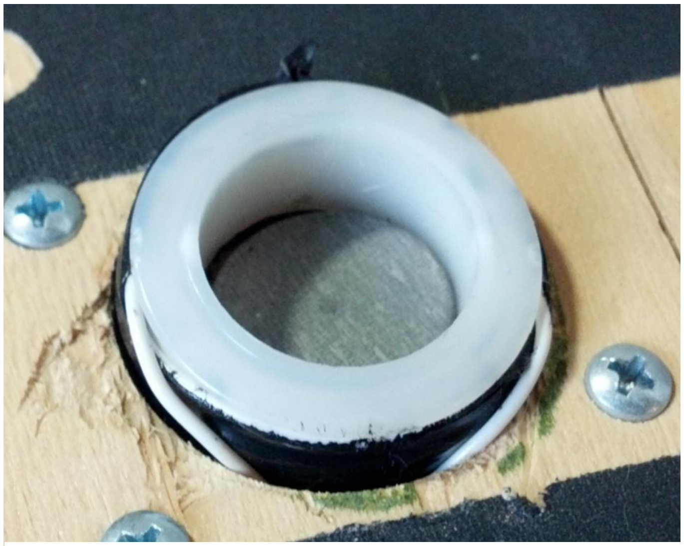


Figure 7: small EMPL coil mounted on the wooden insert

The EMPL designed for the T3V went through several different iterations and design tweaks. Several different coils were tested as seen in Figure 6.

The coils for the EMPL were wound tightly with a minor diameter of ~1” and a major diameter of ~2”. Different coils wound with 125 turns of 30 AWG magnet wire, 30 turns of braided 20 AWG insulated wire, and 25 turns of braided 16 AWG insulated wire were created and tested with the same voltage and projectile. The 30 AWG coil was not tested in the EMPL test plan since it produced such a minimal initial resulting acceleration of the projectile, most likely because of the high impedance of the coil. The plastic spools that were purchased with hookup wire used in the making of the electronics were recycled and acted as the housing for the coils.

These spools were used because their dimensions were similar to the overall desired tactor size.

In an effort to condense the electromagnetic field during firing, the coil with the 16 AWG wire was also shielded with steel pipe around the perimeter of the coil as can be seen in Figure 6.

The projectiles tested were punched out of 19 Gauge sheet steel to a diameter of 15/16” to freely pass through the 1” opening in the plastic coil housing. The projectile used throughout the EMPL test plan weighed 6.3 grams. The projectiles were roughly the size of a U.S. quarter.

The coil assembly was mounted onto the plywood inserts in the vest as seen in Figure 7. For the preliminary user study, after the EMPL test plans were carried out, a simple projectile return system was created to make the tactor more repeatable. The system was created by drilling a small hole through the middle of the projectile and by using a cotter pin to attach a one-inch long spring. The other end of the spring was attached to a thin sheet of plastic, which was fixed to the outside of the plywood insert. Unenergized and unsprung, the projectile sat flush with the closest edge of the coil.

EMPL power supply and control

The impact tactors and vibrotactile motors are controlled from the same microcontroller. The EMPL power supply and control circuitry was designed especially for this application and was made up of a power supply of eight AA batteries feeding into a boost converter circuit (as seen in Figure 8) which, in the EMPL test plan outlined in Appendix I, charges a bank of six 390uF, 450 volt capacitors, wired in parallel, up to different target voltages as seen in Figure 10. The firing mechanism between the capacitor bank and the coil is made up of an automotive relay triggered by an NPN transistor. The relay is an electromechanical switch which can handle the high power of the capacitor bank, while being electronically switched with a manageable 12 volts. The transistor itself is triggered

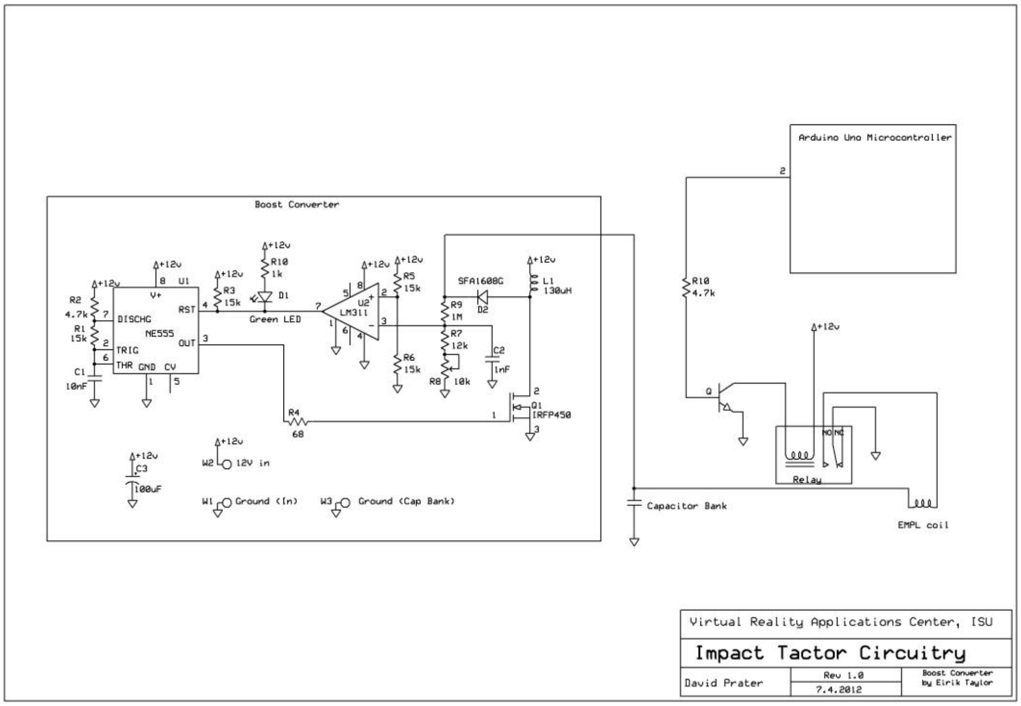


Figure 8: EMPL boost converter and firing circuitry with microcontroller

by a 5 volt signal from an Arduino Uno microcontroller. The microcontroller is powered by a 5v lithium polymer battery and communicates wirelessly to the host

```
int trigger = 2;

void setup() {

  pinMode(trigger, OUTPUT);
  digitalWrite(trigger, LOW);
  Serial.begin(9600);

}

void loop(){
  if (Serial.read() == 13){
    digitalWrite(trigger, HIGH);
    delay(25);
    digitalWrite(trigger, LOW);
    Serial.println(Serial.read());
    delay(1500);
    }
  }
```

Done compiling.

```
Binary sketch size: 2986 bytes (of a 32256 byte maximum)
```

Figure 9: Arduino microcontroller code

controller, whether it is a computer or another microcontroller via an XBee wireless chip. To prevent attenuation of the wireless signal, the power supply, circuitry, capacitor bank, and microcontroller was housed in a plastic 4” x 6” x 2” enclosure rather than a metal one.

The Arduino Uno is an open-source consumer off-the-shelf microcontroller which requires only simple coding, based on the *Processing* language. Figure 9 shows the exact code which is required to be loaded onto the Arduino Uno. In this code, the variable “trigger” is being set to the output pin 2 on the microcontroller, and when a serial command is sent which equals 13 (the ENTER key on a keyboard), pin 2 sends out a signal of 5 volts for 25 milliseconds (the delay command) which in turn delivers 12 volts to the relay, which finally delivers the voltage of the capacitors to the coil. The XBee module is required because it can perform a wireless “handshake” with another XBee module serially using the Serial.read() function as seen on the 7th, 12th and 16th lines of code in Figure 2.

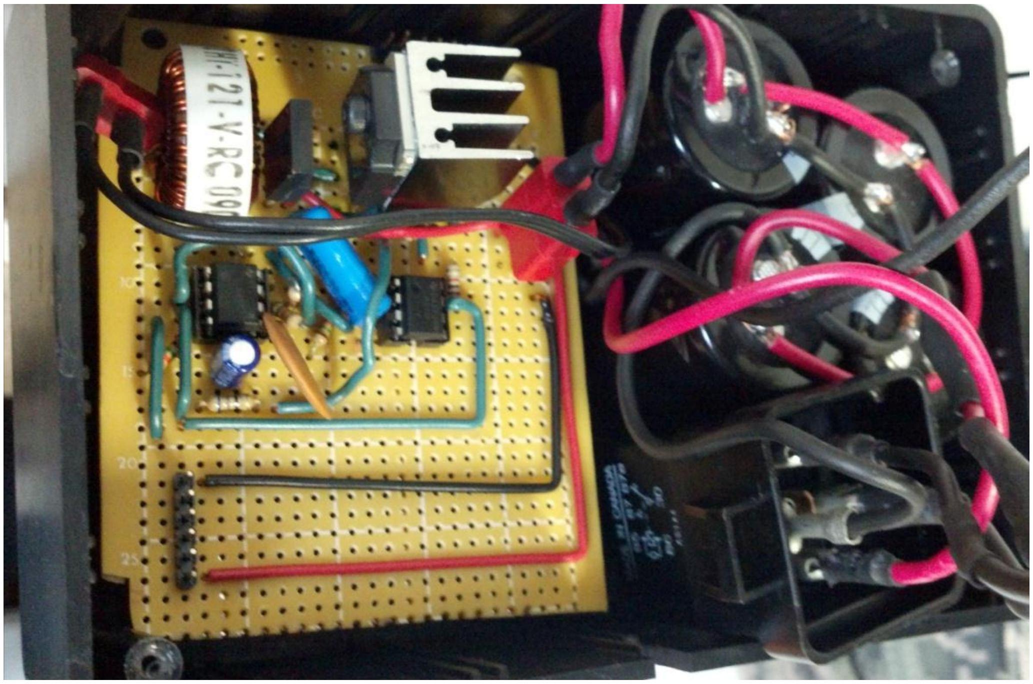


Figure 10: A view of the boost converter circuitry (left), capacitor bank (upper right) and relay (lower right)

Vibrotactile motors

In conjunction with the impact tactor, an array of six vibrotactile motors was arranged in a band around the midsection of the torso, just below the rib cage. These were COTS vibrotactile motors ("Lilypad Vibe Board"), made by *Lilypad*, which are made specifically to be sewn into fabric. Velcro strips were sewn into the vest on the front and back panels where the vibrotactile motors were intended. On the mating part of each Velcro strip, three vibrotactile motors were sewn on by conductive thread. The conductive thread was then woven through the Velcro to the conductive snaps at either end of the Velcro strip, with care taken not to cross threads. The vibrotactile motors were attached to the vest in this way to allow for future expansion of tactors, and also to allow for easy repairs with shortened downtime.

Figure 11: Vibrotactile motors mounted in the T3V

Vibrotactile motor control

The vibrotactile motors were controlled by the same Arduino Uno microcontroller and XBee wireless module which fires the EMPL. The microcontroller can send out single pulses in the forward and in the four diagonal directions, or the vibrotactile band can be made to create waves of vibrations which circle either clockwise or counter-clockwise. The waves of vibrations are meant to be used for wayfinding-type applications where a user needs to get from point A to point B.

Impact Tactor Testing

Different EMPL tactor coils and conditions were quantitatively tested to determine the overall power carried by the projectile and the efficiency of the coil. Other variables measured were the degradation of the AA battery power supply and the time it took for the capacitor bank to be recharged.

Ultimately, the test plan is meant to indicate the quality of the sensation delivered by the impact tactor. A quality impact tactor is herein defined as one which delivers a high impulse, where the impulse, *I* is defined as the integral of the force with respect to time:

$$\boldsymbol{I} = \int_{t_1}^{t_2} \boldsymbol{F}\, \boldsymbol{dt} \qquad \textbf{Equation 1}$$

To validate this tactor design, only the energy of the projectile was calculated, since measuring the duration of the impact of the projectile with a user’s skin or clothing would be particularly difficult, thus from here on, the validation of the tactor will be in terms of energy of the projectile.

The energy of the projectile cannot be directly measured or calculated like that of the capacitor bank, so instead, the flight time of the projectile was measured as it was shot straight up from the coil. The energy of the projectile was calculated based off of a derivation of two equations, the first of which states position of a constant acceleration projectile as a function of time:

$$\boldsymbol{x(t) = x_0 + v_{0x}t + \frac{1}{2}a_x t^2} \tag*{\textbf{Equation 2}}$$

Where $x(t)$ is the position at time t (in meters), x_0 is initial displacement (in meters), $v_{0x}$is the velocity in the direction of travel (in meters/second), and a_x is the acceleration in the direction of travel (in meters/second^2). The proof of this equation will be left to the reader. The second equation is that describing the energy of a system:

$$\boldsymbol{E_{system} = PE + KE} \tag*{\textbf{Equation 3}}$$

Where the mechanical energy of a system E_{system} is equal to potential energy, PE plus kinetic energy, KE (all in Joules). For reasons explained below, the energy of the system is calculated where $KE = 0$. The equation for potential energy is:

$$\boldsymbol{PE = mgh} \tag*{\textbf{Equation 4}}$$

Where m is the mass of the particle (in kilograms), g is the force due to gravity (as 9.8 meters/second^2, and h is the height from which the particle was dropped (in meters). Again, the origin of this equation is purposely left off of this thesis. Here, displacement/position x from $\boldsymbol{x(t) = x_0 + v_{0x}t + \frac{1}{2}a_xt^2}$

Equation 2 and height h from $\boldsymbol{PE = mgh}$

Equation 4 are synonymous with each other. Similarly, acceleration a_x from $\boldsymbol{x(t) = x_0 + v_{0x}t + \frac{1}{2}a_xt^2}$ Equation 2 and the force due to gravity g from $\boldsymbol{PE = mgh}$ Equation 4 also represent the same thing. From this point forward, displacement will be defined as x and the acceleration due to gravity will be defined as g.

The approach to solving for the energy of the system is to think of the projectile not as being fired from the ground, following a parabolic displacement curve and falling back to the same position on the ground, but rather as a problem of the projectile falling from its maximum height with no initial velocity. Since the projectile, in reality, is traveling in a parabolic curve, the position is evaluated at time $t_{total}/2$, since the total time elapsed, t_{total} represents the duration of time between when the projectile is fired and when it hits the ground. $\boldsymbol{x(t) = x_0 + v_{0x}t + \frac{1}{2}a_xt^2}$

Equation 2 can then be simplified as:

$$\boldsymbol{x(t_{total}/2) = \frac{1}{2}a_xt^2} \qquad \textbf{Equation 5}$$

Now, since the equation of motion has been constrained to only represent the potential energy of the system, (the energy waiting to be released by the projectile falling from the apex of its trajectory) the potential energy can be calculated by substituting h from $\boldsymbol{PE = mgh}$ Equation 4 for $x(t_{total}/2)$ from $\boldsymbol{x(t_{total}/2) = \frac{1}{2}a_x t^2}$ Equation 5:

$$\boldsymbol{PE_{projectile} = mg\left(\frac{1}{2}gt^2\right)}$$ **Equation 6**

$\boldsymbol{PE_{projectile} = mg\left(\frac{1}{2}gt^2\right)}$ Equation 6 is the equation that was used to calculate the energy of the projectile during the EMPL tests.

The energy contained in a bank of capacitors is far easier to measure than the energy of a projectile. The potential energy stored in a capacitor, $E_{capacitor}$ (in Joules) is defined as:

$$\boldsymbol{E_{capacitor} = \frac{1}{2}CV^2}$$ **Equation 7**

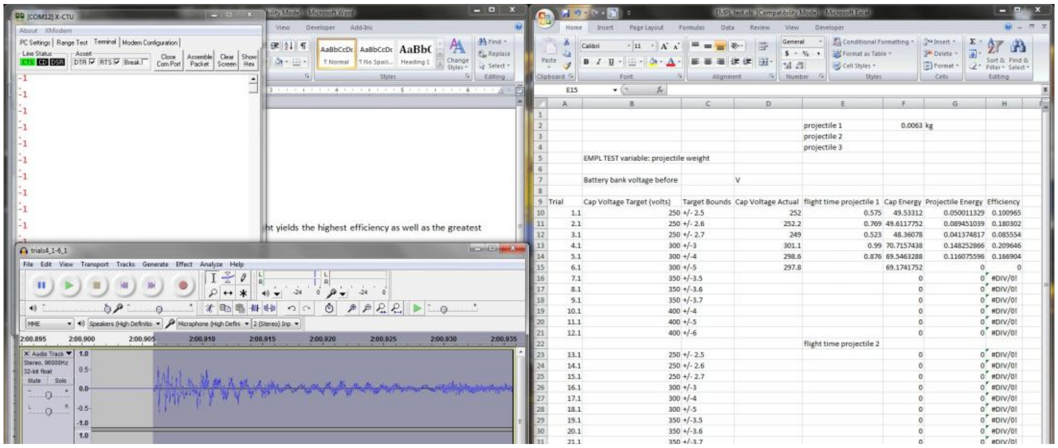
Where C is capacitance (in Farads) and V is voltage (in Volts). This equation was also used during the EMPL tests.

Lastly, the efficiency of the projectile launcher can be easily calculated by comparing the energy of the projectile to the energy stored in the capacitors:

$$\boldsymbol{Efficiency = \frac{PE_{projectile}}{E_{capacitor}} \times 100}$$ **Equation 8**

Designed around Equations 6, 7, and 8, a test plan was written to validate the prototypes and discover under which parameters the projectile launcher best performs. In the full test plan which can be found in Appendix I, different coil designs and different firing durations were explored at different voltages. The results are shown and discussed in Chapters 4 and 5.

The test setup used to perform the EMPL test plan in Appendix I required the use of the EMPL hardware described above, a laptop computer, XBee module and XBee explorer dongle, microphone, multimeter, a small, nonmetallic spacer and a large multimeter, a small, nonmetallic spacer and a large flat surface. The EMPL and coil were placed on the flat surface where there were no obstructions above or around the coil. The coil was placed flat on the surface such that when a positive voltage was applied to the leads, the induced magnetic field would point upwards. Within the coil, the projectile was laid flat on top of the small nonmetallic spacer such that the position of the projectile was directly between the top and the bottom of the coil.



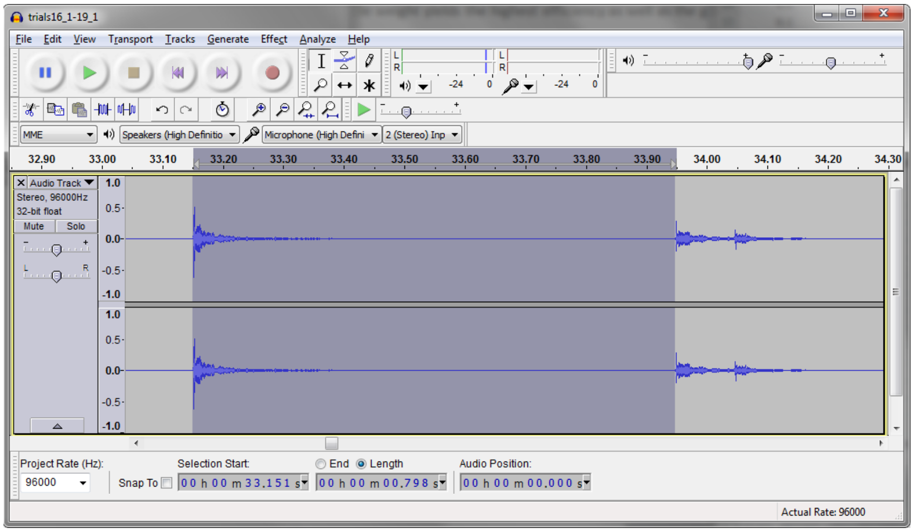
ht yields the highest efficiency as well as the greatest

	A	B	C	D	E	F	G	H
1								
2					projectile 1	0.0063	kg	
3					projectile 2			
4					projectile 3			
5		EMPL TEST variable: projectile weight						
6								
7		Battery bank voltage before		V				
8								
9	Trial	Cap Voltage Target (volts)	Target Bounds	Cap Voltage Actual	flight time projectile 1	Cap Energy	Projectile Energy	Efficiency
10	1.1	250	+/- 2.5	252	0.575	49.53312	0.050011329	0.100965
11	2.1	250	+/- 2.6	252.2	0.769	49.6117752	0.089451039	0.180302
12	3.1	250	+/- 2.7	249	0.523	48.36078	0.041374817	0.085554
13	4.1	300	+/-3	301.1	0.99	70.7157438	0.148252866	0.209646
14	5.1	300	+/-4	298.6	0.876	69.5463288	0.116075596	0.166904
15	6.1	300	+/-5	297.8		69.1741752	0	0
16	7.1	350	+/-3.5			0	0	#DIV/0!
17	8.1	350	+/-3.6			0	0	#DIV/0!
18	9.1	350	+/-3.7			0	0	#DIV/0!
19	10.1	400	+/-4			0	0	#DIV/0!
20	11.1	400	+/-5			0	0	#DIV/0!
21	12.1	400	+/-6			0	0	#DIV/0!
22					flight time projectile 2			
23	13.1	250	+/- 2.5			0	0	#DIV/0!
24	14.1	250	+/- 2.6			0	0	#DIV/0!
25	15.1	250	+/- 2.7			0	0	#DIV/0!
26	16.1	300	+/-3			0	0	#DIV/0!
27	17.1	300	+/-4			0	0	#DIV/0!
28	18.1	300	+/-5			0	0	#DIV/0!
29	19.1	350	+/-3.5			0	0	#DIV/0!
30	20.1	350	+/-3.6			0	0	#DIV/0!
31	21.1	350	+/-3.7			0	0	#DIV/0!

Figure 12: A screenshot taken during testing, with the serial monitor, *X-CTU* in the upper left corner and *Audacity* in the lower left

The microphone was then positioned near to and oriented at the coil and connected to the computer. The microphone was needed to be able to pick up the sound of the projectile firing and again, hitting the same surface from which it was fired so that the total flight time could be measured from the sound file.

To fire the EMPL, the free software *X-CTU* (“X-CTU Software - Digi International,” n.d.) was used as a serial monitor. When the XBee dongle is plugged into the computer, hitting ENTER in the serial monitor sends the serial code to the wirelessly mated microcontroller. Using the free software *Audacity*, the sound of the projectile being fired was captured and reviewed later. **Error! Reference source not found.** shows a screenshot during testing with *X-CTU* in the upper left-hand corner, *Audacity* in the lower left-hand corner and the excel spreadsheet used for recording data on the right side. Analyzing the sound captured from the firing of the EMPL, it was easy to use the cursor to select the time it took from the beginning of the initial launch to right before



Stereo, 96000Hz
32-bit float

Project Rate (Hz): 96000
Snap To ☐
Selection Start: 00 h 00 m 33.151 s
○ End ● Length: 00 h 00 m 00.798 s
Audio Position: 00 h 00 m 00.000 s
Actual Rate: 96000

Figure 13: Screenshot of projectile flight time duration as seen in *Audacity*

the projectile fell back down and hit the flat surface from which it was fired. A screenshot showing the selection of the wave form of the sound of the projectile being fired can be seen in Figure 12. The length of the selection, as seen at the bottom of Figure 12 was then entered into the spreadsheet in the “flight time” column in Appendices II and III.

CHAPTER 4. RESULTS

Introduction

Quantitatively, the impact tactor’s requirements for functioning properly and efficiently have been thoroughly researched and proven in practice. The Electromagnetic Projectile Launcher repeatedly fired projectiles with, in the best case, about 0.1% efficiency of the coil with about 0.1 Joule of energy.

A Usable Tactile Garment

As discussed earlier, the main focus of this project was to create a usable platform for providing haptic feedback primarily for a mixed reality training simulator, which was successfully produced, as seen in Figure 14.

The current state of the T3V remains as a functional and usable proof of concept, which lends itself to be expanded and recreated. Both large and small coils tested herein are mounted to the front panel of the T3V, although the charging circuit and capacitor bank are only currently configured to control one EMPL.

The T3V is also fitted with a functional and customizable array of six vibration tactors around the midsection of the vest. Both impact and vibration tactor systems are controllable wirelessly via computer or alternate microcontroller.

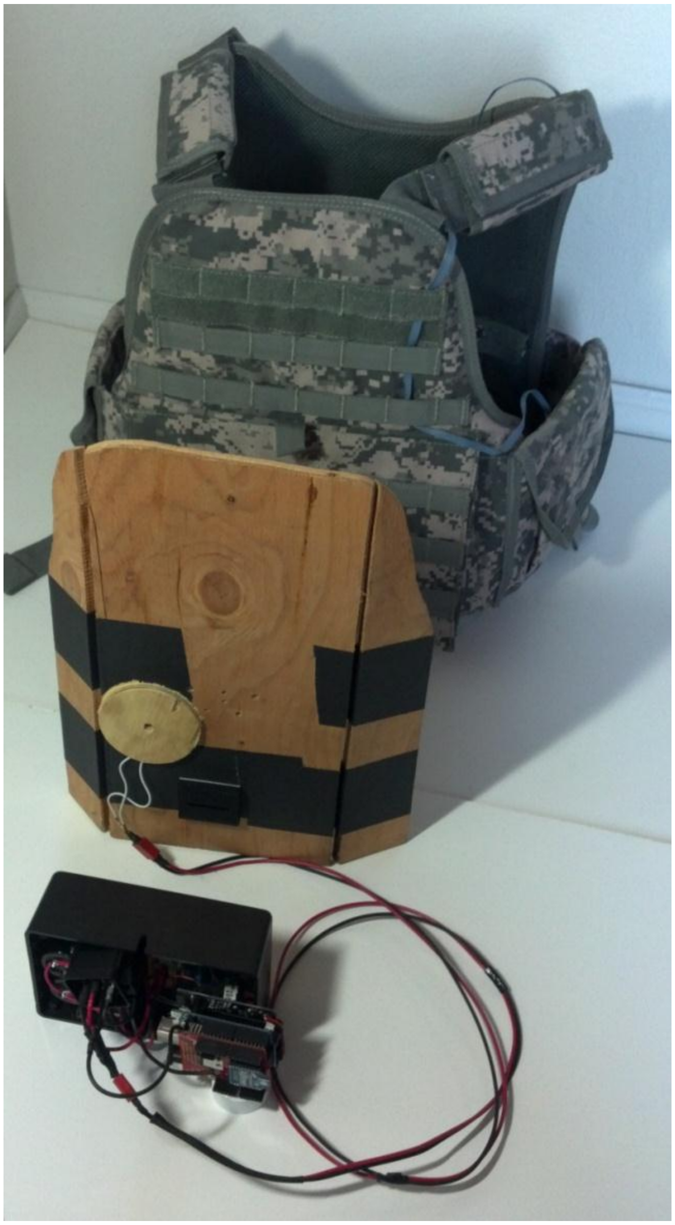


Figure 14: The T3V with the tactor mounted on the insert, and the required circuitry and microcontroller contained within the enclosure

EMPL test results

The EMPL test plan was carried out as described in Appendix I with the equipment described in Chapter 3 and the full results can be found in Appendices II and III.

Experiment 1

In Experiment 1, three different coil designs were tested for efficiency and overall projectile energy, which directly corresponds to the impulse of the tactor ($\boldsymbol{I} = \int_{t_1}^{t_2} \boldsymbol{F}\, \boldsymbol{dt}$ Equation 1). The efficiency of the coil is important because it shows how much of the voltage is actually applied to accelerating the projectile. It was expected that larger coils would be able to transfer more energy to the projectile. Three trials were carried out at three different target voltages. The actual voltages varied slightly since the system was fired as soon as the voltage recovered. For reference to Experiment 2, all trials in Experiment 1 were carried out with a relay fire duration of 20 milliseconds. The relay fire duration is the duration of time that the relay is held closed, which corresponds to the amount of time that the voltage from the capacitors is applied to the coils.

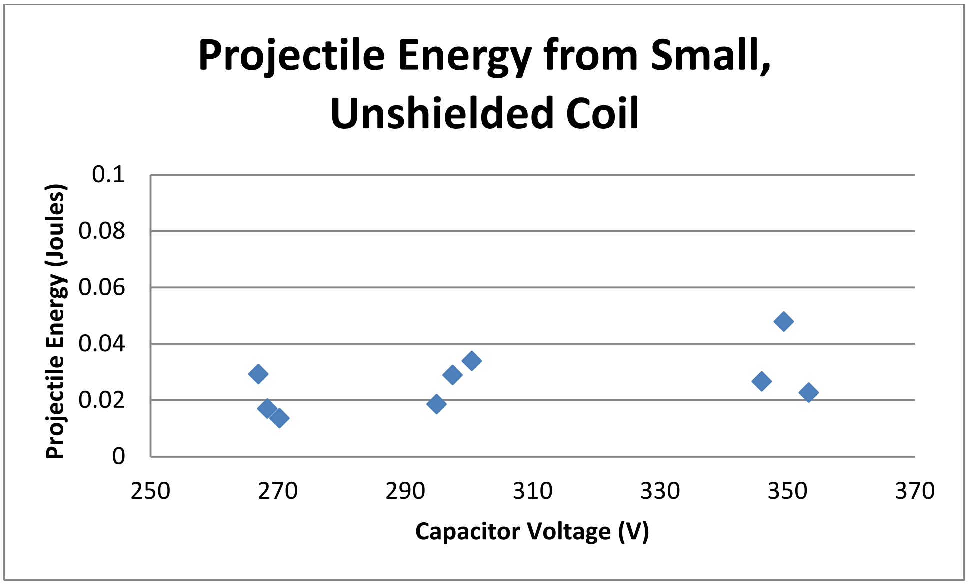


Figure 15: Small, unshielded coil EMPL energy results

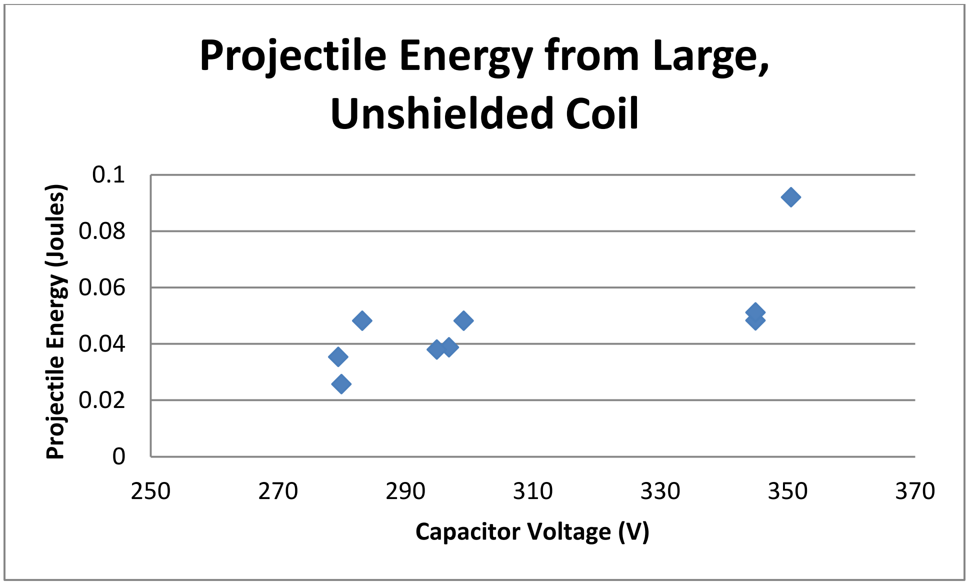


Figure 16: Large, unshielded coil EMPL energy results

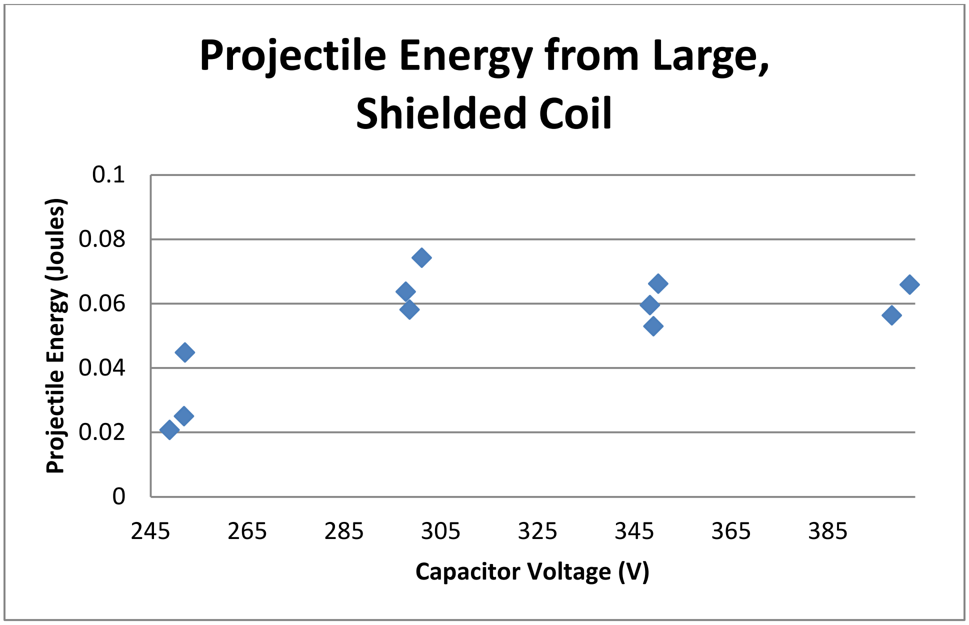


Figure 17: Large, shielded coil EMPL energy results

Error! Reference source not found., **Error! Reference source not found.**, and **Error! Reference source not found.** show the trend of projectile energy vs. capacitor voltage between the small, large, and large shielded coils. It was expected that the coil with the more turns and larger gauge wire (the large coil) would produce better results, which is evident in the data collected. The large, shielded coil seems to have produced the best energy results, however during testing, as is discussed in Chapter 5 below, most of the trials produced projectiles with trajectories less than ideal because of the projectile hitting the edge of the EMPL housing. The average energy of a projectile being fired from the small coil was 0.02 Joules and the average energy resulting from the large coil was 0.06 Joules. The average energy produced with the large shielded coil was 0.05 Joules, however the data was much more consistent. If the single trial which performed exceptionally well fired from the large, unshielded coil were omitted, the average energy would be 0.04 Joules.

The efficiency of the unshielded coil averaged 0.03% as seen in **Error! Reference source not found.**, where the larger coil produced efficiencies varying between almost 0.1% and at the lowest, 0.04%. The overall average efficiency for the large, unshielded coil was approximately 0.06%. Shielding of the large coil also produced an average efficiency of 0.06%.

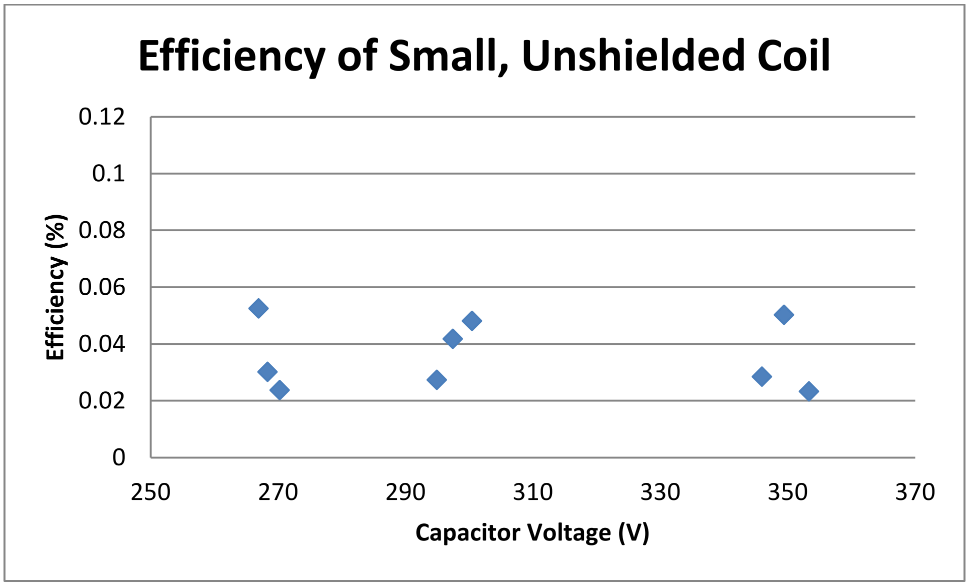


Figure 18: Small, unshielded coil EMPL efficiency results

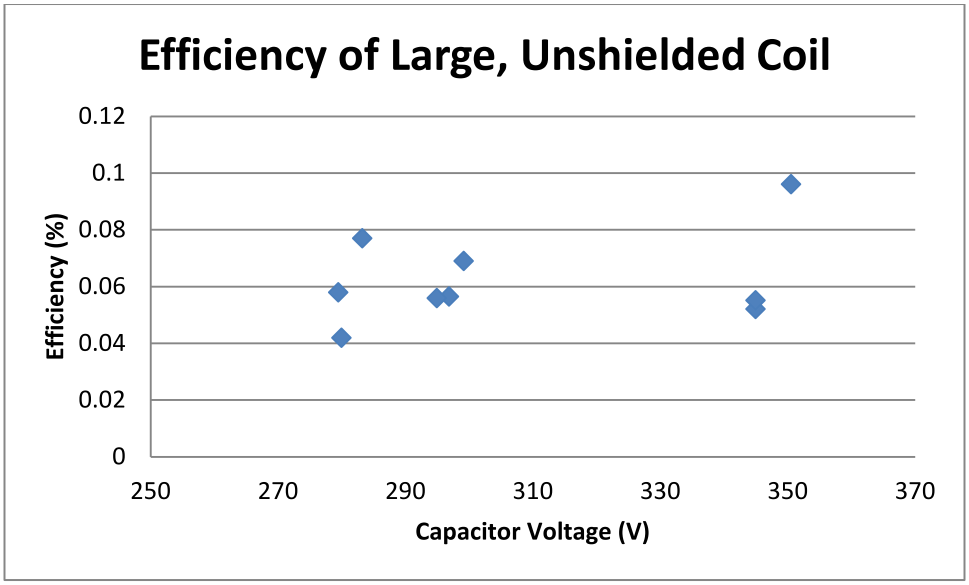


Figure 19: Large, unshielded coil EMPL efficiency results

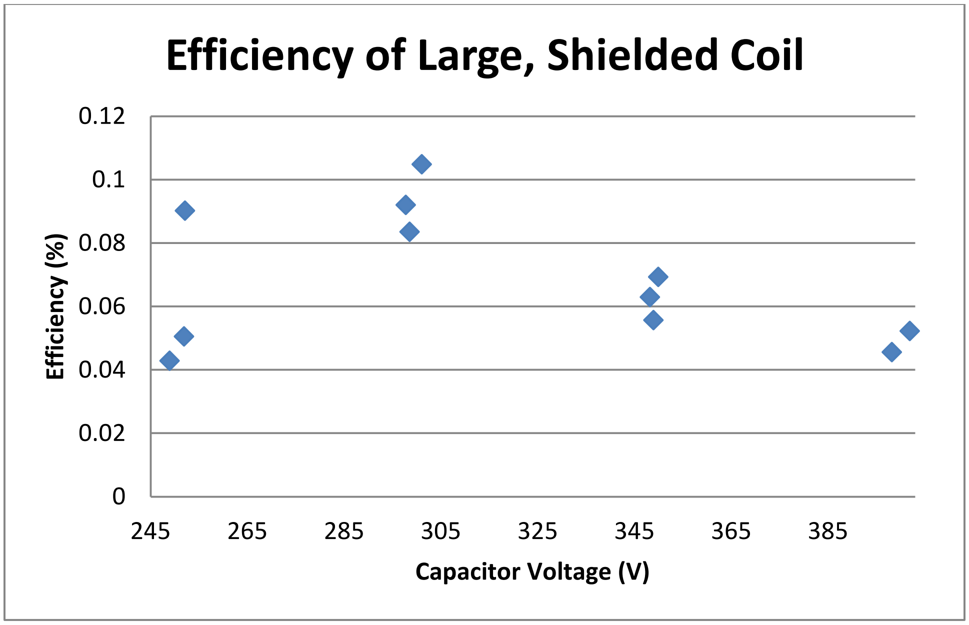


Figure 20: Large, shielded coil EMPL efficiency results

It can be assumed, that under ideal conditions, using the exact setup as described in this thesis, the projectile would travel with a maximum of 0.1 Joules, and at a maximum of 0.1% efficiency to the measured power held in the capacitor bank. The energy density calculated to compare these findings with Desmoulin & Anderson, 2011 was simply obtained by multiplying the energy by the surface area of the projectile. The maximum energy density recorded was approximately 206 joules/m^2.

Experiment 2

Experiment 1 was meant to reveal what coil was best to use, and what voltage that coil required to launch the projectile with the most energy. Experiment 2 was designed to test the importance of another variable: the relay fire duration, or how long the capacitor voltage should be applied to the coils. Experiment 2 showed a subtle, but definite trend in the effect of changing the relay firing duration. The best results in Experiment 1 showed that the projectile was launched with an average of 0.06 Joules however at 30ms, the average projectile energy was shown to be slightly above that figure. Similarly, the efficiency also increases slightly, but generally stays around 0.06%.

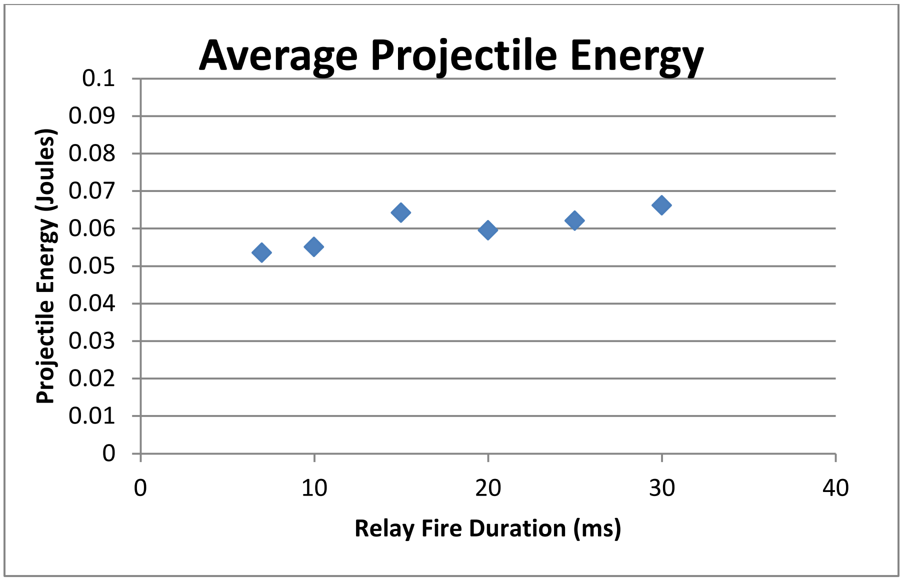


Figure 21: Large, shielded coil relay fire duration vs. average projectile energy

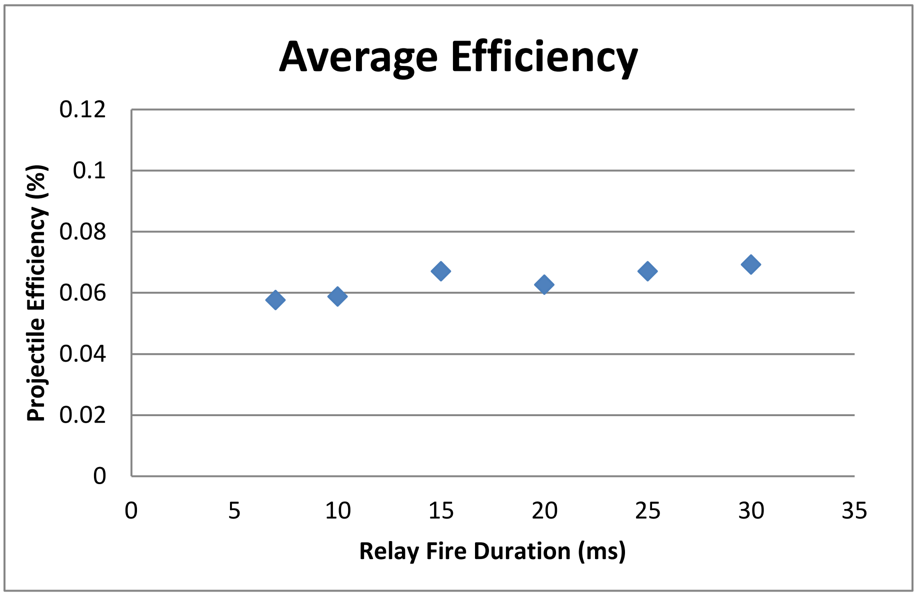


Figure 22: Large, shielded coil relay fire duration vs. average efficiency

EMPL Test Discussion

During the testing, not only was the energy of the projectile calculated, but the EMPL circuitry and components were literally tested to their limits. The early versions of the capacitor charger and EMPL were triggered with a simple pushbutton on the outside of the circuit enclosure. Over a half-dozen switches were fused shut and destroyed since the high current levels of the capacitor bank draining overwhelmed the internal components of the switches.

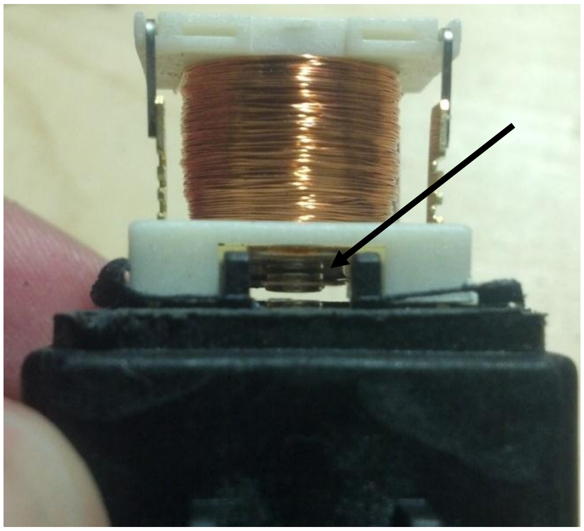


Figure 23: EMPL firing relay failure

For testing, the pushbutton switch was replaced with the automotive relay, which had the benefits of having a much higher power rating, and also being able to be triggered via a computer or microcontroller. During testing, the system failed two different times. The first failure occurred right after trial 11.1 when the voltage was turned up to 400 volts. While developing this system, the problem of over-charging proved to be very hazardous to the components of the system, where on multiple occasions, the 555 timer, the comparator, the MOSFET and the 600v diode all broke down and had to be replaced. After this failure during testing, the trials were limited to only 350 volts so for this system, this is the recommended operating voltage.

The second limit reached was with the relay, which triggered the projectile launcher. This failure was witnessed after Trial 23.2, during the 30 millisecond fire time tests. The relay was fused closed, which was initially witnessed in the lack of residual voltage in the capacitor bank after firing Trial 23.2. It can also be seen in **Error! Reference source not found.** where the protective housing of the relay was cut off to inspect the internal contacts. The arrow shows the location of the contacts that have been fused together. It is assumed that with longer fire times come larger current bursts through the switch, which caused the relay to fail. For this reason, the tests were stopped at 30ms and the recommended fire duration with the current components should be limited to 20-25 milliseconds. If the relay component were swapped for one with a higher power rating, it is possible to push the relay fire duration even longer, but more testing would be necessary to determine the extent to which it can be pushed. Limiting the firing time of the relay does not necessarily limit the impact duration of the projectile.

If the bursts of current do in fact increase with the firing time, then the data collected in Experiment 2 would make sense, with increasing projectile energies with increasing relay fire durations. It is also interesting to note that the average efficiency also increases with increasing fire duration.

The energy density of the EMPL projectile was far less than that shown experimentally to cause bruises in a healthy male (Desmoulin & Anderson, 2011). In the research done by Desmoulin and Anderson, the goal was to find 1) What variable correlates with bruising, and 2) the quantity of that variable. The lowest amount of energy density recorded which caused bruising was approximately 17 kilojoules/m^2. Likewise, the highest recorded energy density (assuming the projectile impacts the skin on the entirety of one face) is approximately 200 Joules/m^2, concluding that the EMPL currently outputs about 1% of the required energy density needed to cause bruising in a healthy individual. If the projectile impacted a participant's skin on an edge, the energy density would increase drastically.

Examining the data, one might notice data points that might seem like outliers, but

Figure 24: Projectile scuffs left on EMPL housing

they are not. It is my opinion that these few points are actually more evident of what a trial under perfect conditions might look like. Trial 19.1 is one of those examples. During this trial, the projectile traveled straight up with very little lateral trajectory. Almost all of the other trials had a sideways component to their trajectories, which was just assumed as the projectile hitting the inside of the coil housing during firing time. In fact, this assumption was correct and is evidenced by the grooves dug into the side of the coil housing by the projectile as seen in **Error! Reference source not found.**. It can be assumed that this tumbling caused by the projectile hitting the walls of the coil housing was somewhat detrimental to the results of these experiments.

Future development of the tactor however could explore different shape projectiles or different techniques of retaining the projectile such that the projectile does not hit the sides of the housing and it is expected that a more developed EMPL tactor could show far greater results.

CHAPTER 5. SUMMARY AND DISCUSSION

Introduction

The prototype tactile vest described herein is meant to provide a stepping stone for future tactile garment and torso-based haptic research, and is not meant to be taken as a finished and polished product. The T3V is certainly a work in progress however, many lessons were learned in researching this subject and creating the prototype tactors and T3V.

System Considerations

It is evident that the larger coil outperforms the smaller coil, but more importantly, that the design of the coil itself plays a big role in having a powerful and efficient impact tactor. Endless combinations of coils, coil wire gauge, voltage and firing times could produce a large amount of data which might point to the most efficient tactor design, but that was not the scope of this thesis. This project and discussion have remained a proof of concept and possible future research platform with which to perform user experiments in mixed or fully virtual reality environments. One important factor which dictates the power of the impact, which was not discussed yet, is the size of the capacitor bank. With larger capacitors and/or more of them to supply more capacitance, an impact tactor system could be designed with a much harder hitting punch.

For future design iterations, a larger capacitor bank is needed, not only for a harder-hitting tactor, but also for a more modular system. If more than one capacitor bank were charging simultaneously, multiple tactors could also be firing simultaneously, adding to the immersiveness of the sensation. Multiple rapid hits on the front of the vest could mean that you've been hit with multiple bullets of light machine gun fire, or two hits in rapid succession on the front and back could indicate that a virtual bullet has just dealt the participant a devastating wound.

With a single impact tactor mounted in the T3V, the two wooden chest and back plates, six vibromotor tactors and the circuitry, microcontroller and power supply to control them, the entire vest weighs in at about seven pounds. The circuitry and power supply weighed in at just two pounds of the total. Expanded to multiple impact tactors and an appropriate capacitor bank and power supply, the vest can be expected to weigh around 10-15 lbs, which is far less than what a typical soldier would carry as a "Fighting Load" which is on average about 62 lbs (Cadarette, Santee, Robinson, & Sawka, 2007).

Potential Risk

The risk of electric shock is high when dealing with experimental electronics, and the potential for injury is high when dealing with high voltage. Extreme care was always used when charging and discharging capacitors and it is recommended that the circuitry and systems explained herein are approached with caution and used with care. The charging system was not designed to be used in harsh environments and it is not to be used in moist environments or be subject to any kind of moisture to avoid any electric shock however for the components designed to be next to the skin, the risk of shock is greatly reduced since the electronics are insulated and shielded.

For future iterations of this project it is also recommended that the circuitry and capacitor bank be housed in a waterproof and non-conducting enclosure. This does however, present the problem of allowing adequate cooling of some of the circuitry components. During testing, the MOSFET and high voltage diode became very hot to the touch and if exposed to the skin for an extended amount of time, could possibly cause burns. The prototype included a heat sink attached to the MOSFET with thermal paste, but it is recommended that the diode also be cooled appropriately.

Future work

One consideration for the impact tactor design was to use a shock to deliver a disincentive to the user. This method was avoided for two reasons. Delivering a shock of electricity could be potentially dangerous but it could also interfere with collecting testing data for user studies in the future. If a user is testing the T3V in a stressful environment, it may be necessary to connect heart beat monitors or galvanic skin response sensors directly to the skin of the user. If the user were delivered a shock, these sensors may pick up false positives or even be damaged.

The microcontroller governing the T3V is easily replaceable, but also readily expandable to incorporate other sensors or control other systems. The third system described earlier, which was unable to be incorporated into the proof of concept was the personalized 3D sound system. Small speakers could be attached to the vest, either on the front and back, or on the shoulders. One possible way to increase the immersiveness of the experience of the Veldt, or other virtual environments where multiple users are sharing the same space, is to provide each user with a small input of personalized sound. Initial pilot testing in the Veldt showed the soldiers valued immersive sound (Gilbert, Pontius, Kelly, & De La Cruz, 2012). Whether it is a bullet whizzing by in a firefight, the annoying sound of flies while trying to diffuse a virtual bomb, or the sound of a virtual car driving through physical space, sounds can provide important clues about the environment. With the T3V, this level of presence could be tested.

Suggested design improvements

In order to create a system that packed a harder punch, the simplest change would be to increase the capacitance of the capacitor bank. The voltage does not necessarily need to be increased. With this type of change however, a relay rated at a higher power may need to be specified, and the coil design may also need to be changed, with more turns and/or with a larger gauge wire.

To decrease recovery time of the capacitor bank, another simple change to the charging system would be to change the power supply (8- AA batteries) to a high-drain supply like lithium-based or SUBC-type NiCAD batteries.

Also, as with any good system, a feedback loop should be built into the software to alert the master computer to status updates or failures of the impact system.

APPENDIX I: EMPL TEST PLAN

Experiment 1

Purpose: Uncover what voltage/coil design yields the highest efficiency as well as the greatest energy.

Procedure: Record the voltage of the battery bank. Charge the capacitors up to within 1% 250v, 300v, 350v and 400v with a bank of 8- 1.5v AA batteries, fire the EMPL and record the time between the launch of the projectile and when it hits the table at the same height of the launch coil. Record the actual voltage of the capacitors right before launch. Perform this exercise with the large, shielded coil, the large, unshielded coil and the small, unshielded coil.

Post-processing:

Calculate

1. Total energy of projectile from elapsed flight time.
2. Calculate energy stored in capacitor bank
3. Calculate efficiency of coil

For each target voltage, create two scatter plots with 1) *Voltage* on the x-axis and *Projectile Energy* in the y-axis and 2) with *Efficiency* in the y-axis.

Experiment 2

Purpose: Uncover what relay firing duration is optimal for producing the greatest projectile energy and efficiency.

Procedure: Using the maximum voltage and the coil that produced the greatest results, repeat Experiment 1 with firing times of 10ms, 20ms, 30ms 40ms.

Post-processing:

Calculate

1. Total energy of projectile from elapsed flight time.
2. Calculate energy stored in capacitor bank
3. Calculate efficiency of coil

Create two scatter plots with *relay firing time* on the x-axis and 1) *Projectile Energy* on y-axis and 2) *Efficiency* on the y-axis

Experiment 3:

Purpose: Discover which is the limiting factor for producing a powerful punch: capacitance, or the coil

Procedure: Rebuild the capacitor bank with 2x as many capacitors and re-test Experiment 2 using the maximum possible voltage and the best performing coil.

Post-processing:

Calculate

1. Total energy of projectile from elapsed flight time.
2. Calculate energy stored in capacitor bank
3. Calculate efficiency of coil

Create two scatter plots with *relay firing time* on the x-axis and 1) *Projectile Energy* on y-axis and 2) *Efficiency* on the y-axis

APPENDIX II. EMPL TEST RESULTS, EXPERIMENT 1

A/4	B	C	D	E	F	G	H	I
5		**EMPL TEST variable:**	**VOLTAGE/COIL**					
6				projectile weight	0.0063	kg		
7				projectile surface area	0.00044	m^2		
8	VAR	**COIL: LARGE, SHIELDED**						
9	Trial	Cap Voltage Target	Cap Voltage Actual	flight time projectile 1	Cap Energy	Projectile Energy	Energy Density	Efficiency
10		(Volts)	(Volts)	(seconds)	(Joules)	(Joules)	(Joules/m^2)	(%)
11	1.1	250	252	0.575	49.53	0.03	56.21	0.05
12	2.1	250	252.2	0.769	49.61	0.04	100.53	0.09
13	3.1	250	249	0.523	48.36	0.02	46.50	0.04
14	4.1	300	301.1	0.99	70.72	0.07	166.62	0.10
15	5.1	300	298.6	0.876	69.55	0.06	130.46	0.08
16	6.1	300	297.8	0.917	69.17	0.06	142.95	0.09
17	7.1	350	349	0.836	95.00	0.05	118.82	0.06
18	8.1	350	348.3	0.887	94.62	0.06	133.75	0.06
19	9.1	350	350	0.935	95.55	0.07	148.62	0.07
20	10.1	400	402	0.933	126.05	0.07	147.99	0.05
21	11.1	400	398.3	0.863	123.74	0.06	126.61	0.05
22	12.1	400			0.00	0.00	0.00	#DIV/0!
23								
24		Battery bank voltage	12.98	V				
25								
26	VAR	**COIL: LARGE, UNSHIELDED**		flight time projectile 1				
27	13.1	250	283.3	0.798	62.60	0.05	108.26	0.08

28	14.1	250	280		0.582	61.15	0.03	57.58	0.04
29	15.1	250	279.5		0.683	60.93	0.04	79.30	0.06
30	16.1	300	299.2		0.798	69.83	0.05	108.26	0.07
31	17.1	300	296.9		0.716	68.76	0.04	87.15	0.06
32	18.1	300	295		0.708	67.88	0.04	85.22	0.06
33	19.1	350	350.6		1.103	95.88	0.09	206.83	0.10
34	20.1	350	345		0.799	92.84	0.05	108.53	0.05
35	21.1	350	345		0.822	92.84	0.05	114.87	0.06
36	22.1	400				0.00	0.00	0.00	#DIV/0!
37	23.1	400				0.00	0.00	0.00	#DIV/0!
38	24.1	400				0.00	0.00	0.00	#DIV/0!
39									
40		Battery bank voltage	12.22	V					
41									
42	VAR	**COIL: SMALL, UNSHIELDED**		flight time projectile 1					
43	25.1	250	270.3		0.423	56.99	0.01	30.42	0.02
44	26.1	250	268.4		0.473	56.19	0.02	38.03	0.03
45	27.1	250	267		0.621	55.61	0.03	65.56	0.05
46	28.1	300	300.5		0.669	70.43	0.03	76.09	0.05
47	29.1	300	297.5		0.617	69.03	0.03	64.72	0.04
48	30.1	300	295		0.495	67.88	0.02	41.66	0.03
49	31.1	350	353.4		0.547	97.42	0.02	50.87	0.02
50	32.1	350	349.5		0.795	95.28	0.05	107.45	0.05
51	33.1	350	346		0.593	93.38	0.03	59.78	0.03
52	34.1	400				0.00	0.00	0.00	#DIV/0!
53	35.1	400				0.00	0.00	0.00	#DIV/0!
54	36.1	400				0.00	0.00	0.00	#DIV/0!

APPENDIX III: EMPL TEST RESULTS, EXPERIMENT 2

A/4	B	C	D	E	F	G	H	I	J
5			**EMPL TEST variable:**	**VOLTAGE/FIRE TIME**					
6			constant: large, shielded coil, 350v		projectile weight	0.0063	kg		
7					projectile surface area	0.000444881	m^2		
8	VAR	Fire Duration	**10ms FIRE**						
9	Trial		Cap Voltage Target	Cap Voltage Actual	flight time	Cap Energy	Projectile Energy	Energy Density	Efficiency
10			(Volts)	(Volts)	(seconds)	(Joules)	(Joules)	(Joules/m^2)	(%)
11	1.2	10	350	350	0.727	95.55	0.04	89.85	0.04
12	2.2	10	350	349	0.51	95.00	0.02	44.22	0.02
13	3.2	10	350	347.4	1.035	94.14	0.08	182.11	0.09
14	4.2	10	350	345.5	1.003	93.11	0.08	171.03	0.08
15	5.2	10	350	344	0.88	92.30	0.06	131.65	0.06
16			**7ms FIRE**				0.00	0.00	
17	6.2	7	350	347.5	0.781	94.19	0.05	103.70	0.05
18	7.2	7	350	344	0.784	92.30	0.05	104.49	0.05
19	8.2	7	350	343	0.949	91.77	0.07	153.11	0.07
20	9.2	7	350	341	0.701	90.70	0.04	83.54	0.04
21	10.2	7	350	348	0.959	94.46	0.07	156.35	0.07
22			**15ms FIRE**				0.00	0.00	
23	11.2	15	350	351.9	0.876	96.59	0.06	130.46	0.06
24	12.2	15	350	349.5	1.133	95.28	0.10	218.23	0.10
25	13.2	15	350	349	0.789	95.00	0.05	105.83	0.05

26	14.2	15		350	349.5	0.922	95.28	0.06	144.52	0.07
27	15.2	15		350	354	0.849	97.75	0.05	122.54	0.06
28			**25ms FIRE**					0.00	0.00	
29	16.2	25		350	350	0.945	95.55	0.07	151.82	0.07
30	17.2	25		350	352.5	0.858	96.92	0.06	125.15	0.06
31	18.2	25		350	350	0.922	95.55	0.06	144.52	0.07
32	19.2	25		350	349	0.8	95.00	0.05	108.80	0.05
33	20.2	25		350	349	0.992	95.00	0.07	167.29	0.08
34			**30ms FIRE**					0.00	0.00	
35	21.2	30		350	351	0.982	96.10	0.07	163.94	0.08
36	22.2	30		350	349	0.859	95.00	0.06	125.44	0.06
37	23.2	30		350	350	0.96	95.55	0.07	156.68	0.07
38	24.2	30		350			0.00	0.00	0.00	#DIV/0!
39	25.2	30		350			0.00	0.00	0.00	#DIV/0!
40			**20ms FIRE (from Experiment 1)**					0.00	0.00	
41	7.1	20		350	349	0.836	95.00	0.05	118.82	0.06
42	8.1	20		350	348.3	0.887	94.62	0.06	133.75	0.06
43	9.1	20		350	350	0.935	95.55	0.07	148.62	0.07

REFERENCES

Babb, C. (n.d.). Infantry Immersion Trainer Begins Training Marines in a Virtual Environment - Office of Naval Research. Retrieved March 25, 2012, from http://www.onr.navy.mil/Media-Center/Press-Releases/2007/Training-Marines-Virtual-Environment.aspx

Beom-Chan Lee, Shu Chen, & Sienko, K. H. (2011). A Wearable Device for Real-Time Motion Error Detection and Vibrotactile Instructional Cuing. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *19*(4), 374–381. doi:10.1109/TNSRE.2011.2140331

Cadarette, B. S., Santee, W. R., Robinson, S. B., & Sawka, M. N. (2007). The Modern Warrior's Combat Load. *Aviation, space, and environmental medicine*, *78*(8), 809–813.

Corley, A.-M. (2010, 26). Tactile Gaming Vest Punches and Slices. Retrieved March 25, 2012, from http://spectrum.ieee.org/automaton/robotics/robotics-software/tactile-gaming-vest-punches-and-slices

Desmoulin, G. T., & Anderson, G. S. (2011). Method to Investigate Contusion Mechanics in Living Humans. *Journal of Forensic Biomechanics*, *2*, 1–10.

Dihoff, R. E., Brosvic, G. M., Epstein, M. L., & Cook, M. J. (2010). Provision of Feedback During Preparation for Academic Testing: Learning is Enhanced by Immediate but not Delayed Feedback. *The Psychological Record*, *54*(2), 4.

Gerardi, M., Rothbaum, B. O., Ressler, K., Heekin, M., & Rizzo, A. (2008). Virtual reality exposure therapy using a virtual Iraq: case report. *Journal of Traumatic Stress*, *21*(2), 209–213.

Gilbert, S., Pontius, J., Kelly, J., & De La Cruz, J. (2012). Perception of Presence in a Mixed-Reality Training Environment. Presented at the Industrial and Systems Engineering Research Cnference, G. Lim and J.W. Hermann, eds.

Heimbeck, D., Frese, M., Sonnentag, S., & Keith, N. (2003). Integrating errors into the training process: The function of error management instructions and the role of goal orientation. *Personnel Psychology*, *56*(2), 333–361.

Hickey, K. (2007, November 15). Virtual training gets real -- Government Computer News. Retrieved March 25, 2012, from http://gcn.com/articles/2007/11/15/virtual-training-gets-real.aspx

Johnson, D. (n.d.). SCENARIO BASED FORCE ON FORCE TRAINING / ITG® Consultants. *Scenario Based Force on Force Training*. Retrieved July 23, 2012, from http://www.itg4.com/Scenario-Based-Force-On-Force-Training.aspx

Jones, L.A., Lockyer, B., & Piateski, E. (2006). Tactile display and vibrotactile pattern recognition on the torso. *Advanced Robotics*, *20*(12), 1359–1374.

Jones, Lynette A., & Sarter, N. B. (2008). Tactile Displays: Guidance for Their Design and Application. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(1), 90–111. doi:10.1518/001872008X250638

Karr, C. R., Reece, D., & Franceschini, R. (1997). Synthetic soldiers [military training simulators]. *Spectrum, IEEE*, *34*(3), 39 –45. doi:10.1109/6.576007

LaBarge, D. (n.d.). The MILES Harness: The Bane of Life at Fort Polk, Louisiana. Retrieved September 26, 2012, from http://politics.knoji.com/the-miles-harness-the-bane-of-life-at-fort-polk-louisiana/

Lombard, M., & Ditton, T. (1997). AT THE HEART OF IT ALL: THE CONCEPT OF PRESENCE. *Journal of Computer Mediated Communication*, *3*(2). Retrieved from http://jcmc.indiana.edu/vol3/issue2/lombard.html

Marston, J. R., Loomis, J. M., Klatzky, R. L., & Golledge, R. G. (2007). Nonvisual Route Following with Guidance from a Simple Haptic or Auditory Display. *Journal of Visual Impairment & Blindness*, *101*(4), 203–211.

Newendorp, B., Noon, C., Holub, J., Winer, E., Gilbert, S., & De La Cruz, J. (2011). Configuring Virtual Reality Displays in a Mixed-Reality Environment for LVC training. Presented at the The World Conference on Innovative VR 2001.

Ombrellaro, M. P., Soto, B., Morris, A. L., Kelly, J. J., & Ombrellaro, P. A. (n.d.). Tactile Wearable Gaming Device. Retrieved from http://www.google.com/patents?id=zwDYAAAAEBAJ

Patent US5980254 - Electronically controlled weapons range with return fire - Google Patents. (n.d.). Retrieved July 4, 2012, from http://www.google.com/patents/US5980254?printsec=abstract#v=onepage&q&f=false

Pollock, B., Winer, E., Gilbert, S., & De La Cruz, J. (2012). LVC interaction within a mixed-reality training system. Presented at the IS&T/SPIE Electronic Imaging 2012.

Schuemie, M. J., Van Der Straaten, P., Krijn, M., & Van Der Mast, C. A. P. G. (2001). Research on presence in virtual reality: A survey. *CyberPsychology & Behavior*, *4*(2), 183–201.

Skinner, B. F. (1953). *Science and human behavior.* New York: Macmillan.

Smith, D. M., & Ntuen, C. A. (1999). Effects of Consequential Feedback within a Mine Safety Awareness Training System. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *43*(21), 1118–1122. doi:10.1177/154193129904302101

Threat-Fire^{TM} | Virtra. (n.d.). Retrieved July 4, 2012, from http://www.virtra.com/threat-fire/

TN Games. (n.d.). Retrieved March 25, 2012, from http://tngames.com/products

TN Games | News | Bullet-proof: GameZone chats with TN Games' Mark Ombrellaro. (n.d.). Retrieved July 3, 2012, from http://tngames.com/news_detail/1/33/Bullet-proof-GameZone-chats-with-TN-Games-Mark-Ombrellaro

Waging War - Immersion Training | Digital Nation | FRONTLINE | PBS. (n.d.). Retrieved from http://www.pbs.org/wgbh/pages/frontline/digitalnation/waging-war/immersion-training/full-immersion.html?play

Wilson, C. (2008). Avatars, virtual reality technology, and the US military: Emerging policy issues.

Wu, S. W., Fan, R. E., Wottawa, C. R., Fowler, E. G., Bisley, J. W., Grundfest, W. S., & Culjat, M. O. (2010). Torso-based tactile feedback system for patients with balance disorders. *Haptics Symposium, 2010 IEEE* (pp. 359–362).

X-CTU Software - Digi International. (n.d.). Retrieved June 27, 2012, from http://www.digi.com/support/productdetail?pid=3352&type=drivers