Multi-Sensor Signatures From Ultrasonic Wire Embedding Used In Hybrid Additive Manufacturing

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MULTI-SENSOR SIGNATURES FROM ULTRASONIC WIRE EMBEDDING USED IN HYBRID ADDITIVE MANUFACTURING

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Master’s Program in Mechanical Engineering

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Dedication

This thesis is dedicated to my grandparents Charlotte Gilliland and Kenneth Gilliland, my Parents, and my aunt and Uncle, for supporting me and allowing me the opportunity to pursue a higher education.
DEVELOPING THE ULTRASONIC WIRE EMBEDDING PROCESS TO ENHANCE ADDITIVE MANUFACTURING USING MULTI SENSOR DATA ANALYSIS

by

PATRICK STEVEN GUTIERREZ, B.S.M.E.

THESIS

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Abstract

Additive Manufacturing (AM) has matured such that its products are used in applications ranging from prototypes to end-use parts; however, to expand the adoption of AM, the inclusion of multiple manufacturing technologies has become a focus area especially when the result is a 3D printed part with an embedded electrical system. The W.M. Keck Center for 3D Innovation has developed the Foundry Multi3D system consisting of two material extrusion AM machines, a robotic arm, and a CNC machine equipped with a laser soldering tool, solder micro-dispensing tool and an ultrasonic wire embedding (USWE) tool. The focus of this paper is on data collected during the use of the USWE system while embedding 24 AWG copper wire into printed polycarbonate (PC) substrates. Data was collected from a one-axis accelerometer and a load cell, both of which were mounted in close proximity to the USWE’s transducer, in addition to power measurements from the USWE’s processor. Process events such as pulse activation, end of pulse activation, and system movements were diagnosed. Pulse duration, clamping force, and amplitude were explored to characterize their effect using data collected during wire embedding events. Tools were developed using to quickly breakdown the complex data produced from the system. Testing and data analysis was able to determine what a successful wire embedding signature would look like, while determining process parameters that could be used to improve the system or could cause deformation and damage to the specimens. Additional testing was conducted on a novel modified USWE tip that had a smaller landing. Testing compared amplitude and optical microscopy observation for deformations and wire-to-wire distance. The tests were able to conclude what negative effects a higher amplitude could cause to parts. The wire-to-wire analysis was able to conclude that there was a high degree of variability when it came to embedding wires that were of such small diameter.
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Chapter 1

INTRODUCTION

1.1 Background

Additive Manufacturing (AM) is the process in which material is placed in a layer-by-layer fashion to build parts. This process has expanded recently from prototyping to the production of end use parts. However, to expand AMs capabilities and increase the number of end use applications, AM has begun including multiple manufacturing methods. This hybrid manufacturing (HM) process enables parts to be multifunctional in their role. Multifunctionality includes both the creation of parts with fiber reinforcement and electrical systems. The incorporation of fiber reinforcement aids in overcoming mechanical performance issues and inherent manufacturing problems such as porosity. Electrical systems included can take advantage of AMs ability to produce lightweight components that can be rapidly deployed.

The focus of this paper would be on the electrical systems that are implemented in the HM produced parts. Typically, the end goal of using electrical systems is to produce parts that can function with their original intended goal with the addition of an active or passive electrical system. Active electrical systems provide the user with the ability electrical power, whereas passive systems do not generate power. Investigation of this area typically includes the use of liquid metals, conductive polymers, inserted wires, and surface deposition. The W.M. Keck Center for 3D Innovation at the University of Texas at El Paso has developed a system that can produce these multifunctional components through the usage of hybrid manufacturing process. The Multi3D Foundry system utilizes two material extrusion (MEX) machines, a robotic arm, and a custom tool system to produce parts. The custom tool system includes a laser solder, micro paste dispenser,
and the ultrasonic wire embedding (USWE) system. Electrical systems are placed into a substrate or cavity that has been deformed using ultrasonic energy. These parts can then be placed back into the MEX machine to encapsulate them.

The aim of this paper was to use multiple sensors to better understand the USWE process that is currently utilized by the W.M. Keck Center for 3D Innovation. As mentioned previously the USWE tool can deform substrates to securely fasten copper wire, however, it was unknown how the parameters affected the embedding outcome. To identify and characterize the process, the use of two sensors, an accelerometer and load cell were mounted on the USWE assembly, additionally, power signals were captured directly from the ultrasonic power supply system. Specimens were built using a Fused Deposition Modeling (FDM, a Stratasys trademark term) system out of polycarbonate (PC). Substrates or cavities were built using the FDM system and would not be machined. Ultrasonic energy was used on copper wire that was placed in the substrate to securely fasten it. Data collected during this process was analyzed and whose events were characterized to better understand the embedding process. Discrimination between data was analyzed to create process conditions that can aid in automatic system and reduce the need for data collection and supervision. Varying parameters were tested and observed such as clamping force and energization duration to determine detrimental effects on the specimen.

1.2 Motivation

For novel technologies to grow and become a viable option when competing against conventional methods, there must be an understanding of the process. To address this, parameters must be experimented with, and data must be collected and analyzed to determine what can be
optimized. The ability for this hybrid process to grow is needed to have the process fully understood.

Consolidation has always been an important and critical factor when working with AM. This process allows for complex and otherwise difficult geometry to be built, creating a process that can combine parts. Consolidation can further be exploited as it provides the ability to reduce the weight of systems which is crucial when working with aerospace and aeronautic projects. This can be further expanded as the ability to incorporate electrical systems which is beneficial for creating multifunctional parts that act as a housing and as an electronic. The critical issue as previously mentioned was understanding what process parameters affect the system while also knowing the best way to mitigate any damage that might occur when implementing these electrical parts.

The usage of ultrasonic embedding can be utilized to capitalize on the consolidation aspect of AM through the incorporation of electrical systems. However, there are limitations in the understanding of the ultrasonic welding process that are still being investigated. It has been found that through the use of in-situ monitoring on these processes can aid in understanding the USWE process. This would in turn be able to be used on further iterations of this system and implementation in the convergent machine that is currently being developed at the W.M. Keck Center for 3D Innovation. In addition, by fully understanding and exploring the parameters being used, the parts that can be produced can have an increase in quality while a reduction of time is needed in identifying parameters that can work with the current project at hand.

1.3 Thesis Objectives

The objectives this thesis will address include the following:
1. Instrument the Ultrasonic Wire Embedding system to characterize three sources of data produced during embedding process.

2. Discrimination of data to produce meaning when comparing embedding parameters.

3. Identify process parameters that limit the plastic deformation to ensure that no lasting damage occurs during the process.

4. Improved process parameters as to minimize pulse duration while still being able to achieve a proper embed.

1.4 Thesis Outline

This outline is meant to give the reader an overview of what the experiments were, what was able to be determined through the dissection of the data collected, and what was determined through the data for further usage and implementation of this system. The literature review in Chapter 2 would give a background of multi-functional parts, the usage of the ultrasonic energy in conventional systems, and in-situ monitoring of ultrasonic welding systems. Chapter 3 would detail the preliminary work done in creating a multiple sensor system, early characterization of signal data, calibration, and specimen design. Chapter 4 outlines the final system design. Chapter 5 would be methodology testing, and data analysis along advancements made using the wire embedding system. Chapter 6 would be the investigation of the results that were found from the data collected in the previous section. Chapter 7 would highlight the important aspects that were found during this process while also discussing the implementation of the system and further progression.
Chapter 2

LITERATURE REVIEW

2.1 Introduction

The focus of this thesis is on utilizing data collected during the USWE process to identify and characterize events to yield improvements on parts produced, provide improved parameters, and gain a further understanding of signals produced. A review of similar applications was conducted over the background of HM and multifunctional components within AM. The understanding of ultrasonic welding (USW) systems was crucial in providing a means to process and work the USWE. Lastly, the characterized work that has been conducted on USW systems through in-situ data collection and signal processing was reviewed to gain a further understanding of the effects that ultrasonic energy has on thermoplastics.

2.2 End-Use Applications

Additive manufacturing (AM) has garnered large interest over the course of its development for the ability to produce parts that are complex in geometries and can be produced a singular piece (Pérez et al., 2020). In recent years AM has managed to mature to the point that end-use applications are the focal point of manufactures. To be able to compete against traditional manufacturing methods, AM has sought to use convergent technologies or hybrid manufacturing (HM). HM is the process in which multiple machines or processes are combined to effectively double the manufacturing process when compared to the single processes (Lauwers et al., 2014). This forward-looking solution can overcome shortcomings and gaps that exist in manufacturing methods. This implementation can be seen with the use of vibration-assisted machining of ferrous and brittle materials. With the addition of the small amplitude and high frequency the diamond
tool can have an increase life expectancy while having improved surface finishes, and better form accuracy (Brehl & Dow, 2008). Similar interest in this area is shown in laser assisted machining which aims to ease the use of hard and brittle materials. By utilizing a focused laser beam to heat local areas and remove soften material, the cutting system leaves high quality and crack-free surfaces (You et al., 2020). Lastly media-assisted machining can supply high pressure cooling lubricants to improve the machining of hard and brittle materials. This process increases cooling and lubrication can reduce the thermal load the tool experiences and allows for higher cutting speeds (Grzesik & Ruszaj, 2021, p.; Klocke et al., 2011).

However, this process is not just limited to conventional manufacturing as AM has taken interest in this area. Hybrid AM process is defined by adding one or more secondary processes or energy sources that can affect the parts quality, the three key features that are associated with this are: fully coupled processes, cooperation, and part and/or process improvement (Sealy et al., 2018). The focal point of this literature review section would be over part and/or process improvement as this process aims to increase part quality, functionality, and process performance. For example, the use of equal channel angular pressing and extrusion yields improved strength and ductility in parts (Azushima et al., 2008). Other examples in this area can be seen using surface treatments such as utilizing plasma (Qian et al., 2008), laser shock peening (Kalentsics et al., 2017), and micro-rolling (Zhou et al., 2016).

2.3 Electronic Implementation

The HM approach for AM has seen parts being produced to serve multifunctional roles through the incorporation of electrical systems or increasing strength through the addition of fiber reinforcements. For instance, it aimed to determine the effects of adding chopped carbon-fiber (CF) into acrylonitrile butadiene styrene (ABS) specifically on fracture toughness (Young et al.,
2018). A double cantilever beam (DCB) test was conducted using ASTM D5528 and ASTM D5045 for the testing geometry. It was observed that the CF that was added lowered the fracture toughness comparative to neat ABS. This was due to the CF acting as a brittle inclusion which is known for its reduction in fracture toughness in polymers (Friedrich, 1985). Similarly, CF was used to reinforce a thermoset plastic named “Onyx” acquired from Markforged® (Ghebretinsae et al., 2019). The plastic used was a micro carbon filled nylon that was the matrix material. Tensile testing was conducted using ASTM D3039 and five specimens were constructed. Results showed a promising 560MPa in tensile strength, however, delamination was the common failure factor in tensile testing. Further work in this area was conducted using long strands of fiber reinforcement. attempted to increase the strength of PC using CF bundles (Jahangir et al., 2019). This attempt was done to address the issue of porosity which is common in AM (Ngo et al., 2018). Samples were prepared using a Fortus 400mc FDM system with ASTM D638 type I specimens being printed where CF used was unidirectional carbon fibric. CF was secured at ends using Permabond 820 high-temperature-adhesive to ensure movement did not occur when fabrication continued. During tensile testing, it was found that the increase of the number of CF bundles increased the yield strength. With an increase of 77% compared to the neat PC samples evaluated. Comparably, continuous CF was used to reinforce polylactic acid (PLA) (Tian et al., 2016). The FDM system used in this was developed independently for this research. PLA was acquired by FLASHFORGE Corp. and carbon fiber from TENAX-J Corp. PLA and CF were both fed into the liquefier combining them before extrusion. ISO 14125:1998 was used for flexural strength testing. With parameters such as flow rate, hatch spacing, layer thickness, and liquefier temperature optimized, printing of the PLA and CF was deemed successful. With a maximum of 27% CF content the average flexural strength was reported to be 335 MPa.
The primary focus of this literature review is on the electrical implementations that are possible with AM. As stated by (MacDonald & Wicker, 2016) to expand the adoption of 3D printing end-use products, fabricated structures need to be more than simple geometries that retain sufficient mechanical strength and shape. An example of this can be found at the W. M. Keck Center for 3D Innovation at the University of Texas at El Paso which has produced 3D-printed electronic circuits since 2004 that can be implemented into cube satellites as 3D-printed modules (Espalin et al., 2014). Of the seven process categories for AM the primary area of interest in implementation of electronics are fused filament fabrication (FFF), direct writing (DW), and ink-jetting (Bekas et al., 2019). An example of utilizing this type of implementation can be seen with Stratasys’s collaboration with Optomec Inc. in fabrication of a 3D printed smart wing for unmanned aerial vehicles (UAV) (David del Frenso, 2013). The process used Stratasys’s FDM system to produce the wings while Optomec Inc. used Aerosole Jet printing to build the circuitry into the UAV’s wing. This example showed the development of a system integrated utilizing a HM approach to produce end use applications.

Electronics implemented into systems can be broken into two categories, passive and active (Tan et al., 2016). Passive components refer to electronics that do not generate power or gain during operation such as resistors or capacitors. Active components generate power or gain during operation such as transistors and diodes. The process of adding copper wires into components has been attempted in implementing passive electronic components into 3D fabricated parts. One such attempt at this has been conducted by pre-impregnating the wires into a filament before extrusion (F. Ziervogel et al., 2021). This process aims to reduce the issues that are typically seen with electronics placed in components, specifically the high resistance and low conductivity seen in conductive pastes, surface deposition and conductive polymers. In this research, the wires were
fed into a modified X350 Pro FFF printer that utilized its dual extruder to print both a Polylactic Acid (PLA) filament and the polymer filament that had wires impregnated into them. The attempt was a success, however, the need to contact these wires was done through contact plates and threaded insert, this process had the contact plate pressed onto the end of the wire, whereas the inserts were placed in a pre-made hole. Through electrical testing the lowest resistance found for screw was 0.009 Ohms with the contact plate having a 0.059 Ohms, in addition, wires were not easily contactable as they were encapsulated. Further work in this area of utilizing wires in active device fabrication can be seen by having wires be fed beneath the extruder nozzle, encapsulating them by printing over them (Saari et al., 2015). The process has the wire function as a fiber and thermoplastic as a matrix to create simple electromechanical systems.

Conductive inks have been similarly applied to aid in the multifunctionality of 3D printed parts (Kazemzadeh Farizhandi et al., 2020). Research has been aimed to create biocompatible and conductive ink that can be 3D printed to create a flexible electronic that can be placed in vitro to a patient. The process would use a commercial Allevi 2 Bioprinter. Filament used were poly glycerol sebacate acrylate (PGSA) mixed with a zinc powder with an average mesh size of <325. Material was found to not have high enough electrical conductivity due to zinc having surface oxidation. The zinc was sintered using acetic acid then added to the PSGA mixture. This confirmed that conductivity increased from $0.0020 \pm 0.0008 \text{ Sm}^{-1}$ to $1.5397 \pm 0.3242 \text{ Sm}^{-1}$ when using a 40% PGSA and 60% zinc blend. Reaching the highest conductivity of $1.6886 \pm 0.4310 \text{ Sm}^{-1}$ on a 30% PGSA and 70% zinc blend. A flexible electronic was successfully built using additive manufacturing however, it still exhibits low conductivity comparative to copper wire and a higher level of resistance ($160.0000 \pm 36.0555 \Omega$). Other attempts to use inks have been made using inkjet printing, a process that has droplets of material be placed before drying or solidifying. The
use of different metals is often utilized to create electrical systems with silver leading the forefront on being a choice candidate due to the low bulk resistivity \(1.59 \times 10^{-9} \, \Omega \cdot m\), however, due to the cost of materials this choice is often not viable for mass production (Beedasy & Smith, 2020).

Work with photo curable resin has been explored to print conductive structures (Tsai et al., 2022). This process takes metal fillers and places them in the resin formula to create a conductive contact without the need for sintering. Due to low filler ratios typically found with this process the conductivity exhibits a lower value than what was desired. Ways to work around this issue can be found by adding conductive metal powders to the process. This requires a sintering step to be conducted after curing to remove the plastic resin, however, the process typically leads to shape deformation and causes the conductive tracks to be difficult to form (Lee et al., 2006).

Further exploration has had research conducted into printing filaments that provide electrical conductivity, thus, eliminating the need of passive electrical systems such as copper wire. One process used FDM technology to print non-conventional polymer nanocomposites to create electrically conductive polymer structures (Gnanasekaran et al., 2017). The polymers consisted of two different blends of Carbon Nanotubes (CNT) and graphene-based polybutylene terephthalate PBT. The first blend was a PBT/CNT mixture and a PBT/G mixture. A commercial desktop printer was used to print the structures evaluated. PBT/CNT, and PBT/G powder mixtures were created and extruded with a diameter of 0.3 mm at 240°C. Results reported that PBT/CNT printed structures offered higher elasticity and conductive properties than the PBT/G mixture, however high resistance was reported with low conductivity. Conductivity peaked at 10 (S/m) which is significantly lower compared to copper at 5.96x10^7 (S/m). Similarly investigated conductive materials that was used in fused filament fabrication (FFF) to build 3D-printed strain gauges (Stano et al., 2020). The process used three different conductive filaments that are commercially
available. AlfaOhm a Polylactic Acid (PLA) filament with CNT, Fabbrix CNT, and Ninjatek Eel a thermoplastic polyurethane (TPU) doped with carbon black. Two different desktop printers were used both containing dual extruders. The materials were found to have increased electrical resistance and variability dependent on layer height along with orientation effect. Parts had to be built using a parallel to build platform to lower conductivity and use a 0.3 mm layer height. While this paper did succeed in creating strain gauges, constraints are placed to lower resistance, but this causes limitations on the 3D printing process.

2.4 Ultrasonic Systems

Ultrasonic welding is a popular method in which thermoplastics are joined together using friction and heat, the process has a wide range of applications such as automotive, aerospace, medical, marine, and electronics (S. Bhudolia et al., 2015; S. K. Bhudolia et al., 2019, 2020). To understand the USWE process, the ultrasonic welding (USW) system that was used needed to be understood before characterization could occur. USW is the process in which ultrasonic energy at high frequencies (15-300 kHz) is used to produce mechanical vibrations (Thapliyal, 2021; Troughton, 2009, p. 2). This solid-state welding process uses a power supply system that converts the power into high frequency and high voltage that is sent to a transducer, the transducer converts that electrical signal into mechanical vibrations. Mechanical vibrations are sent through a sonotrode or horn that acts as an amplifier, the vibrations are directed to the toe or tip of the sonotrode which can vibrate creating friction. The horn design is imperative for any operation that requires ultrasonic energy to be guided/focused on a specific region. If the horn’s design does not meet requirements the resonant frequency would not be achieved, the vibration system would receive impairment in performance, and damage may occur to the generator (Nad & Cicmancova, 2012).
In addition to understanding how the USW system operates, the signals produced during the welding process are still a large focal point in developing the USW. Basic understandings such as the heating process are still under investigation (Zhang et al., 2010). This can be seen as previous understanding of heating of interfaces was from interfacial friction of the contact surface however, the process can be concluded that viscoelastic heating was the main source of heat generation. Further investigation of the effects that welding pressure and welding time has been investigated for optimization of the USW process. An example of this can be seen with the attempt to optimize the welding of PEEK-Carbon composites (Harras et al., 1996). The experiment found that proper joint strength could be obtained within fewer seconds provided the correct conditions were met. Surface pressure at 3.8 MPA and the input energy from the ultrasonic controller was 6.8 J/mm² with a 10% deviation in energy from either direction. Other processes that aim to identify and correlate the data capture using sensors is ultrasonic wire bonding (USB), a process which applies a force and ultrasonic energy to join wires together (Harman, 2010). An example of this is determining if the increase of applied force or amplitude has a positive or negative impact on the bonding process (Mostafavi et al., 2018). This study found that while a slight increase in the loading force does have an impact on the overall joint strength of wires that were bonded, the increase was found to be negligible and if too much force were to be added, a negative impact on bond strength were observed. However, this also found that with increased amplitude and with a constant load force the welding was increased as the wires had a faster bonding rate with over increase in strength. Recent work in this area has attempted to characterize the various stages that occur during the USW process for power and displacement (Villegas, 2015). The goal of this research was to establish connections between the transformations that occurred during the welding of thermoplastic composites and the power/displacement data readings that were obtained
from the ultrasonic welder. The use of CF/PEI was used as the resin functioned as an indicator as it reflowed after continued heat application. A 20 kHz ultrasonic welder was used with the duration of 1 second and welding forces of 1500 N and 300 N were used. During a weld, the signals were broken into stages to clearly identify and discriminate when events would occur. Stage 1 is denoted by a ramping power stage, in this the power would increase linearly to correspond with the amplitude until gradually decreasing and reaching a peak. The second stage had an overall power decrease in a step-like fashion that is attributed to localized melting and re-solidification of the resin as heat is transferred from the affected areas into surrounded cooler zones. With third and fourth stage having a squeeze flow occur with displacement decreasing at the start of three and having the thickness of the weld line decrease until reaching zero at the fourth stage. At stage five, deformation occurs with porosity and delamination beginning to take notice as power begins to decline as the composite’s substrates begin to melt. The main conclusion of this was that the power and displacement data can be utilized for in situ monitoring and determining quality of welds along with adjusting process parameters for the material.
Chapter 3

EXPLORATORY WORK

3.1 Wire Embedding Sensor Testing

The challenge of characterizing ultrasonic wire embedding (USWE) events progressed throughout the development of this technology. Previous work cited had shown that correctly implementing an electrical system was imperative to creating a functional hybrid part. The USWE process offers the capability that other works have shown but with the capability that copper wire offers specifically, the high conductivity of copper (5.96 x 10^7 S/m) and low resistance (1.68 x 10^8 \Omega \cdot m). However, the ability to fully secure the wire without significant deformation and fully understand the process was important, as better understanding can aid in further development and implementation of this process. Data was to be captured and events characterized to fully define improved parameters.

Initial testing utilized an Omega Low-Profile 45 Kg (Omega Engineering, Norwalk, CT, USA) load cell to capture data during the embedding process. The load cell was implemented in proximity to the ultrasonic transducer during testing, shown in Figure 1.
Tests had the ultrasonic horn energize for a pulse duration of 0.50s while moving across the specimen. There would only be movement in the X direction and did not have the horn raise from the specimen until after the programmed G-code had finished. Data captured was insufficient in displaying events that occurred during the embedding process. The data shown in Figure 2 does not provide identification between the process events such as the wire being fully embedded, energization, and system movements, however, the change in load does identify when events occurred but does not provide exact timing.
To further understand USWE events, a second sensor was implemented to capture data. The Omega low-profile 12 kHz (Omega Engineering, Norwalk, CT, USA) accelerometer was initially placed on the specimens during embedding, however, this was phased out as the sensor was integrated onto the tool assembly (Figure 1). This new placement was done to allow data to be captured on any part that required wire embedding without the need of a mounting hole that was placed on the part. The sensor was mounted in proximity and above the load cell being mounted directly into a screw that runs through the load cell. This one axis accelerometer would provide vibrational data during the USWE event. With the sensor operating at 12 kHz, data collected did not have the 20 kHz frequency from the horn to be captured. Data collected proved to be insufficient in identification of USWE pulse activation period Figure 3. This was due to the
horn being continuously dragged against the specimen’s surface, the results created events that did not indicate exact beginning and end periods.

The implementation of a Z direction movement was a self-imposed necessity for further clarifying the data. This movement would provide clarification to the USWE process by having distinct differences between the system movements and embedding events. The use of G-code would have the horn start at a Z zero position on a specimen’s surface, a pulse activation would occur, the horn would then move to the next embedding position but be at a 1-inch Z height above the specimen, the horn would then move to the Z zero position and begin second pulse activation. This process was termed as spot embedding. To provide a consistent period for Z movements a feed rate of 60 inch/min was used to give each Z movement a 1 second time interval. This addition provided clarification in vibrational data and load placement during an embed sequence by giving accurate and consistent periods of movement and deacceleration.
during the embedding process. However, the energization starts, and end periods were not identifiable as the vibration and load changes did not provide sufficient data to determine these events Figure 4.

![Figure 4: Load Cell and Accelerometer Z Movement](image)

Expanding the data collection process with the ultrasonic power delivery system was a self-imposed necessity as the system was able to accurately determine the energization start and end periods. For this the Dukane 20HB240 power delivery system’s signal output was connected to the National Instruments (NI) (National Instruments, Austin, TX, USA) C Series Multifunction I/O Module 9381. When analyzing data with a 0.50 second pulse duration the data curve showed a ramp period that did not reach a plateau or stabilize as shown in Figure 5.
Further investigation found that the ramp up period was set to 0.50s, thus the system was continuously increasing power but was being cut short before the stabilization period. Testing determined that by having the ramp up period be 10% of the total energization time allowed for scalable ramp up times for the different durations assessed.

Duration for the wire embedding process was found to be excessive and had the time reduced from 0.50 s to 0.20 s. This was done as parts produced using the shortened time did not have any negligible defects when using visual observations. In addition, this reduction in time increased the ability to produce parts at quicker speeds and when embedding multiple wires in close proximity to each other (1 mm) there was no deformation found on the parts.

### 3.2 Calibration

Calibration of the sensors was necessary as the initial setup used the NI Data Acquisition (DAQ) default parameters. To confirm that the parameters that were used in the default settings
were incorrect, a weight of -37.81 N was loaded onto the load cell. The weight was checked prior with a scale and had values of -37.81 N confirmed before loading. The natural signal measured was -35.58 N before addition of the weights, when the weights were loaded onto the system the total load was -80.68 N. This reading was higher than what the combination of the two signals would have been at an estimated -73.39 N. The data acquisition sheet from Omega was utilized in calibration of the load cell; the load cell’s virtual instrument (VI) allowed for several parameters to be changed.

After calibration, the characterization of the load cell was checked for the natural signal that was produced. The load produced was an estimated -13.77 N which when added the weights (-37.81 N) produced a -51.58 N, confirming that calibration was successful of the data collection system. In addition, the ultrasonic transducer, sonotrode, connecting screw, and accelerometer assembly be removed to capture the natural signature of the load cell. The signal that was captured during this process was an estimated -1.33 N, which was in approximation to a zero load.

For the accelerometer, the default and new parameters were not compared like the load cells were. The calibration of the sensor was important, and the parameters were changed within the accelerometer’s VI utilizing the calibration sheet provided by Omega, however, during USWE the acceleration of the system was not the focal point. The vibrations that the system would detect during gantry movement and horn energization were focused on and did not require the same calibration test to determine if acceleration were accurate.

An additional leveling system was implemented that would have the vacuum table be mounted onto as shown in Figure 6.
This uses the T-slots that were a part of the CNC system, T-slot studs that were connected to round coupling nuts were mounted 9 inches apart forming a square. At each of the four corners where the coupling nuts were located a 2-inch screw was placed through the platform and mounted into the coupling nuts. A pair of hex nuts with locking washers were used above and below the platform allowing for a level platform that can be secured. The vacuum table was screwed into the leveling platform and was used as an indicator of parallelism when leveling and calibrating the system before embedding.

### 3.3 Signal Characterization

To accurately identify and discriminate signals that were collected during an USWE process, the system was characterized under the following conditions; idle in air, moving in air, and idle on a specimen were captured. In addition, a singular pulse energization was captured in
air and on a specimen without wire. The signals were captured in a relaxed state as shown in Figure 7. This idle state brings an understanding of what the system looks like while not in operation allowing for filtering of noise that could be mistaken for an energization event.

The process had maximum, minimum, median, and average numbers taken for all three of the sensors used as shown in Table 1 below.

Table 1 Idle Air Signal

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accelerometer (g)</th>
<th>Load Cell (N)</th>
<th>Power Delivery (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum value</td>
<td>-0.00266</td>
<td>-13.959</td>
<td>2.20</td>
</tr>
<tr>
<td>maximum value</td>
<td>0.00664</td>
<td>-13.029</td>
<td>37.62</td>
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<td>median value</td>
<td>0.00172</td>
<td>-13.506</td>
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<tr>
<td>average</td>
<td>0.00173</td>
<td>-13.479</td>
<td>2.60</td>
</tr>
</tbody>
</table>

It should be noted that the ultrasonic power delivery system had power spikes during the data collection process; these inconsistencies that occurred do not indicate the horn activating due to
power delivery limitations. However, the rest of the values do indicate that the USWE had a range of 2.20 W – 2.60 W, the clamping force of a -13.959 N – -13.029 N, and acceleration of 0.006645 g – -0.00266 g.

A similar test was conducted with the horn being placed onto a specimen without a wire as shown in Table 2. The horn was loaded for an estimated 25 N and did not have any pulse activation done. When compared to the previous test there were signal differences that were considered to be insignificant, the only exception to this was the load cell due to the clamping force that was added.

Table 2 Idle on-Specimen Signal

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accelerometer (g)</th>
<th>Load Cell (N)</th>
<th>Power Delivery (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum value</td>
<td>-0.00363</td>
<td>21.381</td>
<td>2.20</td>
</tr>
<tr>
<td>maximum value</td>
<td>0.00845</td>
<td>22.392</td>
<td>33.96</td>
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<tr>
<td>median value</td>
<td>0.00161</td>
<td>21.884</td>
<td>2.20</td>
</tr>
<tr>
<td>average</td>
<td>0.00162</td>
<td>21.883</td>
<td>2.48</td>
</tr>
</tbody>
</table>

System movements were captured for the X, Y, and Z directions. The test had a movement of 15 inches in each of the respected coordinates at a feed rate of 60 inches/min. The load and wattage during this time did not experience significant changes as there were no additional forces or activations during this time. However, as previously stated the accelerometer was used to detect system movements and vibrations saw changes during movements. These were useful as identification of system movement was used in identifying when events occurred. As shown in Table 3, the X and Y movements showed insignificant variation between each other, however, the Z movement had a more pronounced effect on the accelerometer. This effect
was attributed to the fact that the axis of the accelerometer was configured for the Z direction.

Table 3 X, Y, Z accelerometer comparison

<table>
<thead>
<tr>
<th>Sensor Accelerometer (g)</th>
<th>X movement</th>
<th>Y movement</th>
<th>Z movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum value</td>
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<td>-0.02597</td>
<td>-0.14920</td>
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<tr>
<td>maximum value</td>
<td>0.027274</td>
<td>0.03244</td>
<td>0.16515</td>
</tr>
<tr>
<td>median value</td>
<td>0.00172</td>
<td>0.00169</td>
<td>0.00157</td>
</tr>
<tr>
<td>average</td>
<td>0.00172</td>
<td>0.00172</td>
<td>0.00157</td>
</tr>
</tbody>
</table>

Multiple pulse energization events were captured to identify power usage while in air. A total of eight pulse activations were captured for this test, each pulse had a duration of 0.20 s with a ramping period of 0.02 s and was carried out at 85% amplitude or 0.0408 displacement. Amplitude refers to the increase of displacement added through the gain of horn and amplitude of the transducer, for the tapered steady decrease horn a gain of 2.4 was multiplied by amplitude percentage with the set amount the ultrasonic system operates with, for this system that was 0.020 mm. A hold period where no energization happened for one second in between each of the pulse activations. Table 4 shows the values that were recorded during the air pulse test, the accelerometer and load cell did not record significant changes during the energization. The amount of power that was collected indicates the pulse activation occurred and that even without a surface to direct this energy into a significant amount of power was utilized.

Table 4 Pulse Energization in Air

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accelerometer (g)</th>
<th>Load Cell (N)</th>
<th>Power Delivery (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum value</td>
<td>-0.00274</td>
<td>-14.055</td>
<td>2.20</td>
</tr>
<tr>
<td>maximum value</td>
<td>0.00660</td>
<td>-13.007</td>
<td>135.33</td>
</tr>
<tr>
<td>median value</td>
<td>0.00176</td>
<td>-13.507</td>
<td>2.20</td>
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<tr>
<td>average</td>
<td>0.00176</td>
<td>-13.479</td>
<td>7.07</td>
</tr>
</tbody>
</table>
A comparison test was conducted with the horn being placed onto the center of the specimen Table 5. This test saw the use of an estimated 35 N with a 0.20 s pulse duration and 0.02 s ramp up period with an amplitude of 85%. The energization of the power delivery system saw a decrease in power used when placed onto the specimen when compared to in air. This was assumed to be caused by the horn sitting in air and having no contact with any objects allowing for the energization to increase freely before reaching a steady state. In addition, there was a lack of wire that was used resulting in less need of energy.

Table 5 Pulse Energization on Specimen

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Accelerometer (g)</th>
<th>Load Cell (N)</th>
<th>Power Delivery (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum value</td>
<td>-0.00363</td>
<td>21.392</td>
<td>2.20</td>
</tr>
<tr>
<td>maximum value</td>
<td>0.00844</td>
<td>21.883</td>
<td>33.95</td>
</tr>
<tr>
<td>median value</td>
<td>0.00162</td>
<td>21.884</td>
<td>2.20</td>
</tr>
<tr>
<td>average</td>
<td>0.00163</td>
<td>21.883</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Additionally, the horn was loaded onto a specimen to determine the distance needed to achieve loads ranging from 0 – 35 N with 5 N increments (Figure 8). This was done to identify the distance needed to reach a certain clamping force. This can additionally be used to identify how much the amplitude effects the system.
3.4 Wire Embedding Specimens

Specimens utilized were printed out of PC that was purchased from Stratasys. The initial iteration of specimens was printed with the following dimensions, 101.6 x 101.6 x 7.62 mm as shown in Figure 9. Each specimen was to have ten substrates/cavities that was 101.6 x 0.457 x 0.762 mm. This allowed for the usage of 24 AWG (0.508 mm) copper wire to be embedded into specimens.
This design proved to be adequate until the need to incorporate the previously mentioned accelerometer. To accommodate the accelerometer a raised platform was implemented into the specimen design which would have the accelerometer be mounted into a hole that was threaded after printed. This platform had a 29.21 x 29.21 x 2.54 mm dimension as shown in Figure 10; however, this inclusion caused the substrates to be shifted 38.8 mm causing overlap during the embedding process. After a brief period, the accelerometer was incorporated into the ultrasonic wire embedder system and had the platform removed.

Figure 9: Original specimen, Dimensions of body top view (left), Dimensions of substrates front view (right)
The current iteration of specimens had the length reduced to a 100.6 x 41.48 x 2.59 mm, this was implemented to reduce the time to produce parts and to consolidate the data being
acquired as shown in Figure 11.

Additionally, the substrate depth was reduced to 0.254 mm, this was done as optical microscopy observations determined that the previous 7.62 mm did not allow for the wire to be fully embedded, instead the wire would sit an estimated 1.5 layers or 0.381 mm above the substrate’s bottommost region shown in Figure 12.

Figure 11: Current specimen, Dimensions of body (left), Dimensions of substrates

Figure 12: Initial channel depth at 3.2x magnification (left), Current channel depth at 3.2x magnification (right)
3.5 Formatting Tools

The data produced during the collection process was difficult to work with and required a substantial amount of time to produce workable data that could be easily used and compared. To remove this issue, tools were created using both MATLAB (MathWorks, Portola Valley, CA, USA) and Excel (Microsoft Corporation, Redmond, WA, USA). Shown in Figure 13 the unprocessed data that was extracted during a wire embedding event. In this the Amplitude – Plot 0 was the accelerometer data, Amplitude – Plot 1 was load cell, and the USW was the power delivery system for the USWE. It can be seen that while the load cell and accelerometer were synchronized, the USWE was not and was required to be set to a time zero. USWE data produced was in volts and required a conversion and load cell produced data in lbs. Additionally, the accelerometer and load cell had data that would skip time. This meant that the total duration of the
event was still there however, not every single 0.001 s was captured.

To fix these issues of data synchronization and conversions of units a MATLAB code was developed (Figure 14). The code would allow the user to bring in an Excel file that was output by the data collection system. The pulse time and ramp time were able to be edited dependent on the process that was being tested. A scaling factor was added to convert the volts into Watts when working with the USWE data. Start and end drop percentage allows edits to be made based on how much of the beginning and the end should be selected should duration change.

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</table>

Figure 13: Unprocessed Data
Once the user variables have been set, the data had the time extracted and then converted into an array. The time between points was then found and then had the signal that was received during data collection be extracted and converted into an array (Figure 15).

Data that had been placed in a graph used a smoothing factor in order to easily find the gradient between the slopes and get the peak of an embed event. This factor can be changed to be higher or
lower depending on what user preference was. Once the gradient had been calculated it was inverted to find the end gradient of the event Figure 16.

Figure 16: Gradient example

Using these gradients, the MinPEAKProminence function was used with the beginning and end gradients to identify positive and negative slopes for the peaks and trough or valleys Figure 17.
Lastly, the peaks were found for the horn when it begins to energize and when it de-energizes. This would take the times found and then shift them to a start time of t=0 to get a starting time. From here the accelerometer, load cell, and USWE energy were plotted and graphed together (Figure 18).

Additionally, cumulative energy was found from the USWE by using the trapz function to find the area under the curve by breaking the graph down into trapezoids. Impulse time was found in a
similar manner for the load cell and spectral analysis for the accelerometer using fast Fourier transformation Figure 19.

```matlab
energy(i) = {[time_zeroed(i), cumtrapz(USWE(start_time_idx(i):end_time_idx(i)))]};
%f1 = figure;

impulse_time = time_load_event_zeroed{i};
impulse_signal = cumtrapz(cell2mat(load_events_zeroed{i}(:,2)));

accel_spectral = fft(cell2mat(accel_events_zeroed{i}(:,2)));
```

Figure 19: MATLAB Cumulative Energy (top), Impulse Time (middle), Spectral Analysis (bottom)

Similar tools have been created using Excel to quickly break down the data and then produce multiple graphs that allow for users to compare rapidly (Figure 20). The data Formatting Tool allows users to bring in data manually in step 1. In step 2, the duration, load, ramp period, and amplitude was able to be changed for labeling the graphs. Step 3 was the attempt to produce a synchronized time for the load cell and USWE power. The True Start Time needs to be equal to the Load Max Time, the Time Shift Factor allows users the ability to shift the times to produce this equality by adding or subtracting time. The graph gives the user a visual aid in synchronization and de-synchronization. The blue table was used to convert the load into newtons and gives an additional visual of the changing time. Lastly in Step 4 the sorting value was a minimum threshold value, meaning that if the power wattage was 24 or higher the data was to be broken down. This value was user set and could be changed dependent on the parameters used during embedding. Pre-Event and Post Event would determine how much time was grabbed before and after the sorting value was picked.
After data had been sorted from the user input the tool it was sent to the Tool Sorting section (Figure 21). There was no user changes done in this section. Data was placed in charts that would determine when events occurred. The event start was listed, and the rows grabbed until reaching the end, the true start was listed and had the time before the ramp up period considered to provide a full chart and not just the middle of the event.

![Figure 20: Formatting Tool User Input](image)

![Figure 21: Formatting Tool Sorting](image)
To continue in ease of data analysis the formatted data was then placed into individual graphs for each of the sensors (Figure 22). A time of t=0 was used to synchronize, and the formatted data was easy to select and move to the Plotting Tool.

![Figure 22: Formatting Tool Output](image)

Data was transferred to the Plotting Tool, this gave users the ability to enter information regarding the test into the graph such as, the test, date, number, success condition, load, duration, ramp up, and amplitude Figure 23. The tool allows for multiple graphs to be plotted simultaneously allowing for easy of comparison between data.
From this input tab, eight tabs were used to graph the eight different events that were found during the data formatting section (Figure 24). The load and accelerometer were graphed against each other to identify patterns that happened in both and had the power separate but compared to the other plotted events. The tool allows for 4 tests to be easily and quickly built and compared on the same tab without having to move between other tabs unless there was need to view other events.

Figure 23: Plotting Tool USWE, Load Cell, and Accelerometer User Input screen
To further advance the USWE system and produce parts that utilize smaller wire and pitch distances, modifications were made to an ultrasonic welding tip. A 12.4 mm diameter titanium tip was used that had modifications made to the landing section. As shown Figure 25 in the tip was modified in a conical style to maintain the geometry and distance that was used during wire embedding but had a reduction in size to 0.26 mm.

Figure 24: Plotting Tool USWE, Load Cell, and Accelerometer Output

3.6 Novel Tip Design
This horn was used to embed 34-gauge (0.16 mm diameter) copper wire into cavities that were 0.28 mm in width and had a pitch distance of 0.22 mm. As shown in Figure 26, the wires would run parallel to each other for 15.57 mm before reaching a connector that could be inserted and
soldered onto after embedding.

Figure 26: Connector specimen
Chapter 4

SYSTEM DESIGN

Overview

In Chapter 3 the work detailed directly influenced the ultrasonic wire embedding and data collection process. The direct understanding of the wire embedding process was considered and addressed using each of the accompanying sensors previously mentioned. Repeatability was prioritized to ensure that consistent data collection was achieved during an embedding process. Figure 27 displays an image with the set-up of the sensors used. The sensors were primarily placed near the ultrasonic converter to maximize the precision of the data collected.
4.1 Ultrasonic horn and Power Supply

The ultrasonic systems utilized a Dukane IQ 20HB2402CR1 power delivery system, this system uses a 20 kHz frequency transducer with a horizontal bench chassis, 2400 Watt with a 200-240 V line input, an LCD status panel, and a remote amplitude control board. A titanium tapered steady decrease ultrasonic horn was used with a titanium tip (12.7 mm diameter), both provide a reduction in wear and uneven patterns that can occur after multiple usages. The power delivery
system works to provide the horn within a range of 19.4 kHz to 20.4 kHz, for testing purposes the frequency was left at the free running frequency setting (Hz) of 19.9 kHz. The power supply allows users to change the amplitude used during activation, the range from 20% to 100% was available, this allowed for the system to output 0.020 mm of displacement. In addition, the horn added a 2.4x gain to the 0.020 mm at the maximum 100% amplitude leading to 0.048 mm of displacement. For this process, amplitude was varied to determine the effects that different amounts of displacement had on wire embedding. This system additionally allows users to input a ramp up and a ramp down time for ultrasonic activation. Ramp up allows the horn to reach maximum amplitude over a set period (0.250 s to 1.250 s), whereas the ramp down time de-amplifies the horn over a given period (0.250 s to 0.000 s).

4.2 Load cell

The ultrasonic horn had two different clamping loads added prior to wire embedding, the loads were changed to compare the effects on the USWE. To ensure a consistent and repeatable force was applied to the surface of the parts a load cell was implemented. The load cell used was an Omega Low-Profile 45 Kg rated unit shown in Figure 28, data was read by a National Instruments C Series Strain/Bridge Input Module 9237 with a 4-Channel Analog -25 mV/V to +25 mV/V reading. Data was recorded at 1.00 sample per second (S/s) using National Instruments LabVIEW software and used. Additionally, the load cell was used to capture and identify events during a wire embedding process.
4.3 Accelerometer

An accelerometer was implemented to further assess the wire embedding process. The accelerometer’s frequency response was considered, and it found that it would not be able to capture the ultrasonic horns frequency of 20 kHz as the range was limited to 12 kHz. This would not pose an issue as the movement of the horn during an embedding process was the area of interest. The one-axis accelerometer used was an Omega ACC797 Premium Low-Profile Accelerometer 12kHz frequency rated shown in Figure 28. Data collected was captured in g’s where one g was equal to 9.81 m/s² with a maximum of 50 g. Associated module used was a National Instruments C Series Sound and Vibration Input Module 9234 with a 4-Channel Analog -5 V to +5 V. Data collected at 1.00 S/s using National Instruments LabVIEW software.
4.4 Power Measurements

To further the understanding of the ultrasonic embedding process, the period in which the ultrasonic pulse activation occurred was required. To implement this data collection the Dukane IQ 20HB1202CR1 system output was utilized. Wires were connected to Pins 13 (ground) and 15 (power signal monitor output) which were soldered to a National Instruments C Series Multifunction I/O Module 9381. Module 9381 was an 8-Channel Analog Input and Output with a range from 0 V to +5 V. This module was specifically used as the low output from ultrasonic system was difficult to capture using a large voltage scale. Data was collected at 1.00 S/s using National Instruments LabVIEW software. Data collected was converted from volts into Watts using the conversion factor found in the Dukane operating manual (1 VDC = 0.001 W).

4.5 Data Collection

The integration of three data collection systems was done through the use of three virtual instruments (VI). These VIs would as the communication method between the sensors and the modules. Data collected was taken directly from the VI and from the cRIO, this was done as the load cell and accelerometer used a different capturing system than the power delivery system.

The load cell and accelerometer used the data acquisition (DAQ) assistant as it provided the customizability needed when working with sensors. The power delivery signal used the Real-time (RT) scan engine as the process enables the use of I/O channels to capture and store data. These two different scanning methods to capture data were split into their own VIs that were used as a global variable to start and stop them as shown in Figure 29. This main VI would bring both of the RT and DAQ VIs into a single VI, which would initialize both and have them deploy and run immediately after one another. This did cause a delay in starting times however this issue was fixed by setting the start times to zero for comparison.
The DAQ assistant VI as previously mentioned was used for the ability to set parameters that were used by the sensors as shown in Figure 30. This allowed for each sensor to be calibrated and set to the specifications that the vendors provided. In addition, the sensors were combined to follow a singular internal clock. This clock was set to continuously gather samples at a rate of 1 S/s.
This data would enter a while loop that was used to determine the overall time the system ran using at a start time of zero \((t = 0)\) outside of the loop that would enter and then be subtracted from the number of times the loop was counted Figure 31. Doing so would provide the total duration by subtracting \(t\) by the number of times the loop was recorded to have run for. The data was sent into an index array which would transpose the data. From there, the data was sent into an index array which was used to split the data into two different forms. Data was combined with time into a bundle function that was sent to a build array to create a graph that showed both acceleration and
Due to the RT data acquisition system being a different software than the DAQ the setup did not require any inputs or sensor calibration. The RT structure was placed in a flat sequence
which initializes various stages of the process Figure 32.

When saving the data acquired during events the technical data management (TDM) file format was used. This process saves data onto the CRI0 or onto a USB device plugged into the cRIO port. Data was saved using the USB setting. A start time would initiate in the first sequence and data would have a save file created Figure 33.
In the next sequence data was put in a timed loop that was synchronized to the scan engine and have a period of 1 and priority of 10. These numbers were set to capture data in the period required (0.001) and had the priority number be selected based on execution. Period was the time elapsed between two iterations and priority was the set execution priority of the first frame. From this timed loop data was sent from a global buffer into a while loop that would have the time be in seconds in the thousands be sent into a case structure that would build the array from the time and data. The array data was reshaped and then sent to the TDMs file. The final sequences was used
to save and shutdown the RT sequence once the global stop variable was activated Figure 34.

Once this was completed the global stop variable was used on the main VI to end sequences on both the RT and DAQ VIs.
Chapter 5

METHODODOLOGY

5.1 Experimental Setup

In this research the main goal was to characterize the ultrasonic wire embedding process and produce improved process parameters for future implementations. Parts were produced out of PC using a Stratasys Fortus 400mc FDM (Stratasys, Eden Prairie, MN) system. 24-gauge copper wire with a diameter of 0.508 mm and 34-gauge copper wire with a diameter of 0.16 mm were embedded into the PC parts. Parts were transferred from the FDM system onto the CNC router (Techno CNC Systems, Ronkonkoma, NY). Wires were placed manually onto the substrate before lowering the horn into a Z zero position. Z zero was set prior using the load cell to attain the force needed before setting the height as a Z zero in the CNC interface. Once secured, the wire was extended to the end of the substrate. G-code was written to have the wire embedding be done in a spot-welding way, the horn energizer then de-energizes beginning to move in a vertical direction over to the next embedding position, the horn then lowers itself into the new position before the next pulse energization. Each of the three sensors would capture data during this process and was exported into Excel and MATLAB for data processing. Various parameters and ultrasonic tips were experimented with during this process.

5.2 Leveling

Before testing, the adjustable leveling platform had the ultrasonic tip be placed on the four corners of the vacuum table. During testing it was deemed necessary that the clamping force used was consistent as changes in force can lead to varying quality of embeds. A clamping force of 35 N was set on the upper right corner of the vacuum table and had the positioned zeroed. The
horn was then move to each of the four corners and held for 5 seconds. Horn movements were
done using the spot-welding method, the horn was placed in each corner and be moved vertically
to each of the other respected corners before lowering. This was done to get more accurate
leveling readings and not to damage the vacuum table or horn assembly. The mean, standard
deviation and variance were calculated and used to compare the changes in reading of the load
cell.

5.3 Pulse Duration

The total energization period was investigated to determine if the use of 0.20 s was
excessive and could be reduced while still having wires that were fully secured. Settings used were
0.02 s ramp up duration with a 35 N clamping force and 95% amplitude. Time periods used were
0.20 s, 0.15 s, and 0.05 s. In addition, two securing pulses of 0.20 s were used and then had the
time reduced to 0.05 s.

5.4 Clamping Force

Varying amounts of clamping force were utilized during the testing process to investigate
the effects it had on wire embedding. Testing was conducted on parts with 5 N, 35 N, and 747 N.
Loads used the load cell to ensure the correct force was applied during the process. The air
pressure system was used to counter these loads using a constant 1.7 Bar for all the loads except
for 747 N, which, required 5.5 Bar to operate. Clamping force was set on the specimen prior to
the placement of wire. Amplitude was kept at 85%, a pulse duration of 0.20 s, and a ramp up
duration of 0.02 s with 24-gauge wire used.
5.5 Amplitude

The power delivery system allowed for varying amounts of amplitude to be supplied to the transducer ranging from 20% to 100%. Amplitude varied from 75%, 85%, and 95% of the total displacement distance. Pulse duration was kept at 0.20 s with a 0.02 s ramp up duration. The clamping force used in this testing varied as follows: 5 N, and 35 N. Testing used 24-gauge copper wire. The air pressure system was used to counter these loads using a constant 1.7 Bar for all the loads.

5.6 Novel Tip Design Amplitude

During testing, four specimens were constructed, each containing six channels that had a pitch distance of 0.221 mm between them, the channels were machined out using a 0.254 mm end mill. The modified tip was used to embed 34-gauge wire at 25% (0.024 mm) and 85% amplitude with a 0.010 s pulse duration, 0.02 s ramp up time, and a clamp force of 35 N on two specimens. One wire was embedded onto each of the specimens and the effects that the amplitude had on the substrate and part quality were investigated through microscopy observations. The other two specimens had the 34-gauge wire embedded at 25% amplitude at 0.010 s pulse duration with a 0.02 s ramp up time and a clamp force of 35 N. All six wires were embedded on each of the specimens totaling for twelve wires. Pitch distance was observed with shortest and widest measurements being taken. The deviation from the estimated pitch distance was noted and investigated.
Chapter 6

RESULTS

6.1 Leveling Test

The first position was used as the zero position and had a mean reading of 16.88 N, position 2 had an increase in mean of 20.86 N, position 3 increased higher to a mean value of 25.35 N, and position 4’s mean reduced to 13.31 N (Figure 35). As the horn was moved to the right side of the vacuum platform, the loads increased the further away from the position 1. With position 3 being the highest of the values, while position 4 was lower than all values reported. Using the load cell, the detection of these changes were observed and recorded. These changes could be used to make corrections to provide a constant and consistent load throughout the embedding process. The mean that was found from the four calculated mean values was to be an estimated 19.10 N with a standard of deviation at 5.18. This correlation indicates the next value that was reported with the deviation was 24.282 N or 13.914 N from the mean. The variance of the data was found to be 26.87 N. Distance away from the mean was calculated by subtracting each of the measured mean values for positions 1 – 4 and subtracting from the previously mentioned 19.10 N.
6.2 Duration Testing

Initial testing of both the 0.20 s pulse duration saw a large decrease in load and an increase in vibration, this was thought to have been a region of interest where the wire had successfully been embedded into channel. This area can be seen in the accelerometer signature (Figure 36) and the load cell signature (Figure 37), where the amplitude was 95% with a 0.20 s pulse duration and a 0.02 s ramp up time with a 35 N clamping force.

Figure 35: Clamping force recorded at vacuum platform corners

<table>
<thead>
<tr>
<th>Load from mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.) -2.21 N</td>
</tr>
<tr>
<td>2.) +1.76 N</td>
</tr>
<tr>
<td>3.) +6.25 N</td>
</tr>
<tr>
<td>4.) -5.79 N</td>
</tr>
</tbody>
</table>
Figure 36: Accelerometer Event 2 Initial 0.20 s Test
The area of interest occurred at an estimated 0.05 s time period, in an attempt to reduce the overall time and energy usage a test was conducted with the time was used. This time was attempted but did not successfully embed the wire, after the first embed event, the wire would spring out of the placement and did not stay within the channel. Another test was conducted with 0.15 s and had the wire be held manually in place. Similar to the 0.05 s wire, the 0.15 s pulse duration was unsuccessful in embedding the wire, however, data was captured for this process. As
shown in Figure 38 the accelerometer had a similar peak during the second event.

![Figure 38: Accelerometer Event 2 Initial 0.15 s Test](image)

When looking at the load cell for the same event 2, the trough that was noticed in the successful 0.20 s was noticed Figure 39.
This disproved the notion that these peaks and troughs were indications of a successful embed. Upon further inspection however, the charts showed an additional peak that denoted a successful and unsuccessful embed event. A comparison of the accelerometer for the 0.20 s and 0.15 s was done at that peak.
The 0.20 s accelerometer denotes a sharp peak that begins just before the vibrations have a begin to sharply decrease in magnitude whereas the 0.15 s accelerometer does not exhibit this and had a rounded peak that occurred before a decrease in magnitude as shown in Figure 40.

Figure 40: Accelerometer 0.20 s (left), Accelerometer 0.15 s (right)

Figure 41: Load Cell 0.20 s Event 2 (left), Load Cell 0.15 s Event 2 (right)
The load cell reading indicated that there was no peak that occurred before the magnitude drops during the embedding event, however, this peak does occur at the 0.15 s Figure 41. This was important observations as it was used to further determine if successful embedding occurred.

Initial embedding events were observed to need more power when embedding. This can be seen when looking at the first event from 0.20 s 95% amplitude test. By taking the area under the curve for the power delivery system and comparing amongst the 8 events, event 1 requires a large amount of energy while embedding Figure 42.

![Figure 42: Estimated Cumulative Energy (J)](image)

The first two events were identified and determined to need additional pulse durations to achieve a successful embedding event. Reasoning for this was based on previous wire embedding testing, if the first two events were not successful in embedding the wire the third event would dislodge and undo the previous two wire embedding events. An attempt to produce a successful
embed event was conducted using two 0.20 s pulse durations to secure the wire and then attempting to embed the wire at the 0.05 s duration for the remain six. The second and third events were taken and compared for both the load cell and accelerometer.

![Figure 43: Securing event 2 Accelerometer 0.20 s (left), Lower duration event 3 Accelerometer 0.05 s (right)](image)

With the previous found information regarding the identification of a successful embed, the accelerometer graphs shown in Figure 43, indicate the embed was successful with the use of securing pulses as the definitive sharp peaks happened in both the 0.20 s and 0.05 s pulse duration. When looking at the load cell data there was no peaks before load begins to fall, however, it should be noted that the sharp peak for the second securing pulse upon further close up flattens before the drop Figure 44. It can be concluded that these events were indicator for the rounded ultrasonic tip having a successful embed. In addition, that using a securing pulse duration works and allows for the reduction in time for the remaining wire embedding events.
Various clamping forces were tested to identify and determine if any negative effects were seen while working with the specimens. The clamping force of 35 N control as testing using this force had yielded successful wire embeds. A comparison test was conducted on the highest load that could be achieved 747 N. Event 2 was used to compare both the tests for a wire embed event. As shown in figure x, the amount of power that was received into the substrate and wire for the 747 N test was significantly higher. Maximum power used was an estimated 700 W whereas the 35 N test was below 350 W for the maximum power and the estimated cumulative energy that was transferred was 41049.6 J for the 35 N and 102521 J for the 747 N Figure 45. This significant difference in power and energy can be due to the increase in load, as the tips surface area begins to have more contact with the surface of the substrate it was able to increase the amount of power and energy that can be transferred, this had been seen in literature when an increase of clamping force was added.

Figure 44: Securing event 2 Load Cell 0.20 s (left), Lower duration event 3 Load Cell 0.05 s (right)

6.3 Clamping Force
The acceleration for the 35 N saw a peak at 0.20 g and a trough of -0.04 g whereas 747 N saw a peak of 0.048 g and a trough of -0.04 Figure 46. Both did experience similar trend lines and troughs but did not exhibit the same peak. This was due to the clamping force not allowing for movement thus creating less vibrations.
The load experienced during the wire embedding event saw similar trends, indicating that the embedding event overall should be considered a success (Figure 47).

However, this force applied would not be used when working with specimens that were meant to be encapsulated. The reasoning for this was due to excess load, there were noticeable deformities that were from the tip, meaning that the despite getting pass data, there was damage that occurred to the part, in addition, the force being so large it would dislodge the specimens from their support material.
A reduction of load to 5 N was compared against the 35 N control test. The power used was similar with the amount of force that was applied, with only an estimated 100 W difference between the tests and had an estimated cumulative energy used was found to be 41049 J and 34735 J with an estimated 6300 J between them Figure 48.

![Graphs showing power and cumulative energy for 35N and 5N forces.](image)

Figure 48: 35N USE and estimated cumulative energy event 2 (left), 5 N USWE and estimated cumulative energy event 2 (right),

Acceleration saw a similar signatures during the embedding process, with both having an estimated 0.20 g for the max peak. However, the 5 N force saw more vibrational movement as the reduction in force allowed for more oscillations Figure 49.
Lastly the load cell for the 5 N saw several troughs occurred that with both being below an estimated -2 N Figure 50. Despite this, there was not a notable change in the signatures when embedding occurred.

Despite these results it was not conclusive when comparing against the control 35 N test, the 747 N and the 5 N as each of the tests resulted in similar signatures and had the 35 N showed the peak. Further comparisons were made plotting both the clamping force and accelerometer
together to determine if any irregularities or symmetries occurred. Shown in Figure 51, the embedding process for 35 N there was symmetry that happened during the process between the load cell and accelerometer.

Figure 51: 35N Test Clamping Force (orange), Acceleration (green)

When compared to the 5 N test there was also symmetry that occurred (Figure 52). This being
that whenever the load cell detected change the accelerometer also detected this event.

Through this it had been concluded that the peaks that occurred before the embedding event did not indicate a successful or unsuccessful embed. What can be gathered was that when the sensors begin to move in a synchronized fashion the process was successful. This can be compared to the 747 N test where the load was too heavy and as such did not see any of these events (Figure 53).
It should be noted that with this large amount of clamping force the system becomes unstable as the horn to change its position with each embedding event. However, unlike previous data shown, there was no sharp decrease in load and saw a gradual decrease over the course of an estimated 0.1 s. This significant drop could indicate the wire was in successfully in the cavity but had not been secured, the gradual decrease seen in the 747 N may indicate that the load had already pushed the wire into the cavity and when pulse activation occurs the plastic was...
being deformed as shown in Figure 54.

![Image: Figure 54: 35 N successful (Top), 747 N unsuccessful (Bottom)](image)

From this it can be concluded that both of the 5 N and 35 N loads were successful and that a reduction in load can aid in reducing time needed to create successful wire embeds.

### 6.4 Displacement Amplitude

The usage of multiple amplitudes was done to determine the effect that the additional displacement would have on wire embedding. 35 N at 85% was the control with comparison to the 75% and 95% amplitudes at that clamping force. The comparison between the USWE power between the three tests was graphed in Figure 55. It should be noted that the power delivered for 95% amplitude was higher than both the 75% and 85% amplitudes, respectfully. This increase in
power was likely due to the increase from amplitude, the additional distance gained from 95% amplitude was 0.0456 mm, causing more load to be added.

![Figure 55: 35 N 75% amp (orange), 35 N 85% amp (blue), 35 N 95% amp (gray)](image)

When comparing the accelerometer and load cell data for the data collected there was similarities between the 75% and 95% amplitudes as the signatures appeared to have a synchronized behavior after the large peak that was denoted by the accelerometer Figure 56.

![Figure 56: 75% amplitude (left), 95% amplitude (right)](image)

However, when compared to the 85% amplitude there was no synchronization that
occurred and thus this control could be considered to be a failed embed event for the second pulse activation. When compared to the third event in the control group this synchronization occurred after that large peak as shown in Figure 57.

Figure 57: 85% amplitude event 2 (left), 85% amplitude event 3 (right)

Additional testing was conducted at 5 N at 75%, 85%, and 95%. Similar to before the USWE power was compared against each other, the Figure 58 showed that power while lower for the 75% was still in close proximity to the other two amplitudes. No large discernable differences were seen besides sharp peaks that occurred which could only be lasted for a singular point before returning to a stable plateau.
However, when comparing the acceleration and load cell data, the 85% had synchronization between the sensors (Figure 59). Comparatively both the 75% and 95% amplitude saw the signals not have this occurred, however, the clamping force used in the 95% amplitude was significantly lower than the 75% and 85% amplitudes. This error in the load was caused by the leveling platform being unlevel.

As for the 75% never reaching that synchronization needed this does occurred for other events in that embedding process which the cause was the reduction in amplitude at that loading
force allowed for there to be less contact with the substrate. However, it can be concluded that with this synchronization data, the ability to identify when specific events failed was capable and that multiple levels of amplitude were viable for wire embedding but there was still dependability on the load being applied.

6.5 Novel Tip Design

The single wire embedded specimens had each wire be embedded and secured in the channel however, the lower amplitude specimen was considered a pass whereas the higher was considered a failure. As shown in the Figure 60 below, the 25% amplitude did not cause any surface deformation and had the remaining 5 channels still be viable for wire embedding. The 85% amplitude was a failure due to the large cavities that the horn created when wire embedding. These cavities caused the plastic to deform and rendered only the last channel on the far-right side to be viable for wire embedding.

![Figure 60: 25% amplitude (left), 85% amplitude (right)]
The USWE power collected during the embedding of the two amplitudes was shown in Figure 61 for the first event. Power from this showed that with a larger amount of amplitude applied to the substrate and copper wire more energy was sent into the specimen. Additionally, it should be noted that the power for the 85% amplitude does experience a similar spike that indicates the embedding event was a failure. For this process, the spike was denoted as a point of failure as the equipment used was different than the conventional horn tip.

![Power Graph](image)

Figure 61: 25% amplitude power event 1 (blue), 85% amplitude power event 1 (orange)

Event 4 for both of the amplitudes was shown in Figure 62. For these events, the power indicates as before that the increase in amplitude increases the amount of power that was received through the work piece. Additionally, the spike that was seen in previous power events was noticed here for the 85% amplitude.
Data collected from the load cell and accelerometer indicates that the 25% amplitude did not experience significant load change during the wire embedding process. Shown in Figure 63 the acceleration and load cell graphs for event 1 of both the 25% and 85% amplitude. The force experienced by the 25% amplitude did not have a substantial change during the wire embedding process whereas the 85% amplitude saw the load decrease and only slightly raise after this.

Figure 62: 25% amplitude power event 4 (blue), 85% amplitude power event 4 (orange)
decrease.

This can be attributed to the fact that additional displacement added at 25% was 0.012 mm whereas the 85% was 0.0408 mm. The load change was considered evidence that the plastic was melted due to the amount of heat caused by the friction and the more concentrated landing part of the ultrasonic tip (0.254 mm). Previous tips used were all flat with a larger area of contact (12.7 mm) whereas the tapered conical shape was thought to act as an additional energy guide.

Figure 63: 25% amplitude clamping force (blue) and acceleration (teal) event 1, 85% amplitude clamping force (orange) and acceleration (green) event 1

This can be attributed to the fact that additional displacement added at 25% was 0.012 mm whereas the 85% was 0.0408 mm. The load change was considered evidence that the plastic was melted due to the amount of heat caused by the friction and the more concentrated landing part of the ultrasonic tip (0.254 mm). Previous tips used were all flat with a larger area of contact (12.7 mm) whereas the tapered conical shape was thought to act as an additional energy guide.
similar to the ultrasonic horn. Further investigation in this was checked at the fourth event during the wire embedding process Figure 64. The events had similar signals as the first event in which the force experienced by 25% amplitude saw only an increase during the wire embedding event, this can be attributed to the leveling platform being slightly unlevel causing a height that was higher than initially starting with. The sharp dip seen in this graph was the event being over. However, the 85% amplitude sees a sharp decrease in load and then a slight raise before the event was completed. This along with the first event saw significant deformation to the plastic
that left cavities in the specimen.

Further work in this area saw the use of the other two aforementioned specimens. Using current successful parameters of 0.1 second pulse duration with a 0.02 second ramp up time and 25% amplitude with an estimated 35 N clamping force, twelve 34-AWG wires were successfully embedded and fastened into the channels. To understand the discrepancy that the wire embedding process had at this current stage images were taken on an optical microscope using

Figure 64: 25% amplitude clamping force (blue) and acceleration (teal) event 4, 85% amplitude clamping force (orange) and acceleration (green) event 4
1.25x magnification, the images looked at 3.56 mm of the specimen from the top section opposite to where the Molex connector was positioned (Figure 65).

![Figure 65: Specimen 1 at 1.25x (left), Specimen 2 at 1.25x (right)](image)

Distance between wire to wire was noted and counted using the edge detector that was available from NI Vision (National Instruments, Austin, TX, USA). Shortest and widest of the wire-to-wire distances were taken into account and had their pixel distance taken. Images were converted into grayscale to use the edge detector feature. The distance between the wires had a were sectioned using the following; the first number was the specimen (1 or 2) and the section looked at (1-5), it should be noted that the whole section was looked at in the image and not just the placement of the label. The pixels were converted using the following equation

\[
\frac{0.254 \text{ mm}}{198 \text{ Pixels}} = \frac{x}{\text{Pixels Distance}}
\]

to determine the total distance from the wires. Data was taken from both of the specimens and put into two tables that had the average, standard deviation, variance, and range calculated.

Table 6 showed that the variation between the widest and shortest distances of each of the wires would indicate that there was failure to maintain the fabricated distance of 0.254 mm. The
average of both the widest and shortest was larger by 0.1391 mm and 0.0754 mm respectfully. A standard deviation of 0.0612 mm and 0.0646 mm was found with a difference in ranges of 0.1501 mm – 0.1629 mm.

Table 6 Wire-to-wire distances specimen 1

<table>
<thead>
<tr>
<th>Specimen - Section</th>
<th>Widest (mm)</th>
<th>Shortest (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>0.4182</td>
<td>0.3323</td>
</tr>
<tr>
<td>1-2</td>
<td>0.2848</td>
<td>0.2181</td>
</tr>
<tr>
<td>1-3</td>
<td>0.4118</td>
<td>0.3810</td>
</tr>
<tr>
<td>1-4</td>
<td>0.4349</td>
<td>0.3541</td>
</tr>
<tr>
<td>1-5</td>
<td>0.4156</td>
<td>0.3618</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.0612</td>
<td>0.0646</td>
</tr>
<tr>
<td>average</td>
<td>0.3931</td>
<td>0.3294</td>
</tr>
<tr>
<td>variance</td>
<td>0.0037</td>
<td>0.0042</td>
</tr>
<tr>
<td>range</td>
<td>0.1501</td>
<td>0.1629</td>
</tr>
</tbody>
</table>

Similar to the previous table, Table 7 showed that the wire also did not manage to maintain the 0.254 mm distance that was expected during the fabrication of these specimens. With a larger standard of deviation in the both the widest and shortest distances. This can be attributed to the section 2-3 which was an outlier when compared to the other four results due to the wires close proximity to 2-4.
Both tests were considered failures with their inconsistency with the distance between wires. However, when attempting to soldering to the Molex connector there appeared to be no issues given the position of the wires. It should be noted that the wires do need to maintain a certain distance and these issues can be corrected through the implementation of a lead that can hold the wire straight and flush to the channel. Using this tip provides a reduction in pulse duration and amplitude, aiding in providing improved process parameters. While there had not been testing conducted on smaller gauge wires, it could be anticipated that the larger diameter wires can be embedded using this modified tip.

Table 7 Wire-to-wire distances specimen 2

<table>
<thead>
<tr>
<th>Specimen - Section</th>
<th>Widest (mm)</th>
<th>Shortest (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>0.4028</td>
<td>0.2707</td>
</tr>
<tr>
<td>2-2</td>
<td>0.3348</td>
<td>0.2707</td>
</tr>
<tr>
<td>2-3</td>
<td>0.7145</td>
<td>0.4041</td>
</tr>
<tr>
<td>2-4</td>
<td>0.3669</td>
<td>0.0936</td>
</tr>
<tr>
<td>2-5</td>
<td>0.3348</td>
<td>0.2425</td>
</tr>
<tr>
<td>standard deviation</td>
<td>0.1611</td>
<td>0.1106</td>
</tr>
<tr>
<td>average</td>
<td>0.4308</td>
<td>0.2563</td>
</tr>
<tr>
<td>variance</td>
<td>0.0259</td>
<td>0.0122</td>
</tr>
<tr>
<td>range</td>
<td>0.3797</td>
<td>0.3104</td>
</tr>
</tbody>
</table>
Chapter 7

DISCUSSION

This research helps expand the hybrid technology that is currently being implemented to incorporate electronics into AM fabricated parts. With the ability to increase functionality of parts, this enhancement will be able to create end use parts that can be implemented into aeronautical and astronautical applications. This is a large area of interest as the functionality of parts aids in reduction of weight while providing a cleaner internal system as wires can be stored in the part itself. The future of the W.M. Keck Center is the combination of the ultrasonic wire embedding tool in a system incorporates all the Multi3D with the addition of multiple axis, this system is known as the All-in-One. However, to correctly implement the ultrasonic wire embedder into the system there needed to be basic understanding of the process parameters and the impacts that this had on the parts. The expansion of the system is apparent as the use of 34-gauge wire was used in parts which at the time of writing is the smallest wire to ever be used, but it does open a new door for analysis on data captured from there as it does not follow the similar trends seen when using the flat round tip. In addition, the ultrasonic horn does create friction and thus generates heat which if implemented into the All-in-One multi axis printer should be investigated as the chamber is heated and could cause damage to the parts. Furthermore, when embedding wire for long durations the adhesive that is used to secure the specimens begins to burn. This is another area that can be investigated as the total amount of energy lost during a embed may indicate that the further optimization can be made during the embedding process. Lastly the auto leveling system the is currently being developed would a large contribution to the system as incorrect loading can be detrimental to the overall process and the part. Lastly, a system to mount and hold the wire during embedding was advantageous as the current process requires drilling into a horn to produce a
cavity that the wire can be fed into, this can cause frequency to change due to the altered shape of the horn and may lead to inferior quality wire embedding results. This wire mount can be seen to especially useful when embedding the smaller wires as even with constant in person monitoring the variation is larger than expected.
References


https://doi.org/10.1016/j.precisioneng.2007.08.003

David del Frenso. (2013, March 1). Revolutionary “Smart Wing” Created for UAV Model Demonstrates Groundbreaking Technology.


Appendix

MATLAB Code for Data Analysis

clear all
clc

% declare known information and processing variables
pulse_time = 0.20; % in seconds
ramp_time = 0.02; % in seconds
power_scale_factor = 1000; % this will scale the raw data to power in W
start_drop_perc = 0.6; % this is the drop from peak to define start or end of event
end_drop_perc = 0.98; % this is the drop from peak to define start or end of event
filename = "SN 0.20_0.02_8Amp";
time_err = 0.003;
load_tare_val = -3.5; % -3.5 N needs to be tared to brind load to 0 at no load at horn

% create string and open file
filetype = "xlsx";
full_file_name = append(filename,’.’,filetype);
num = readtable(full_file_name);

% files should have signals in following order
% column 1: USWE time
% column 2: USWE signal
% column 3: accel time
% column 4: accel signal
% column 5: load time
% column 6: load signal

% split columns and create arrays for USWE
time_USWE = num(:,1); % extract time column
USWE = table2array(time_USWE); % convert to array
time_step = time_USWE(2)-time_USWE(1); % calculate the time step between measurements
USWE = num(:,2); % extract voltage signal column
USWE = table2array(USWE)*power_scale_factor; % scale voltage to power and convert to array

% split columns and create arrays for accelerometer
accel = num(:,3); % extract time column
time_accel = table2array(time_accel); % convert to array
time_step_accel = time_accel(2)-time_accel(1); % calculate the time step between measurements
time_accel = rmmissing(time_accel); % remove empty cells
accel = num(:,4); % extract voltage signal column
accel = table2array(accel); % scale voltage to power and convert to array
accel = rmmissing(accel); % remove empty cells

% split columns and create arrays for accelerometer
load = num(:,5); % extract time column
load = table2array(time_load); % convert to array
time_step_load = time_load(2)-time_load(1); % calculate the time step between measurements
time_load = rmmissing(time_load); % remove empty cells
load = num(:,6); % extract voltage signal column
load = table2array(load); % scale voltage to power and convert to array
load = load-load_tare_val;
load = rmmissing(load); %remove empty cells

%create plot for raw data - USWE POWER
figure(2);
plot(time_USWE,USWE);
ylabel('USWE power (W)');
xlabel('time (s)');
legend('1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northwest');
title(append('USWE power from one sequence (raw data)
,-",filename)));

%create plot for raw data - ACCELERATION
figure(3);
plot(time_accel,accel);
ylabel('acceleration, g (g)');
xlabel('time (s)');
legend('1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northwest');
title(append('Acceleration from one sequence (raw data)
,-",filename)));

%create plot for raw data - CLAMPING FORCE
figure(4);
plot(time_load,load);
ylabel('clamping force (N)');
xlabel('time (s)');
legend('1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northwest');
title(append('Clamping force from one sequence (raw data)
,-",filename)));

%smooth the noisy data to easily find gradient
USWE_smooth = smoothdata(USWE,'gaussian', 'SmoothingFactor', 0.25); %smooth to easily find gradient
USWE_prime=gradient(USWE_smooth); %calculate the gradient
inv_USWE_prime=max(USWE_prime)-USWE_prime; %invert to find gradient valley at end of event

%pks, locs = findpeaks(USWE_prime,time_USWE,'MinPeakProminence',1,'Annotate', 'extents'); %identifies peaks for positive slopes
[valley,locs_val] = findpeaks(inv_USWE_prime,time_USWE,'MinPeakProminence',1,'Annotate', 'extents'); %identifies valleys for negative slopes

events = {};
events_zeroed = {};
events_zeroed_accel = {};
accel_events = {};
energy = {};
search_range_idx = uint16(2*(ramp_time/time_step)); %index range from peak/valley for searching drop in gradient

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f5 = figure(4); % for accel data
f6 = figure(5); % for load data
f7 = figure(6); % for impulse data

for i=1:size(pks)
    peak_time_idx(i) = find(time_USWE == locs(i));
    peak_time_idx(i) = uint16(peak_time_idx(i)); % convert to unsigned integer
    valley_time_idx(i) = find(time_USWE == locs_val(i));
    valley_time_idx(i) = uint16(valley_time_idx(i)); % convert to unsigned integer

    % identify when the horn is first energized via peaks
    start_time(i) = find(USWE_prime(peak_time_idx(i)) == search_range_idx; uint16(1), 'last');
    start_time_idx(i) = start_time(i)+peak_time_idx(i)-ramp_time/time_step;
    start_time_idx(i) = uint16(start_time_idx(i)); % convert to unsigned integer

    % identify when the horn is fully de-energized via valleys
    end_time(i) = find(USWE_prime(valley_time_idx(i)) == search_range_idx; uint16(1), 'first');
    end_time_idx(i) = valley_time_idx(i)+end_time(i);
    end_time_idx(i) = uint16(end_time_idx(i)); % convert to unsigned integer

    % shift the time array to start at t = 0
    time_zeroed(i) = [transpose([0:time_step:time_step*(end_time_idx(i)-start_time_idx(i))]);

    events(i) = [(time_USWE(start_time_idx(i):end_time_idx(i)), USWE(start_time_idx(i):end_time_idx(i)));
    events_zeroed(i) = [(time_zeroed, USWE(start_time_idx(i):end_time_idx(i))]);

    % ACCELEROMETER - BEGINNING
    start_time_accel = find(time_accel >= (time_USWE(start_time_idx(i)) - time_err) &
                          time_accel >= (time_USWE(start_time_idx(i)) + time_err), 1, 'first');
    end_time_accel = find(time_accel >= (time_USWE(end_time_idx(i)) - time_err) &
                          time_accel >= (time_USWE(end_time_idx(i)) + time_err), 1, 'first');

    start_time_accel_zero = start_time_accel - start_time_accel(l);
    end_time_accel_zero = end_time_accel - start_time_accel(l);
    time_accel_event(l) = time_accel(start_time_accel:end_time_accel);

    time_accel_event_zeroed(l) = cellfun(@(x) x - time_accel(start_time_accel),
    time_accel_event(l), 'un', 0);

    accel_events(l) = find(time_accel(start_time_accel:end_time_accel) accel
                          (start_time_accel:end_time_accel));
    accel_events_zeroed(l) = [(time_accel_event_zeroed(l) accel(start_time_accel:end_time_accel));

    figure(9);
plot(cell2mat(accel_events_zeroed(i,:)1),cell2mat(accel_events_zeroed(i,:)2));
hold on;

accel_spectral = fft(cell2mat(accel_events_zeroed(i,:)2));

% find the trough that may indicate full embedding
% [troughs(i),trlocs(i)] = findpeaks(-accel_events_zeroed(i,i)(1,2)(1,:), 'NPeaks', 1,'MinPeakHeight', 0.1);
% trough_mag(i) = troughs(i)
% troughs_time(i) = accel_events_zeroed(i,i)(1,1)(trlocs(i))

% acc = detrend(acc,'linear');
N = length(time_accel_event_zeroed(i,:));
dt = mean(diff(time_accel_event_zeroed(i,:)));
fs = 1/dt;
P2 = abs(accel_spectral/N);
P1 = P2(1:N/2+1);
P1(2:end-1) = 2*P1(2:end-1);

f = fs*(0:(N/2))/N;
figure(10);
%plot(cell2mat(accel_events_zeroed(i,:)),accel_spectral);
plot(f, P1);
hold on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% ACCELEROMETER - END %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% LOAD CELL - BEGINNING %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

start_time_load = find(time_load >= (time_USWE(start_time_idx(i))-time_err)) & time_accel >= (time_USWE(start_time_idx(i))+time_err),1,'first');
end_time_load = find(time_load >= (time_USWE(end_time_idx(i))-time_err) & time_accel > (time_USWE(end_time_idx(i))+time_err),1,'first');

start_time_load_zero = start_time_load - start_time_load(1);  
end_time_load_zero = end_time_load - start_time_load(1);  
time_load_event(i) = time_load(start_time_load:end_time_load);

time_load_event_zeroed(i) = cellfun(@(y) y - time_load(start_time_load), time_load_event(i), 'un', 0);

load_events(i) = [(time_load(start_time_load:end_time_load) load(start_time_load:end_time_load))];
load_events_zeroed(i) = [(time_load_event_zeroed(i) load(start_time_load:end_time_load))];

impulse_time = time_load_event_zeroed(i);
impulse_signal = cumtrapz(cell2mat(load_events_zeroed(i)(:,2)));
plot(cell2mat(load_events_zeroed{i}(:,1)),cell2mat(load_events_zeroed{i}(:,2))); hold on;

figure(8);
plot(impulse_time,impulse_signal);
hold on;

energy(i) = (time_zeroed(i),cumtrapz(USWE(start_time_idx(i):end_time_idx(i))));

% f1 = figure;

% plot(time_zeroed, USWE(start_time_idx(i):end_time_idx(i)));
% ylabel('Power (W)');
% ylim([0 750]);
% xlabel('time (s)');
% y = energy(i); y(2);
% yyaxis right;
% ylabel('estimated cumulative energy (J)');
% plot(energy(i)(:,1),y);
% ylim([0 12000]);
% hold on;
end

figure(1)
plot(time_USWE,USWE,time_USWE,USWE_smooth,time_USWE,USWE_prime,locas,pks,'x',locas_val,
valley,'v',time_USWE(start_time_idx(i)),USWE_prime(start_time_idx(i)),'o',time_USWE(end_time_idx(i)),USWE_prime(end_time_idx(i)),'o')
legend('all USWE signals','Smooth USWE','gradient','Location','northwest');
title('USWE analysis for identifying start and end times of events');
ylabel('Power (W)');
xlabel('time (s)')

figure(5)
for i=1:1(2)
    hold on;
    plot(time_zeroed{i}(:,1), USWE(start_time_idx(i):end_time_idx(i)));
end

ylabel('Power (W)');
xlabel('time (s)');
legend('1','2','3','4','5','6','7','8','Location','south','NumColumns',2);
title(append("USWE power signals from one sequence",num2str(i),filename));
plot ENERGY

figure(6);
for i=1:1(2)
    hold on;
    t=energy{i};
    y=energy{i};
    plot(t,y);
end

ylabel('estimated cumulative energy (J)');
xlabel('time (s)');
legend(['1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northwest', 'NumColumns', 2]);
title(append('Estimated cumulative energy from one sequence','--',filename));

format CLAMPING FORCE plot

figure(7)
legend(['1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northeast', 'NumColumns', 2]);
ylabel('Clamping force, F (N)');
xlabel('time (s)');
title(append('Clamping force, F, from one sequence - ', filename), 'VerticalAlignment', 'bottom');

format IMPACT plot

figure(8)
ylabel('Impact (N s)');
xlabel('time (s)');
legend(['1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northwest', 'NumColumns', 2]);
title(append('Estimated impact from one sequence', '--', filename));

format ACCELERATION plot

figure(9)
ylabel('acceleration magnitude, g');
xlabel('time (s)');
legend(['1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northeast', 'NumColumns', 2]);
title(append('acceleration magnitude', '--', filename));

format ACCELERATION AMPLITUDE Spectrum plot

figure(10)
title('Single-Sided Amplitude Spectrum of a(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')
legend(['1', '2', '3', '4', '5', '6', '7', '8', 'Location', 'northeast', 'NumColumns', 2]);
set y limits for all plots

figure(1); ylim([0 800]);
figure(2); ylim([0 800]);
figure(3); ylim([-3 1.5]);
figure(4); ylim([-2 200]);
figure(5); ylim([0 800]);
figure(6); ylim([0 120000]);
figure(7); ylim([-0.5 180]);
figure(8); ylim([0 25000]);
figure(9); ylim([-3 1.5]);
figure(10); ylim([0 0.1]);

save figures

f1_filename = "USWE analysis for start and end points";
f2_filename = "raw USWE power";
f3_filename = "acceleration amplitude raw data";
f4_filename = "clamping force raw data";
f5_filename = "USWE power signals (aligned)";
f6_filename = "cumulative energy signals (aligned)";
f7_filename = "clamping force signatures (aligned)";
f8_filename = "impact signal (aligned)";
f9_filename = "acceleration amplitude signature (aligned)";
f10_filename = "acceleration spectrum signature (aligned)"

saveas(figure(1), f1_filename, 'png')
saveas(figure(2), f2_filename, 'png')
saveas(figure(3), f3_filename, 'png')
saveas(figure(4), f4_filename, 'png')
saveas(figure(5), f5_filename, 'png')
saveas(figure(6), f6_filename, 'png')
saveas(figure(7), f7_filename, 'png')
saveas(figure(8), f8_filename, 'png')
saveas(figure(9), f9_filename, 'png')
saveas(figure(10), f10_filename, 'png')
Pulse Duration Test 35N-0.20s-0.02s-95\% amplitude USWE Sample (MATLAB)

Pulse Duration Test 35N-0.20s-0.02s-95\% amplitude Load Cell Sample (MATLAB)
Pulse Duration Test 35N-0.20s-0.02s-95% amplitude Accelerometer Sample (MATLAB)

![Graph 1](image1)

Pulse Duration Test 35N-0.15s-0.02s-95% amplitude USWE Sample (MATLAB)

![Graph 2](image2)
Pulse Duration Test 35N-0.15s-0.02s-95% amplitude Load Cell Sample (MATLAB)

Pulse Duration Test 35N-0.15s-0.02s-95% amplitude Acceleration Sample (MATLAB)
Pulse Duration Test 35N-0.20s(x2)-0.05s(x6)-0.02s-95% amplitude USWE Sample (MATLAB)
Pulse Duration Test 35N-0.20s(x2)-0.05s(x6)-0.02s-95% amplitude Load Cell Sample (MATLAB)
Pulse Duration Test 35N-0.20s(x2)-0.05s(x6)-0.02s-95% amplitude Accelerometer Sample (MATLAB)
Clamping Force Test 35N-0.20s-0.02s-85% amplitude USWE Sample (MATLAB)
Clamping Force Test 35N-0.20s-0.02s-85% amplitude Load Cell Sample (MATLAB)
Clamping Force Test 35N-0.20s-0.02s-85% amplitude Acceleration Sample (MATLAB)
Clamping Force Test 5N-0.20s-0.02s-85% amplitude Load Cell Sample (MATLAB)
Clamping Force Test 5N-0.20s-0.02s-85% amplitude Acceleration Sample (MATLAB)
Clamping Force Test 747N-0.20s-0.02s-85% amplitude USWE Sample (MATLAB)
Clamping Force Test 747N-0.20s-0.02s-85% amplitude Load Cell Sample (MATLAB)
Clamping Force Test 747N-0.20s-0.02s-85% amplitude Acceleration Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-75% amplitude USWE Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-75% amplitude Load Cell Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-75% amplitude Acceleration Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-85% amplitude USWE Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-85% amplitude Load Cell Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-85% amplitude Acceleration Sample (MATLAB)
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Amplitude Test 5N-0.20s-0.02s-95% amplitude Load Cell Sample (MATLAB)
Amplitude Test 5N-0.20s-0.02s-95% amplitude Acceleration Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-75% amplitude USWE Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-75% amplitude Load Cell Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-75% amplitude Acceleration Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-85% amplitude USWE Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-85% amplitude Load Cell Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-85% amplitude Acceleration Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-95% amplitude Load Cell Sample (MATLAB)
Amplitude Test 35N-0.20s-0.02s-95% amplitude Acceleration Sample (MATLAB)
Amplitude Test 35N-0.10s-0.02s-85% amplitude Load Cell Sample (MATLAB)
Amplitude Test 35N-0.10s-0.02s-85% amplitude Acceleration Sample (MATLAB)
Amplitude Test 35N-0.10s-0.02s-25% amplitude USWE Sample (Excel)
Amplitude Test 35N-0.10s-0.02s-25% amplitude Load Cell Sample (Excel)
Amplitude Test 35N-0.10s-0.02s-25% amplitude Acceleration Sample (Excel)
Vita

Patrick Steven Gutierrez began his undergraduate career in 2015 at the University of Texas at El Paso. Worked with the United States Navy, specifically, Strategic System Programs which manages and operates the US’s ballistic missile fleet for the US Navy. He worked with facility engineering to solve operation environmental issues along with implementing a section in their ordinance document for replacement parts. Additionally, worked with flight control over ensuring compliance with the testing equipment.

In 2020 he graduated with his bachelor's degree in Mechanical Engineering and went into his master's degree the fall of 2020. In October of 2020 he began working at the W.M. Keck Center for 3D Innovation as a Graduate Research Assistant. During this time, he worked on producing training content for the DRIVE AM program, which is Driving Research Innovation and Value through Education Additive Manufacturing. The goal is to train military and DoD personal to enhance their workforce and the defense supply chain. Worked for the Aerospace Corporation to determine mechanical effects of embedded electronics.