ME450 Design and Manufacturing III

Fall 2015

Final Report

Team 20: Indoor Location Technology
ME 450 Section #5, Team #20

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Executive Summary

Many people rely on GPS to reach destinations, but once the destination is reached, there is no system for navigation to a desired location inside a building. With an indoor positioning system (IPS), users could view their location in a building and determine indoor routes. Additionally, the Federal Communications Commission (FCC) has set an objective to implement IPS to improve Enhanced 911 (E911) accuracy. Currently, there are over 200 start-ups and large firms in competition to develop IPS with most utilizing signals such as Bluetooth Low Energy (BLE) or WiFi for their product. None of these products have emerged as a frontrunner for IPS since the main challenge of finding balance among cost, capability, accuracy and longevity has not yet been achieved.

A better IPS product can be developed using magnetic positioning to generate a magnetic field using an extremely low frequency (ELF) signal. ELF consumes little energy and can travel through walls and objects; therefore avoiding troublesome issues encountered with BLE and WiFi. The main challenge with magnetic positioning is the size of the copper coil used to generate the magnetic field: it must be large enough to create a strong field, yet small enough for integration as a beacon into building infrastructure.

The ELF beacon is rectangluar-shaped for placement above doorways to tag users upon entering a room. Tagging occurs when the user’s smartphone magnetometer detects the dipole magnetic field of the beacon. The field is generated using a set-up that mimics a signal generator: Arduino Uno connected to Arduino Motor Shield, running C-code to create an ELF square wave, powered by batteries. By setting each beacon frequency to a distinctive value, user location can be determined based on unique identification.

The prototype beacon’s coil was wound by hand; therefore the largest gauge wire could not be used due breakage risk and the prototype is not fully optimized in terms of size. Future plans include winding a 40 gauge wire by CNC machine with atleast 2 layers to optimize size. The necessary magnetic field strength can be achieved with a beacon that is 0.03 m^3 in volume (an 85% decrease from the volume of the prototype of the project).

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1.0 Problem Description and Background

As personal location technology becomes more widespread, the concept becomes more widely known and previously impossible ideas become plausible. Today's GPS technology can pinpoint the position of a smartphone to around 30m. Location information is used in a variety of cell phone applications, but it is also helpful in emergency situations when 911 is called. The GPS location is sent to the dispatcher which helps first responders reach the emergency site faster. This location information is an excellent start, but not always helpful if the person is inside a complex building. The accuracy of the location, often represented by the area inside a circle in most map applications, varies depending on the geography, presence of obstacles, and number of cell phone towers nearby. If a person is in a multi-story building or place with weak signal, GPS location alone may not be enough. To remedy this, there has been a push to improve enhanced 911(e911) so that the dispatcher will have the target location within 10m accuracy. The overall goal is to optimize a prototype "beacon" module to improve user location accuracy inside buildings to fulfill e911 and other initiatives that require higher resolution location information, such as pinpoint location inside a building. The necessary technology using ELF (Extremely Low Frequency) exists, but the current prototype beacon is very large. The intention of this project is to minimize the size of the technology without compromising its output, then integrate the beacon into current infrastructure in a way that can be easily implemented.

1.1 Literature Review

There are currently several products for IPS on the market, but the technology required is still in the research and development stages.[1] The signals researched range from BLE[2] to augmented realities[3], but the majority of competitors use BLE.[1] Two of the most notable products on the market are iBeacon (an Apple technology) and RFID (Radio- frequency identification) tags (by Zebra Technologies). There are many other start-up and large firms that have expressed interest in developing indoor location technology, but have not yet emerged with a product.

iBeacon can determine a user's proximity to a beacon through a smartphone application that detects such devices using BLE[2] by identifying numerous beacons simultaneously, then calculating its relative distance from each (Triangulation)[4, 5]. This technology is mainly used in malls or museums (a concept known as "Smart Buildings"[6]) to send the user updates, ads or promotions based on their location and provide indoor mapping to assist the user in reaching a location.[7]

The iBeacon can be easily implemented by simply placing the beacon on a surface with or without adhesive, but consumers report that the beacons tend to fall off walls or get knocked off surfaces. Consumers also report that Bluetooth drains their phone battery. Consequently they turn off their phone signal and the beacons are rendered useless.[8] Although BLE has an accuracy of 0.5-1.0m[9], it has both low signal and amplitude resulting in a short range that requires more beacons to triangulate.[10] If more beacons are used, it will not only become costly, but the accuracy still can only increase to a certain level until the number of beacons is irrelevant.[11] In addition iBeacon is only compatible with iOS phones[12], so a significant part of the population is unable to use this technology.

In July 2015, Google released their own version of BLE indoor location called Eddystone which supports both Android and iOS.[13] Beacon hardware such as Estimote is now available using iBeacon or Eddystone[14], but since the Google technology only differs from Apple by being compatible for all users, the same problems with iBeacon will also exist for Eddystone. Zebra Technologies' RFID tags are used largely in industry as an inventory tracking system since they are passive[15] and do not require line-of-sight (a particular orientation) during the scanning process, unlike bar codes.[16, 17] Zebra Technologies also recently partnered with the NFL to incorporate RFID tags into players' uniforms to track their movements. Unlike the tags used in industry, the RFID tags are active and actually send out their own radio frequencies.[18] Both of these types of RFID tags have major downsides in terms of use for indoor location tracking; the passive RFID tags used for inventory tracking cannot transmit signals through objects or walls[1] and the active tags now being incorporated into NFL players' uniforms are battery-powered[18], which greatly increases power consumption.

Table 1: Overview of Signal Types for Indoor Location Technologies [1]

Category	Advantages	Disadvantages
Signal		
Inertial	No infrastructure need	Needs a reference system to reduce errors and determine initial position
Optical	High accuracy	In most cases is unfeasible to unknown places; requires high computational power
Geomagnetism	Requires only a magnetometer, being accessible for many devices	Needs mapping the enviroment in a offline phase; Suffers from holes
Radio	Can cover large areas; can take advantage of existing infrastructure; requires small amount of landmarks	Suffers from interference caused by objetcts and walls
Ultrasonic	High accuracy	Suffers from interference caused by humidity; requires high amount of landmarks
Measure Method		
Angulation	Requires only two reference points	Requires directional antennas
Dead-reckoning	Infrastructure independent	Requires another system to make periodic corrections and to provide initial position
Fingerprinting	Robustness	Unfeasible to unknown places; mapping phase can be expensive
Lateration	Position can be estimated based on reference points	Need at least three reference points
Proximity	Robustness	Requires high amount of landmarks
Scene Analysis	High accuracy	Requires high computional power
Infrastructure		
Created	Feasible to unknown places	Needs setup phase
Existing	No setup phase	Unfeasible to unknow places
No infrastructure	No setup phase; feasible to unknow places	Currently unfeasible

Table 1[1] shows a comparison of some of the different signals that could be utilized for indoor location technology as well as pros and cons for each. For instance, optical signals have an advantage of high accuracy combined with low power consumption and small beacon size, but they require line-of-sight [19] which is a large disadvantage. Ultrasonic signals also offer high accuracy, but they require a great deal of infrastructure and are so expensive that most users would not be able to afford it. [20] Out of all of the options shown in the table, radio signals are commonly explored by developers in their work [1], but of all the major companies and startups exploring indoor location technology, most find their focus with BLE/Wi-Fi.

The major difference between the ELF technology and iBeacon/Eddystone is the use of location versus proximity. iBeacon and Eddystone use BLE to determine the proximity of a user to the beacon, but not to pinpoint the user's exact location. The goal with ELF is to provide this information to the user. There are other companies utilizing Wi-Fi, radio frequency (Zebra Technologies' RFID tags in NFL uniforms) and cellular RF to achieve similar goals, but such a low frequency such as ELF has major advantages including its kilometers-long wavelengths and lack of interference caused by objects or walls.

2.0 User Requirements

Table 2 shows the design requirements of the beacon.

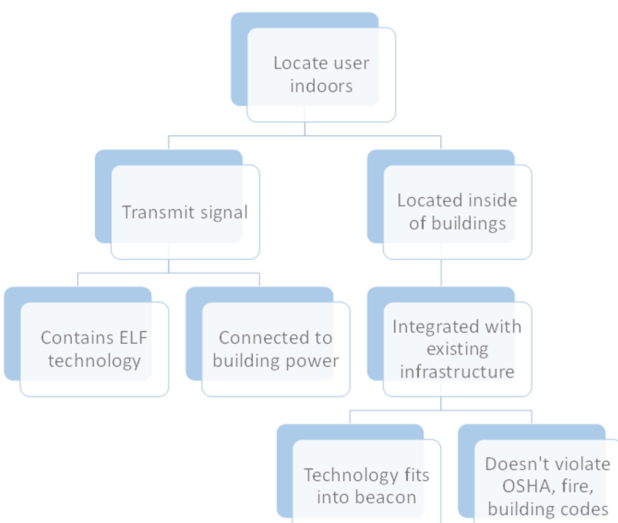
Table 2: Design requirements for beacon

User Requirements
Beacon integrated into infrastructure
All users can tag and triangulate
Low power consumption
Doesn't violate building, OSHA, fire codes
Easily implemented
Technology fits into beacon

3.0 Concept Generation

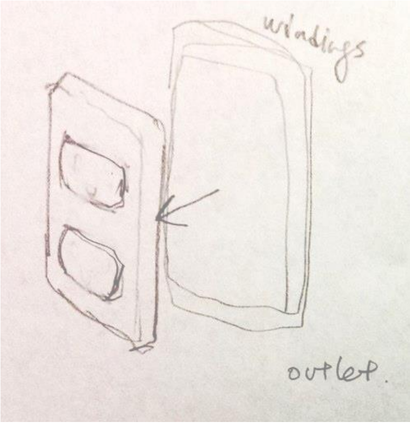
The concept generation stage includes creation of the functional decomposition. This decomposition, whose main purpose is to determine all required functions is shown in Figure 1.

Figure 1: Functional decomposition for locating user indoors



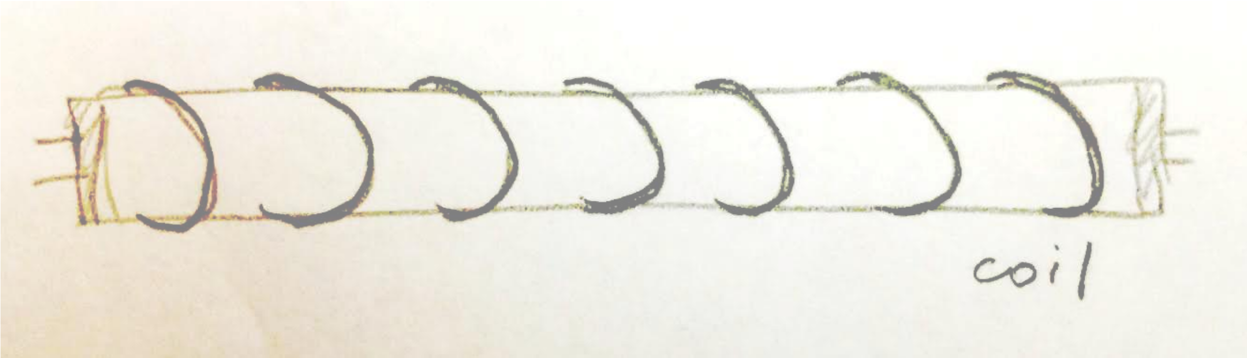
One concept from the outlet category is shown in Figure 2: a beacon integrated into the cover of an outlet. This concept takes the wire windings and coils them in any pattern desired so long as the windings fit in the volume of an outlet cover. This concepts allows flexibility of wire windings loop design and is easily implementable into existing infrastructure because electric outlets are standardized. The main downside to this design is that outlet covers are flat and small, which will limit the surface area within the windings.

Figure 2: Beacon integrated into cover of an outlet



Another concept from the lighting fixture category (Fig. 3) is a beacon integrated into a fluorescent lightbulb, often found in office settings. This concept takes the wire windings and coils them around the fluorescent bulb for maximum surface area inside the windings while affecting the volume of the original fluorescent light bulb minimally. This concept also joins the beacon and light bulb into one product, easing the transition when installing into existing light sockets. The fluorescent with a coil beacon can simply replace the previous fluorescent without any other process change. The main downside to this design is that the coil runs along the full length of the fluorescent and may block out some of the light generated. The light also may not be turned on all the time, which will require an internal power source for the beacon when the lights are off if the beacon is to remain functional in a dark room.

Figure 3: Beacon integrated into fluorescent light bulb



A third concept (Fig. 4, pp. 8) is to include beacons into fire alarms, since fire alarms are regularly positioned in buildings. Because one goal of improved indoor location sensing is e911 for improved first responder response, it would not be unusual to group the beacon with an existing safety feature. The wire windings would fit inside the warning light housing for the fire alarm and present fire alarm spacing should be sufficient for the range the beacon is designed for. The main downside to this design is that fire alarm housing may vary depending on the age of the building. For widespread application into existing infrastructure, it is best to work with an aspect that is standardized.

Figure 4: Beacon integrated into fire alarm

Complete list of concepts generated can be found in Appendix A.

3.1 Concept Selection

Various infrastructures and devices were considered in the concept selection, then compared based on their level of fulfillment of the design criteria. In this stage, infrastructure such as light bulbs, fire alarms, exit signs and power outlets were considered. Initially the light bulb was chosen, then replaced by a concept in which the beacon hangs above a door.

The different design criteria had different weight, with ease of implementation having the highest. The criteria of existing code compliance, volume allowed and ease of dispersion in a building are equally important and therefore were given the same weight. The mass criteria is still an important part of the design, but was given the lowest weight since other criteria took priority.

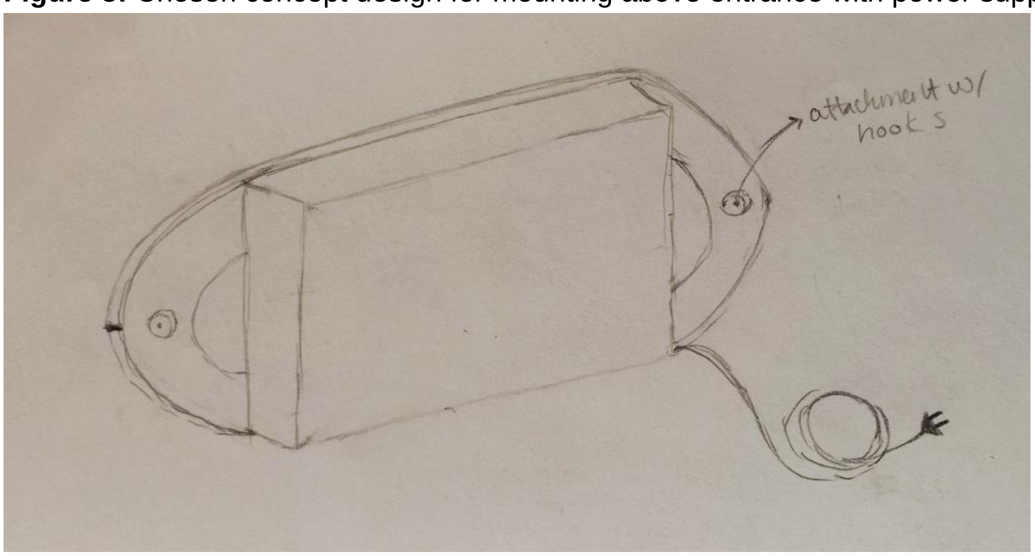
While the light bulb can be easily implemented, doesn't violate any codes and would be easy to disperse in a building, this structure cannot support the necessary mass or volume. The exit sign and smoke detector also allow the beacon to be easily dispersed, but are lacking in available volume. The smoke detector is also not necessarily located in an area of the room that can easily tag the user. The wall outlet would not violate any building codes, in addition to being easy to implement, but there is very little volume and mass available, rendering this concept obsolete.

Originally the light bulb was selected, but after completing an initial engineering analysis of the original chosen concept (fluorescent light bulb), it became clear that the design was not feasible. With the volume and wire windings trade-off study, the volume could not be minimized enough to fit on the fluorescent bulb while still achieving a strong enough magnetic field. For preliminary stress, moment and fracture point analyses, the fluorescent bulb was found to not be robust enough to support the design. Due to these findings, a new concept was developed and chosen. In this concept, the beacon is in the shape of a box with mounting supports and a power cord utilizing a wall outlet for power. This concept does not constrain volume or mass as much as the previous concepts. It is also easily dispersed throughout a building, can be easily implemented and complies with building codes.

4.0 Concept Description

The chosen concept is a beacon in the shape of a box with mounting supports and a power cord utilizing a wall outlet. The power cord will need to be long in case a wall outlet is not nearby and components such as plastic clips can be utilized to keep the cord against the wall on its path to the wall outlet. This design allows it to be mounted on any surface, but ideally above a door in order to easily tag users. Inside the beacon there will be copper coils, winding parallel along the largest dimension. Setting up the windings in this fashion will give the maximum range from the beacon since when walking under a door, users will pass through the strongest portion of the magnetic field. The proposed model is displayed in Figure 5.

Figure 5: Chosen concept design for mounting above entrance with power supply from cord



For this project, a scaled proof-of-concept will be built. The packaging and copper coil will be a quarter of the full-size beacon, but the electrical components such as the Arduino, Arduino Motor Shield and connecting cord will remain the same size. Due to these differences in scaling, only the copper coil will be contained inside the packaging and the electrical components will be outside. Instead of a power cord connected to a wall outlet, the proof-of-concept can be powered using either AA batteries, a USB to Type M Barrel or a Wall Power Adapter to Type M power cord. The selected power source will then be connected to the power port on the Arduino. The Arduino is also connected to a computer with an A-B USB cable. This connection is necessary to send a signal generated with a C-code to create the magnetic field. Figure 6 shows an isometric view of the prototype with labeled components. Since the prototype was quite large, a scaled model (5:1) was created for the purpose of this project. Figure 7 shows the actual prototype and set-up.

Figure 6: Isometric view of prototype CAD

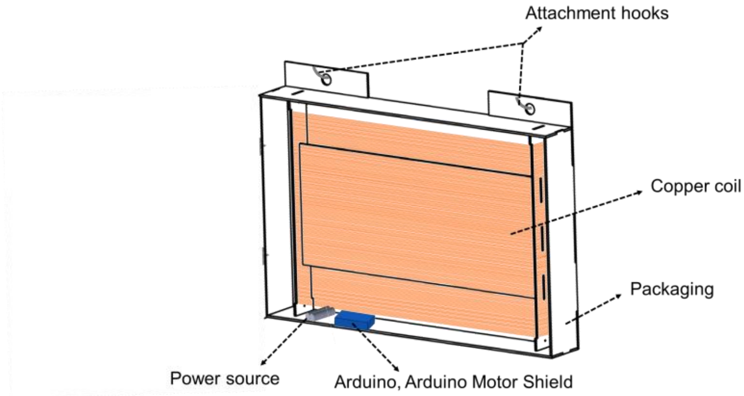
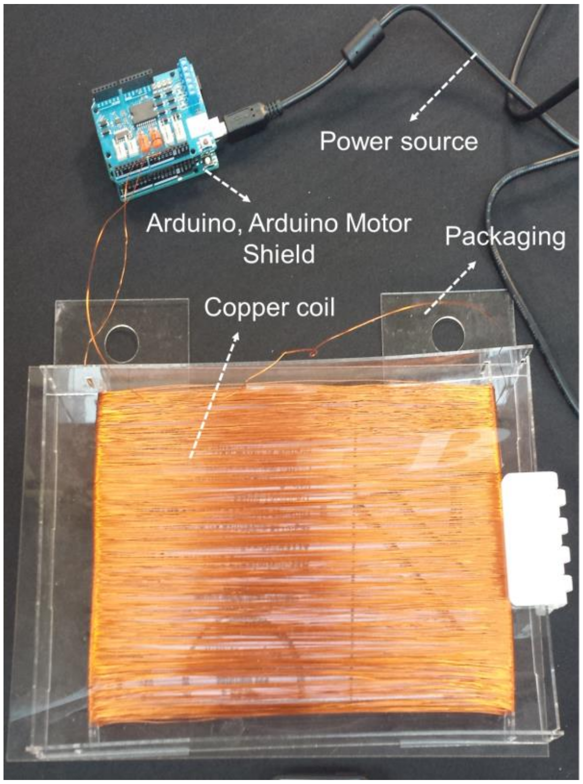


Figure 7: Front view of prototype



5.0 Engineering Specifications

The engineering specifications were determined once a viable concept was chosen. Table 3 shows these specifications for a full-sized prototype in addition to a scaled proof-of-concept. For the purpose of this project, only the scaled proof-of-concept will be built in order to reduce copper consumption and costs.

Table 3: Technical specifications for full-size and scaled models

Desired Technical Specifications		Model	
		Full-sized Prototype	**Scaled (5:1), Proof-of-Concept**
Magnetic field strength	> 300 nT	B = 380 nT	B = 380 nT
Volume (L x W x H)	< 0.06 m^3	V = 0.02 m^3	V = $1 * 10^{-5}$ m^3
Power source/use	< 5 W	Power cord, P << 5W	Batteries or cord, P = 1.5 W
Signal range	> 10 m	r = 2.5 m	r = 0.5 m
Mass	< 25 kg	m = 15 kg	m = 5 kg

Table 3 shows the technical specifications (listed in order of importance) needed to fulfill the user requirements and produce a functioning device. The majority of specifications were determined through theoretical calculations and a trade-off study between volume and magnetic field strength (see 7.1 for details). The following section explains how each value was determined.

Magnetic field strength: This specification is by far the most important since the magnetic field must be strong enough to be perceived by the magnetometer in the user's phone. For this reason, the actual strength used in the beacon is greater than the minimum value.

Volume: The volume must be compact enough to allow the beacon to be easily integrated into existing infrastructure, while still large enough to fit the needed technological equipment. This specification is especially affected by the orientation of the wire windings.

Power Source/Use: Minimizing power consumption of the beacon is one of the more important specifications since the success of the product is largely based on it. The beacon has a greater chance of success against competitors if it is connected to building power and therefore causing little to no increase in a building's electric costs.

Signal Range: The desired signal range of 10m was found to be unachievable since volume of the beacon and strength of the magnetic field take precedence. A value of 2.5 m was chosen since this range is great enough to reach and tag a user upon entry into a room if the beacon is placed above the entrance.

Mass: The mass range of the device is quite flexible since, with the chosen concept design, the device will be able to support up to 25 kg. The estimated total mass of the beacon is currently 5 kg and well within limits.

6.0 Key Design Drivers and Challenges

A challenging aspect of the design process was having to determine many of the technical specifications later in the project timeline during engineering analysis, due to minimization requirements. The maximum gauge of wire that could be used in the prototype greatly constrained how much the beacon size could be minimized. These design driver analyses are given in the following table 4, all of which were analyzed through theoretical modeling.

Table 4: Design Drivers

#	Design Driver	Description	Importance	Design Driver Analysis	Validation
1	Technology fits into beacon	Current set-up needs to be minimized	Larger beacons cost more and are difficult to implement	Volume and wire winding tradeoff study	Test of physical prototype
2	All users can tag/triangulate	Users must be able to receive location from nearby beacons	Product is pointless if you cannot triangulate	Analysis to optimize magnetic field	Test for user-to-beacon distance
3	Easily implemented	Beacon must be integrated into infrastructure	To achieve ease of integration, beacon must be part of product and not purchased separately	Static analysis to determine shape and support system of packaging	Test of physical prototype
4	Doesn't violate OSHA, fire, building codes	Technology must abide by federal laws for use in commercial buildings	Without abiding by law, product cannot be commercialized	Check all codes and ensure product adheres to all related	Checklist of federal requirements

This table shows the design drivers for the project, why they are important and how they will be analyzed and validated. Drivers 1 and 2 are combined into one group for analysis: a trade-off study between volume and wire windings (design driver 1) to maximize the magnetic field (2) while keeping the volume of the beacon at a reasonable size. This analysis mainly utilizes the fields of electricity and magnetism to determine the values of the magnetic field, circuit components and wire orientation. Design driver 3 involves solid mechanics; specifically static analysis to determine the maximum mass the beacon can support by determining the optimal shape of the packaging and the best type of fasteners for attachment to a surface. This analysis will also influence the chosen material for the packaging. Design driver 4 does not relate to a specific scientific field, but is nevertheless important for implementation.

7.0 Engineering Analysis

The following sub-sections detail the engineering analysis performed for our design.

7.1 Theoretical Modeling of Design Drivers 1 and 2

To ensure the beacon coil design can broadcast a discernible signal at the required range, theoretical modeling of the coil electromagnet was performed. Using the Biot Savart law (Eq. 1) integrated over the cross-sectional area of the coil, the relationship between field strength and variables length, width, height, current, beacon orientation, and wire gauge was determined.

Equation 1: Biot Savart Law

$$B(r) = \frac{\mu_0}{4\pi}\int_C \frac{Id(l \times r')}{\|r'\|^2}$$

Where *B(r)* is the magnetic field strength at radius r away from the center of the coil. μ_0 is the vacuum permeability constant. *I* is the current. *r'* is the vector pointing from the center of the coil to the measured point. To solve this equation for our purposes, it is assumed that the user will pass through the point of strongest field strength, perpendicular to the coils, simplifying the *r'* vectors into scalars and the cross product to be multiplication. An averaged *r'* value was used from the center of the coil due to coil symmetry and the fact that the distance from the measured point to the coil is significantly greater than dimensional variations in the coil. Hence, the integral is approximated over the coil contour to be constant and the formula integrated with respect to r in two dimensions and multiplied by the contour dimensions, cross-sectional area and number of windings. These simplifications and unit conversion to have the magnetic field value in the simplified formula (Eq. 2) which is used in the theoretical calculations shown below.

Equation 2: Simplified Biot Savart Law

$$B(r) = 200\frac{IAN}{r^3}$$

Where *A* is the coil cross-sectional area, *N* is the number of windings, and *r* is the distance from the beacon center to the measured point.

7.1.1 Beacon Orientation

Since the magnetic field of a coil is the strongest perpendicular to its cross-sectional area, the beacon is designed to be oriented vertically so the point of greatest magnetic field strength lies under the door where the user passes through.

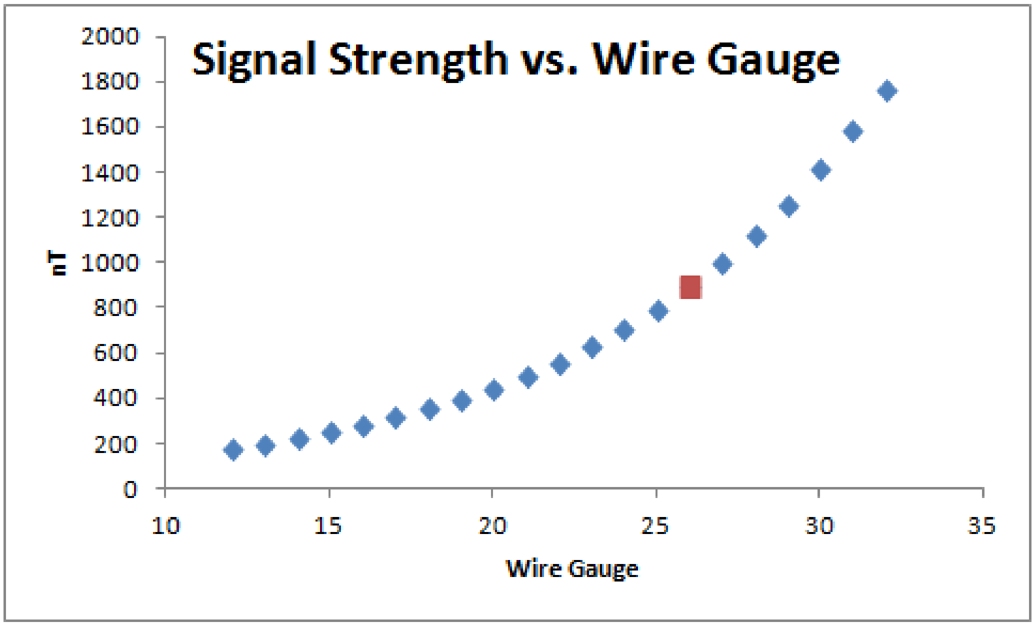
7.1.2 Current

For an electromagnet, the greater the current running through the windings, the greater the magnetic field. The electronic chip being considered has a maximum current rating of 600mA, so the beacon current will be set to 500mA.

7.1.3 Wire Gauge

Higher wire gauge represents thinner wire diameter. Thinner wire permits more windings in the same amount of space, which increases the magnetic field strength (see Fig. 8). Thinner wire is also easier to break and higher gauges are not plausible to work with for hand winding a prototype. Due to this, a 26 gauge wire was chosen since it is a reasonably high gauge without being so brittle as to break with hand applied tension. Future prototypes for this beacon module can be constructed with higher gauge wire if the manufacturing process can be automated with tighter applied force constraints.

Figure 8: Exponential relationship between signal strength and wire gauge



7.1.4 Width

Since the beacon is designed to be installed above doors, the maximum dimension for length is the width of the door, 0.8m.

7.1.5 Length and Height

These dimensions were optimized by iterating through a matrix (see Fig. 9 on pp. 14) of possible values, evaluating points for their resultant magnetic field strength at required range. A length of 0.06m and height of 0.5m was chosen because it fulfilled the minimum field strength of 300nT at a distance of 2.5m while minimizing volume and being a reasonable shape for installation. This size of coil will yield a magnetic field strength of 380nT.

Figure 9: Optimization matrix used to determine packaging dimensions

Crossectional Area Optimization

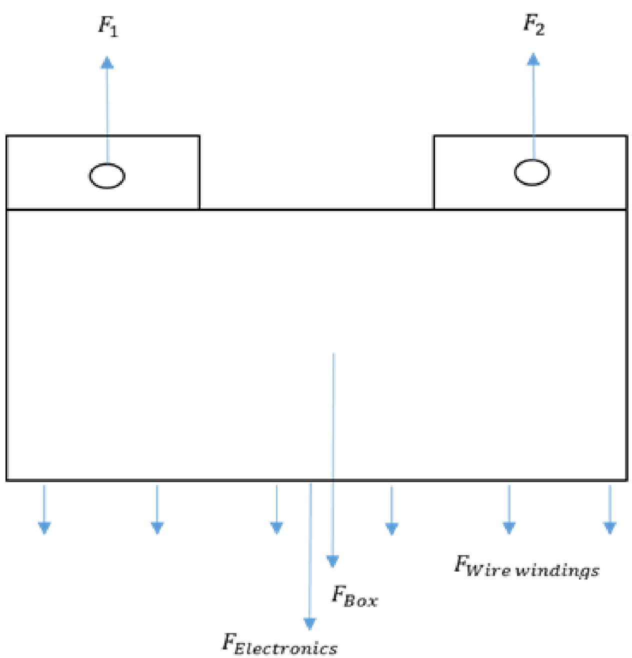
Width	Length: 0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.2	0.3	0.4	0.5
0.1	12.67766	25.35532	38.03298	50.71064	63.3883	76.06596	88.74362	101.4213	114.0989	126.7766	253.5532	380.3298	507.1064	633.883
0.2	25.35532	50.71064	76.06596	101.4213	126.7766	152.1319	177.4872	202.8426	228.1979	253.5532	507.1064	760.6596	1014.213	1267.766
0.3	38.03298	76.06596	114.0989	152.1319	190.1649	228.1979	266.2309	304.2639	342.2968	380.3298	760.6596	1140.989	1521.319	1901.649
0.4	50.71064	101.4213	152.1319	202.8426	253.5532	304.2639	354.9745	405.6851	456.3958	507.1064	1014.213	1521.319	2028.426	2535.532
0.5	63.3883	126.7766	190.1649	253.5532	316.9415	380.3298	443.7181	507.1064	570.4947	633.883	1267.766	1901.649	2535.532	3169.415
0.6	76.06596	152.1319	228.1979	304.2639	380.3298	456.3958	532.4617	608.5277	684.5937	760.6596	1521.319	2281.979	3042.639	3803.298
0.7	88.74362	177.4872	266.2309	354.9745	443.7181	532.4617	621.2054	709.949	798.6926	887.4362	1774.872	2662.309	3549.745	4437.181
0.8	101.4213	202.8426	304.2639	405.6851	507.1064	608.5277	709.949	811.3703	912.7916	1014.213	2028.426	3042.639	4056.851	5071.064
0.9	114.0989	228.1979	342.2968	456.3958	570.4947	684.5937	798.6926	912.7916	1026.891	1140.989	2281.979	3422.968	4563.958	5704.947
1	126.7766	253.5532	380.3298	507.1064	633.883	760.6596	887.4362	1014.213	1140.989	1267.766	2535.532	3803.298	5071.064	6338.83

7.2 Theoretical Modeling of Design Driver 3

The following analysis was completed to determine the packaging for a full-scale prototype that would be positioned above a door. The proof-of-concept being built to fulfill the purpose of this project cannot be a true 5:1 model of the full-size, since components such as the Arduino, Arduino Motor Shield and batteries cannot be scaled down. The packaging cannot be uniformly scaled due to the size of these components being unchangeable. For this reason, theoretical analysis will only be completed for the full-scale prototype as a reference for future work on the packaging.

Static analysis can be used to ensure that the beacon packaging structure and support are sufficient to hold the ELF technology, aid in designing the optimal packaging shape and in choosing the best type of fasteners. The material selected for the packaging structure is acrylic, since it is a strong, lightweight material. The entire structure would be held at the points labeled F_1 and F_2 in Figure 8 with stainless steel hooks. This figure (10) shows the free body diagram for static force analysis of the beacon.

Figure 10: Free body diagram of beacon structure



The set of force equations for the packaging are shown below in Equations 3.

Equations 3: Static force equation for structure with component values

$$\sum F = F_1 + F_2 - \sum F_{Electronics} - F_{Box} - F_{Copper\ Coil} = 0$$

$$\sum F_{Electronics} = F_{Arduino} + F_{Motor\ Shield} + F_{Connecting\ Cords} = 0.8\ N$$

$$F_{Box} = 70N$$

$$F_{Copper\ Coil} = 25N$$

$$F_1 = F_2 = 48N$$

Since the maximum force for F_1, F_2 is 122.5N (determined by the maximum load allowed on each hook), this prototype design is feasible and the hooks would be able to hold the beacon. Also, the forces are evenly distributed along the device with the most force centered at the middle of the device. The electronic components (Arduino, Arduino Motor Shield) would be placed in the open area of the coil on the support used in the winding process. A moment analysis of this device shows that the likely fracture point for this device is at the center. Since the majority of the weight of the beacon is evenly distributed except for the light-weight electrical components, this constraint is easily met.

7.3 Theoretical Modeling of Design Driver 4

After a thorough study, we have decided that design driver 4 is negligible as we could find no OSHA, building, or fire codes that could be applied to our beacon design.

8.0 Risk Analysis

An Indoor Location Sensing Beacon is designed to be a commercial product, so we have conducted a thorough risk analysis using DesignSafe.

designsafe Report

Application:	ME450 Deliverable 10D:FMEA	Analyst Name(s):	Matt Evans, Rachel Menchak, Helen Lai, Fernando Pichardo
Description:	Indoor Location Technology: Beacon Module	Company:	ME450 Team 20
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	operator normal operation	electrical / electronic : energized equipment / live parts User conact with live current in beacon coil windings	Minor Remote	Negligible	Ensure beacon installed in location out of user reach or with protective cover to prevent tampering	Minor Unlikely	Negligible	
1-1-2	operator normal operation	electrical / electronic : lack of grounding (earthing or neutral) Loss of ground connection in electrical circuit	Moderate Remote	Negligible	Ensure beacon housing is insulated from live coil windings	Moderate Unlikely	Low	
1-1-3	operator normal operation	electrical / electronic : water / wet locations Condensation on beacon module	Minor Likely	Low	Weatherproof circuitry	Minor Likely	Low	
1-2-1	operator misuse - (add description)	mechanical : break up during operation Beacon module falling from elevated position	Moderate Unlikely	Low	Minimize beacon weight and ensure module is securely mounted to wall. Design beacon housing to resist vibration and typical hanging stresses	Moderate Unlikely	Low	
1-2-2	operator misuse - (add description)	electrical / electronic : energized equipment / live parts User conact with live current in beacon coil windings	Minor Remote	Negligible	Ensure beacon installed in location out of user reach or with protective cover to prevent tampering	Minor Unlikely	Negligible	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-3	operator misuse - (add description)	electrical / electronic : lack of grounding (earthing or neutral) Loss of ground connection in electrical circuit	Moderate Remote	Negligible	Ensure beacon housing is insulated from live coil windings	Moderate Unlikely	Low	
1-2-4	operator misuse - (add description)	electrical / electronic : water / wet locations Condensation on beacon module	Minor Likely	Low	Weatherproof circuitry	Minor Likely	Low	
1-2-5	operator misuse - (add description)	slips / trips / falls : falling material / object Beacon module falling from elevated position	Moderate Unlikely	Low	Minimize beacon weight and ensure module is securely mounted to wall	Moderate Unlikely	Low	
1-2-6	operator misuse - (add description)	heat / temperature : radiant heat Heat from beacon running condition if it comes into physical contact with person	Minor Remote	Negligible	Ensure beacon housing is insulated from live coil windings	Minor Remote	Negligible	
2-1-1	maintenance technician set-up or changeover	mechanical : break up during operation Beacon module falling from elevated position	Moderate Likely	Medium	Minimize beacon weight and ensure module is securely mounted to wall. Ensure worker has secure footing and strength to install beacon at elevated position	Moderate Unlikely	Low	
2-1-2	maintenance technician set-up or changeover	electrical / electronic : energized equipment / live parts User conact with live current in beacon coil windings	Minor Remote	Negligible	Unplug beacon during installation	Minor Unlikely	Negligible	
2-1-3	maintenance technician set-up or changeover	electrical / electronic : improper wiring High current short circuit	Moderate Unlikely	Low	Include a fuse in the beacon circuit to protect electronic circuit and people from high current	Moderate Unlikely	Low	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-4	maintenance technician set-up or changeover	electrical / electronic : water / wet locations Condensation on beacon module	Minor Likely	Low	Weatherproof circuitry	Minor Likely	Low	
2-1-5	maintenance technician set-up or changeover	slips / trips / falls : falling material / object Beacon module falling from elevated position	Moderate Likely	Medium	Minimize beacon weight and ensure module is securely mounted to wall. Ensure worker has secure footing and strength to install beacon at elevated position	Moderate Unlikely	Low	
2-1-6	maintenance technician set-up or changeover	ergonomics / human factors : excessive force / exertion Hooks for holding up beacon difficul to securely mount	Moderate Unlikely	Low	Design for hooks to be installable with power tools or other methods that decrease force necessary for installation	Moderate Unlikely	Low	
2-1-7	maintenance technician set-up or changeover	ergonomics / human factors : posture Beacon designed to be in difficult to reach spot that may tax electrician	Minor Likely	Low	Train staff on proper installation methods to limit risky procedures	Minor Likely	Low	
2-1-8	maintenance technician set-up or changeover	ergonomics / human factors : lifting / bending / twisting Lifting a heavy beacon module to an elevated position for installation	Moderate Likely	Medium	Minimize beacon weight and have a second worker support the first worker in lifting the beacon to the desired height	Moderate Likely	Medium	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-1-9	maintenance technician set-up or changeover	heat / temperature : radiant heat Heat from beacon running condition if it comes into physical contact with person	Minor Unlikely	Negligible	Ensure beacon housing is insulated from live coil windings. Disconnect power to beacon when performing maintainence, perhaps allowing time for the module to cool before making adjustments	Minor Unlikely	Negligible	
2-2-1	maintenance technician adjust controls / settings / alignment	mechanical : break up during operation Beacon module falling from elevated position	Moderate Unlikely	Low	Minimize beacon weight and ensure module is securely mounted to wall	Moderate Unlikely	Low	
2-2-2	maintenance technician adjust controls / settings / alignment	electrical / electronic : energized equipment / live parts User conact with live current in beacon coil windings	Minor Remote	Negligible	Make frequency adjustment possible when the beacon is not powered	Minor Unlikely	Negligible	
2-2-3	maintenance technician adjust controls / settings / alignment	electrical / electronic : water / wet locations Condensation on beacon module	Minor Likely	Low	Weatherproof circuitry	Minor Likely	Low	
2-2-4	maintenance technician adjust controls / settings / alignment	slips / trips / falls : fall hazard from elevated work Unstable footing at elevated work position making adjustments to beacon module	Moderate Likely	Medium	Pair maintanence staff so one person is always paying attention to risky actions and able to support	Moderate Unlikely	Low	
2-3-1	maintenance technician misuse - (add description)	mechanical : pinch point Fingers caught between beacon module and wall or other closing features	Moderate Unlikely	Low	Design installation procesure to limit possible methods fingers can be caught	Moderate Remote	Negligible	
2-3-2	maintenance technician misuse - (add description)	mechanical : break up during operation Beacon module falling from elevated position	Moderate Unlikely	Low	Minimize beacon weight and ensure module is securely mounted to wall	Moderate Unlikely	Low	

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-3-3	maintenance technician misuse - (add description)	electrical / electronic : energized equipment / live parts User conact with live current in beacon coil windings	Minor Unlikely	Negligible	Unplug beacon during installation	Minor Unlikely	Negligible	
2-3-4	maintenance technician misuse - (add description)	slips / trips / falls : fall hazard from elevated work Unstable footing at elevated work position making adjustments to beacon module	Moderate Likely	Medium	Pair maintanence staff so one person is always paying attention to risky actions and able to support	Moderate Unlikely	Low	
3-1-1	passer by / non-user work next to / near machinery	noise / vibration : interference with communications Beacon set to broadcast at wrong frequency	Moderate Unlikely	Low	Design beacon module to be capable of broadcasting in ELF range only	Moderate Unlikely	Low	
3-2-1	passer by / non-user walk near machinery	mechanical : break up during operation Beacon module falling from elevated position	Moderate Unlikely	Low	Minimize beacon weight and ensure module is securely mounted to wall	Moderate Unlikely	Low	
3-2-2	passer by / non-user walk near machinery	electrical / electronic : energized equipment / live parts User conact with live current in beacon coil windings	Minor Remote	Negligible	Unplug beacon during installation	Minor Unlikely	Negligible	
3-2-3	passer by / non-user walk near machinery	electrical / electronic : water / wet locations Condensation on beacon module	Minor Remote	Negligible	Weatherproof circuitry	Minor Likely	Low	

The highest risk aspect to the product is lifting the beacon to its intended installation position above the door during setup. Because the beacon is designed to be positioned above a door, it cannot be reached from a normal standing position on the ground. Installation or maintenance requires a ladder or some mechanism to bring the electrician to the proper height. Lifting a heavy beacon module to this height without stable footing on a ladder can be dangerous and taxing to the electrician. The beacon weight can offsetting their center of balance and take up hands that would otherwise be used to support themselves. These factors increase the likelihood of a fall from the elevated work position, resulting in bodily injuries such as concussions, bruises, and broken bones. One existing control for this type of risk is to pair up electricians into teams so there is always one person watching for potential dangers and provide support if their partner is in a precarious position. The second electrician can also help lift the beacon module to the proper height from the floor where they have stable footing. The fall risk of the first electrician decreases significantly as they do not have to carry the beacon up the ladder with them and the ladder can be further stabilized by their partner. In our design, we will work to minimize beacon weight and size for easier handling, although this highest risk is deemed acceptable because implementing design changes for lifting the beacon would add unnecessary and costly functionality to the product.

9.0 Discussion

If the prototype were to be designed differently from the start, the same concept for implementation would be used, but the size would have been further optimized, then scaled up for building purposes instead of the other way around. The strengths of the design are that it achieves the desired magnetic field strength and can be detected by the magnetometer in a smartphone and also has low power consumption. The greatest weakness is that it is relatively large in size still and therefore uses a signifcant amount of copper wire.

To improve the design, the size optimization was repeated with the maximal wire gauge achieve minimal copper usage and the smallest possible coil size. According to the new calculations a magnetic field of 480 nT can be achieved with 40 gauge wire with a beacon volume of 0.003 m^3. The further revised beacon has an 85% decrease in volume from the full-size prototype designed for this project and achieves a theoretical field strength that is 100 nT greater. The further revised beacon also utilizes a circular cross-sectional area (radius = 0.08 m) instead of a rectangular to achieve maximal cross-sectional area to surface area along with the concept of multiple layer coils by having 2 layers. The further revised beacon would still be attached above a door entrance and have a range of 2.5 m. To make these modifications, a CNC winding machine must be used with a circular jig of radius 0.08 m.

Recommendations for this project include utilizing the redesigned coil detailed above to achieve a smaller beacon size. It is also recommended to research the material for optimization. Copper is quite expensive and this factor could limit its implementation as a beacon into buildings. By using a different magnetic or magnetic alloy material, the cost per beacon could be reduced to a competitive price. This change would also help a magnetic positioning IPS to be competitive in the market against other products.

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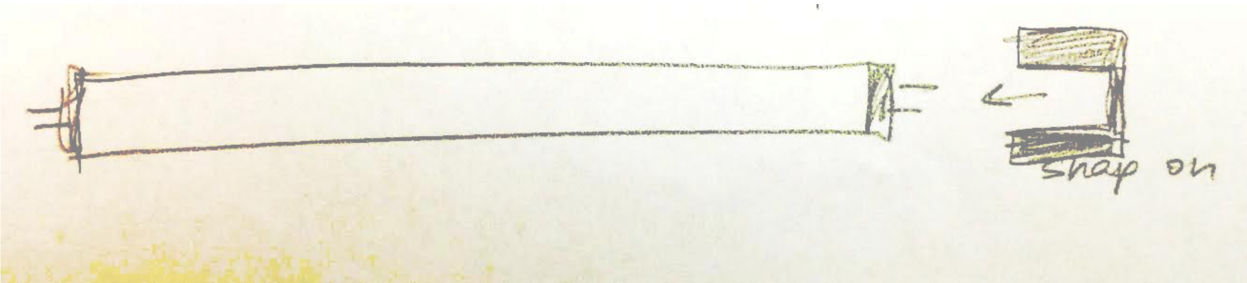
Appendix A: Concept Generation

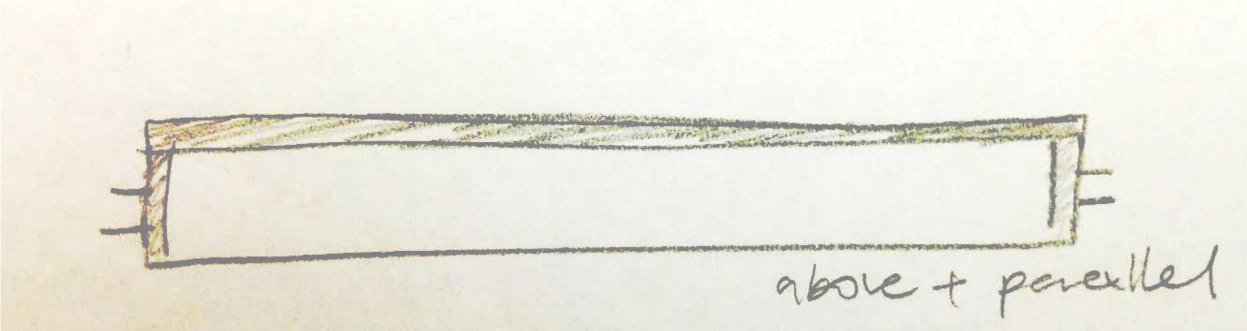
The following sections shows concepts individually developed by team members.

A.1 Lighting Fixtures

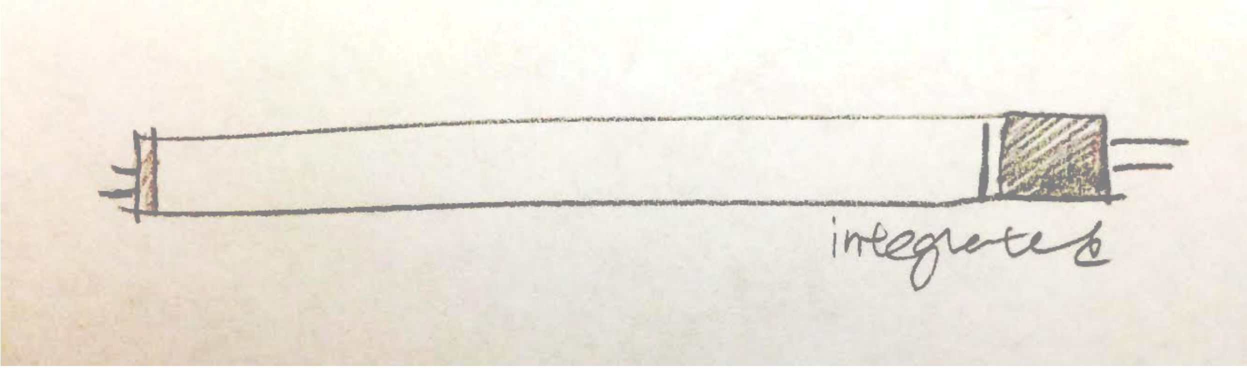
Snap On



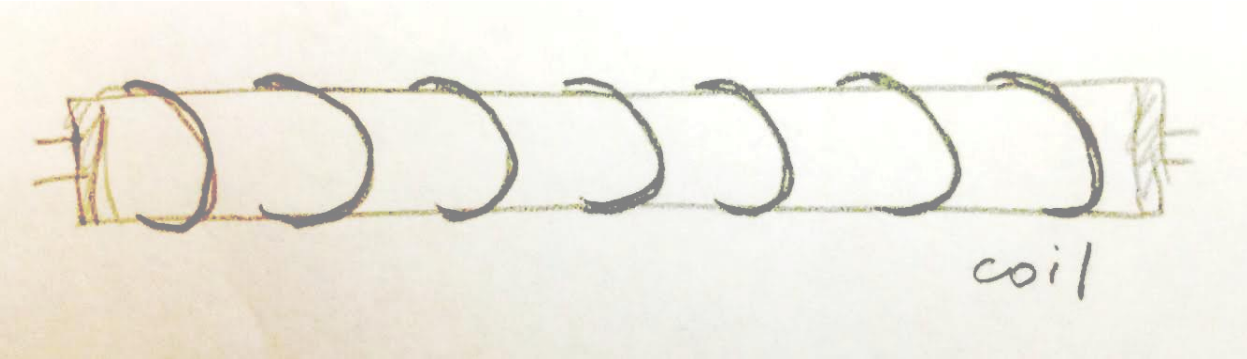
Above Parallel



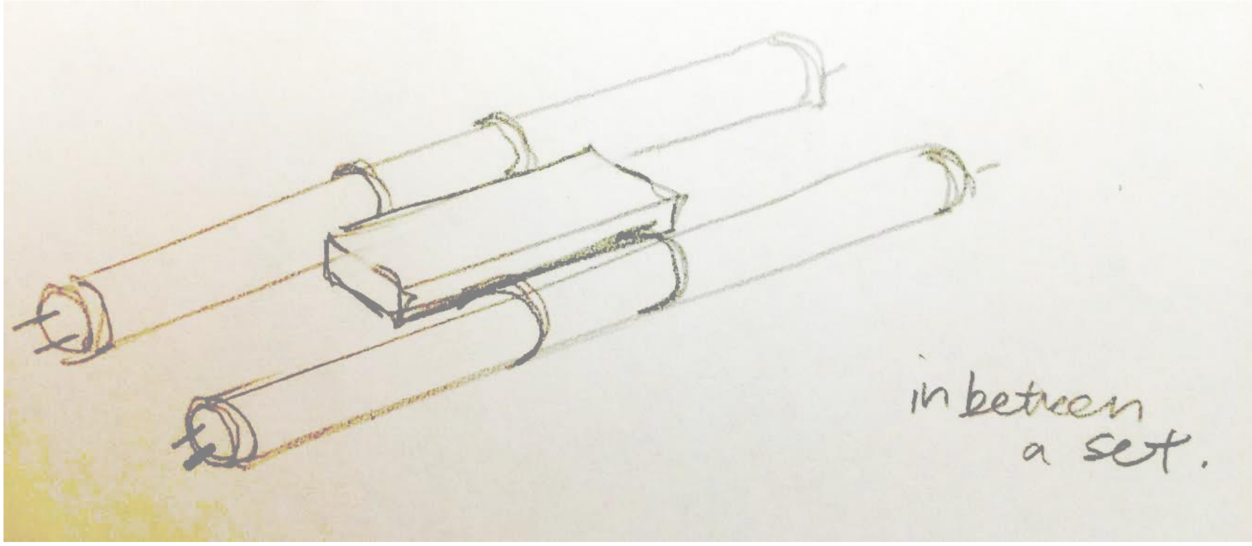
Shorten Bulb (Integrated)



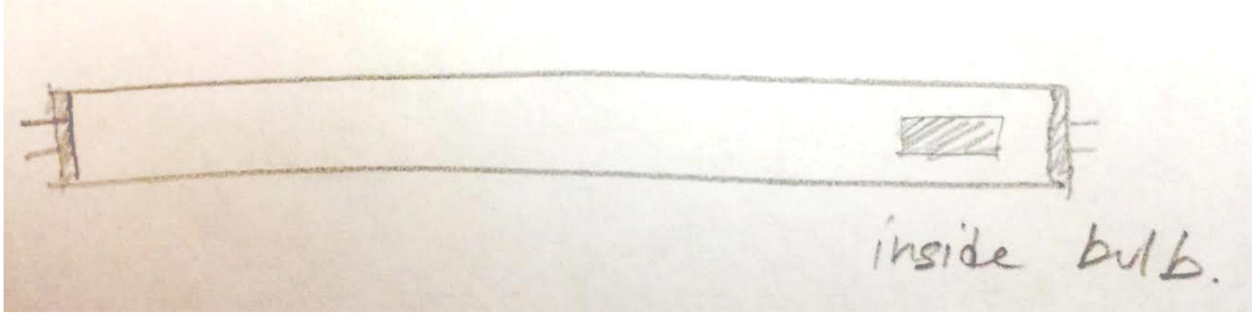
Coil



In-between a set

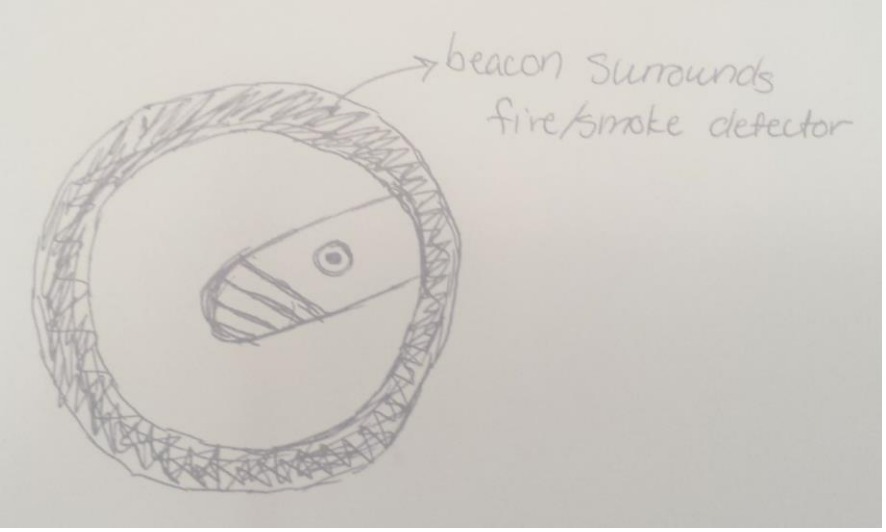


Inside Bulb

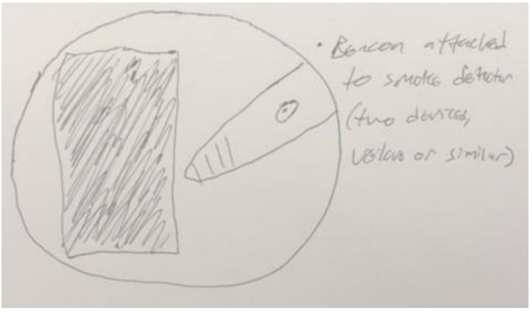


A.2 Safety Systems (Fire Alarm, Smoke Detector, Exit Sign, etc.)

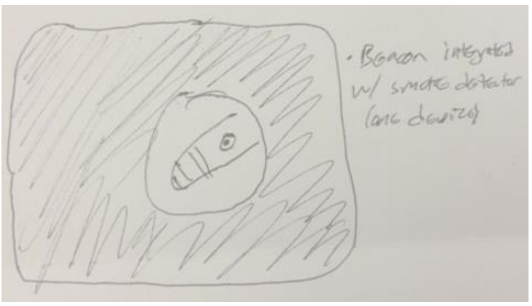
Surrounding smoke detector



Attached to smoke detector



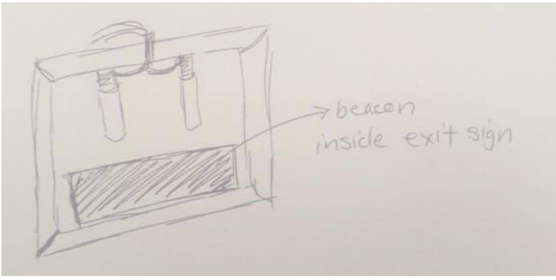
Integrated with smoke detector



Encasing exit sign

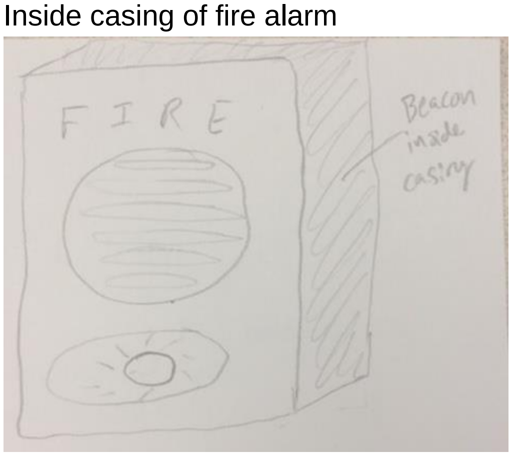
Attached to top of exit sign

Inside of exit sign



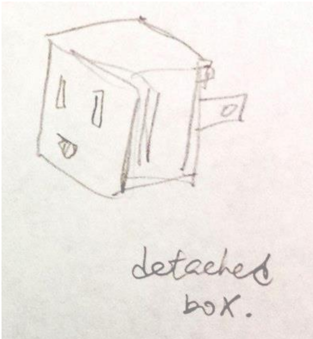
Beneath fire alarm

Inside casing of fire alarm

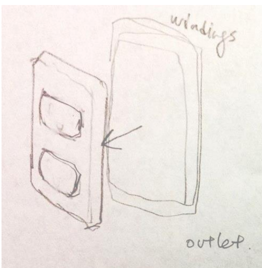


A.3 Outlets/Power

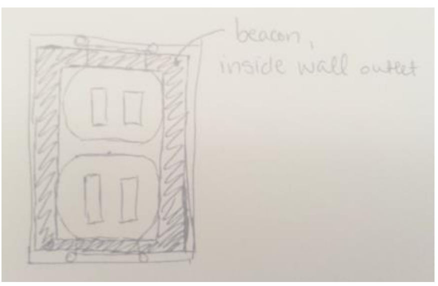
Detached Box



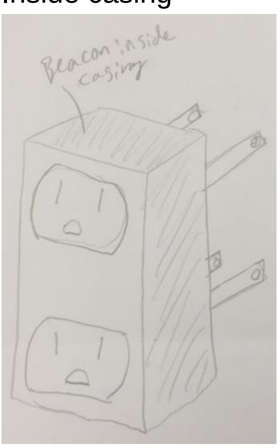
Outlet Cover



Inside wall outlet

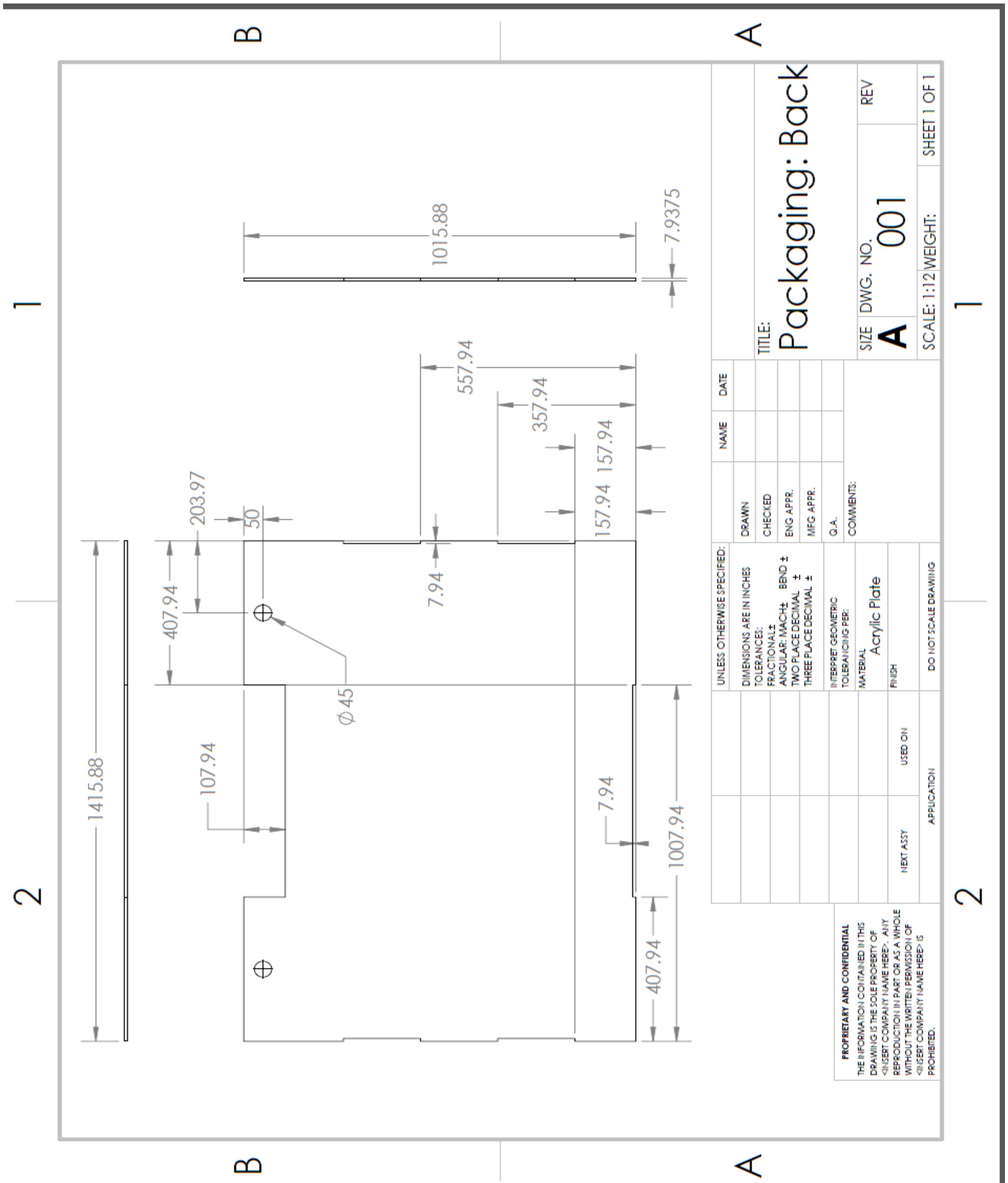


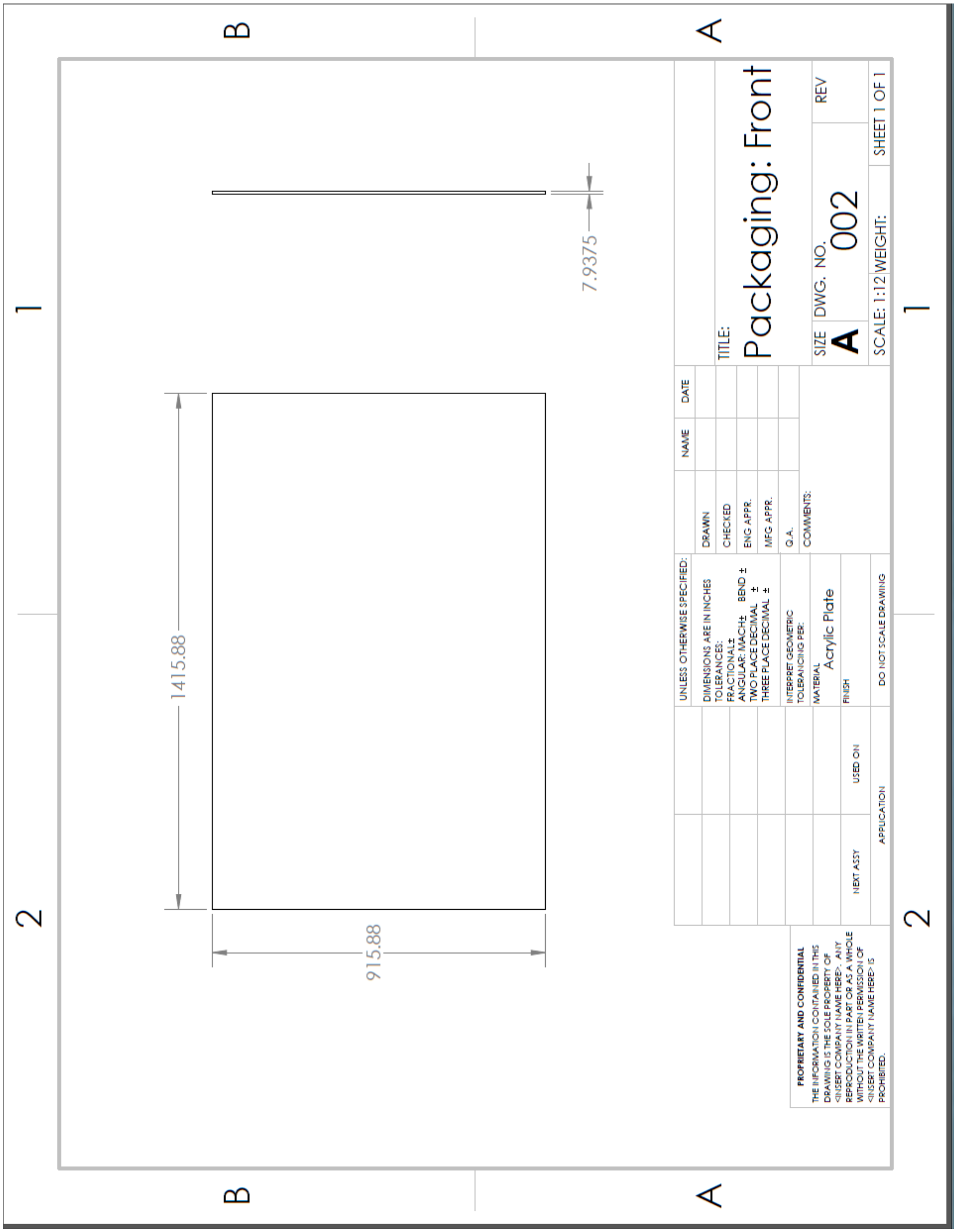
Inside casing



Appendix B: Engineering Drawings

B.1 Part Drawings

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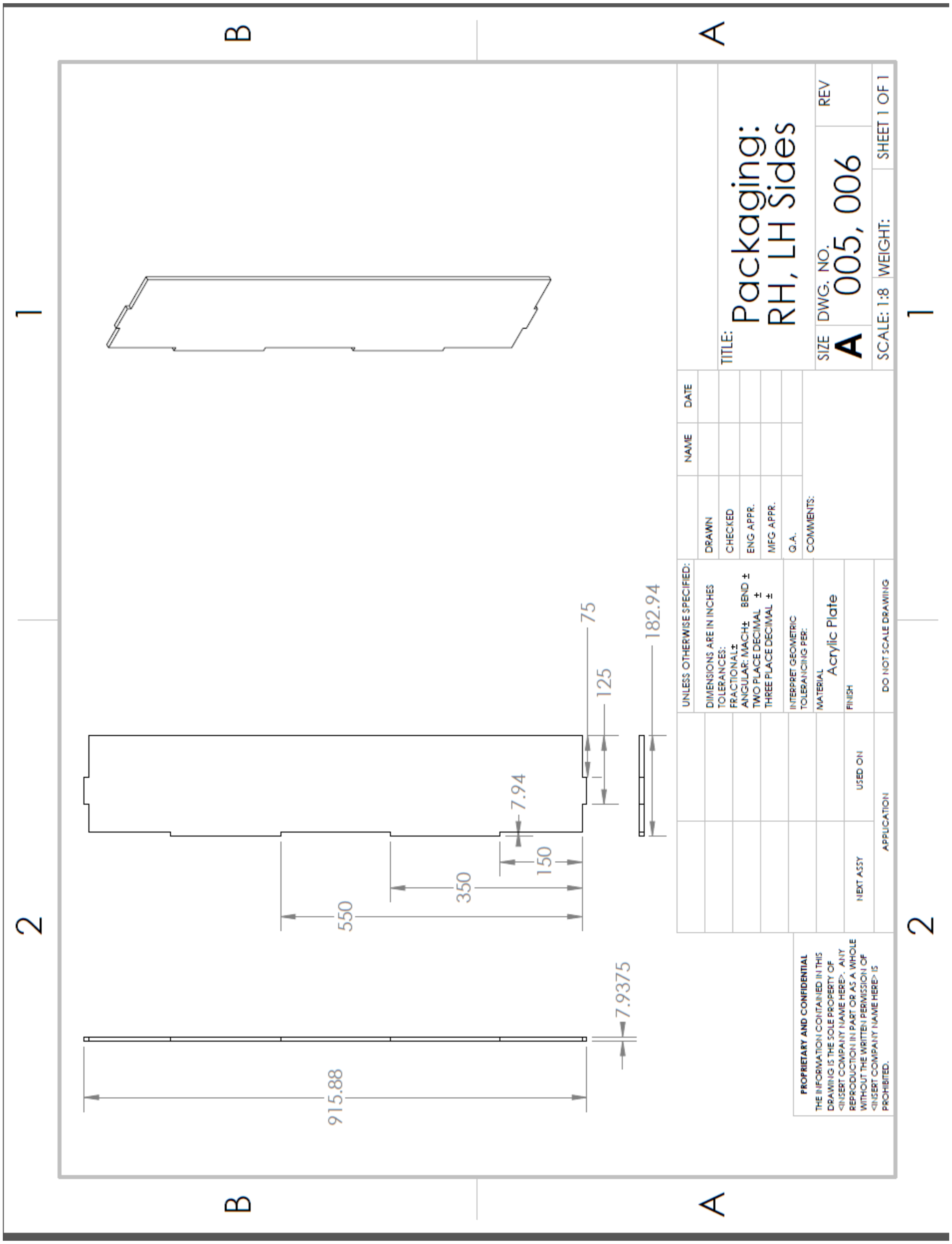

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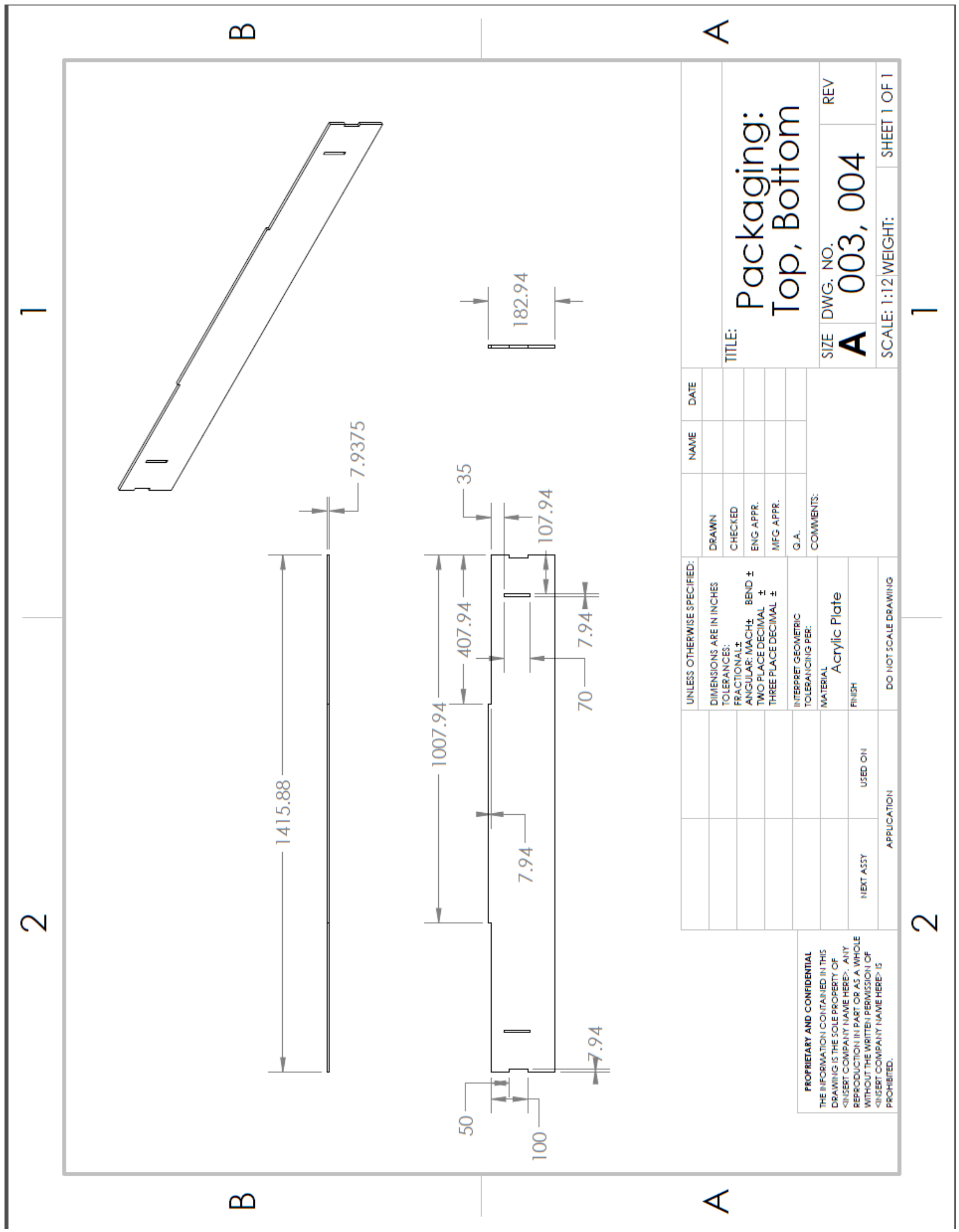
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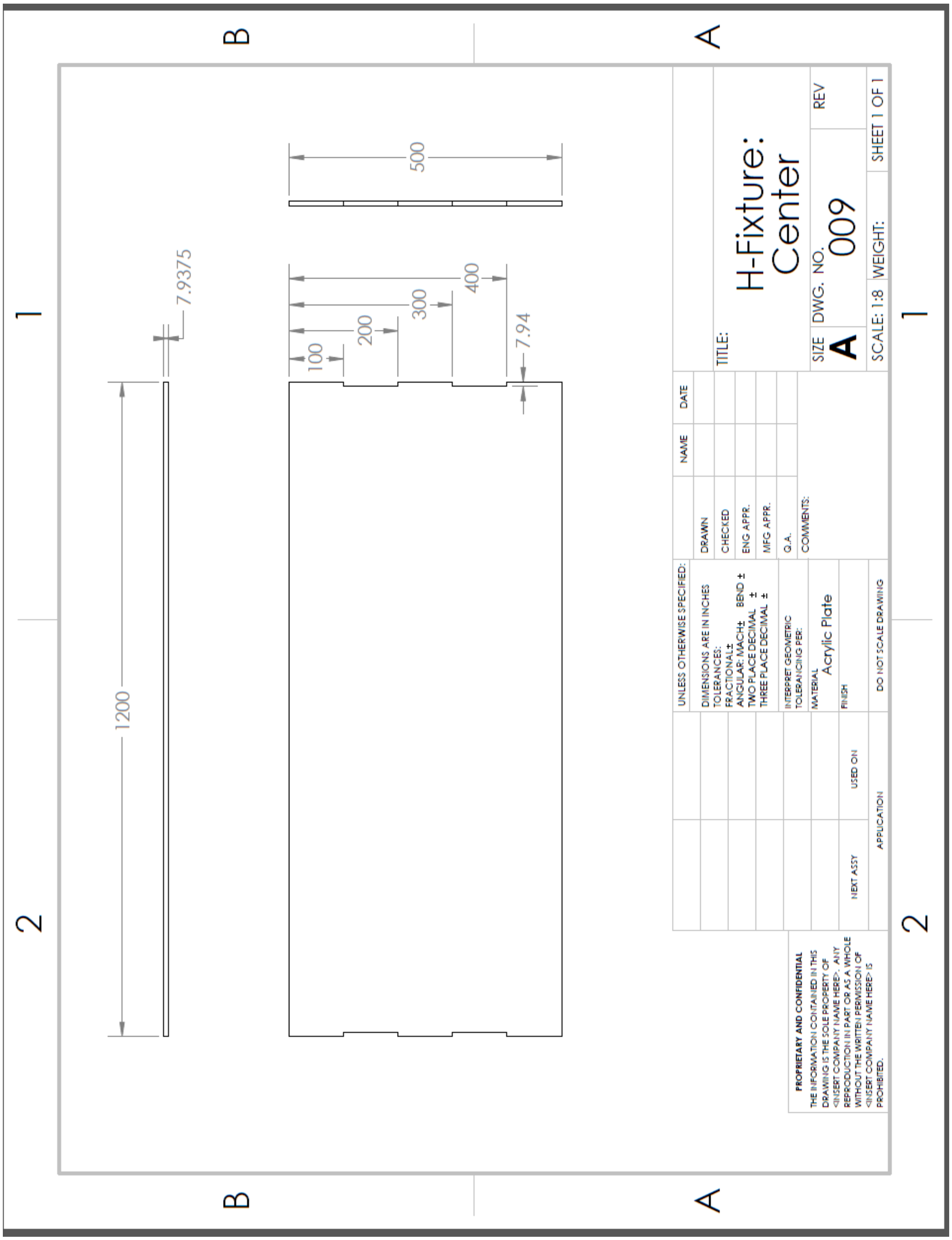
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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
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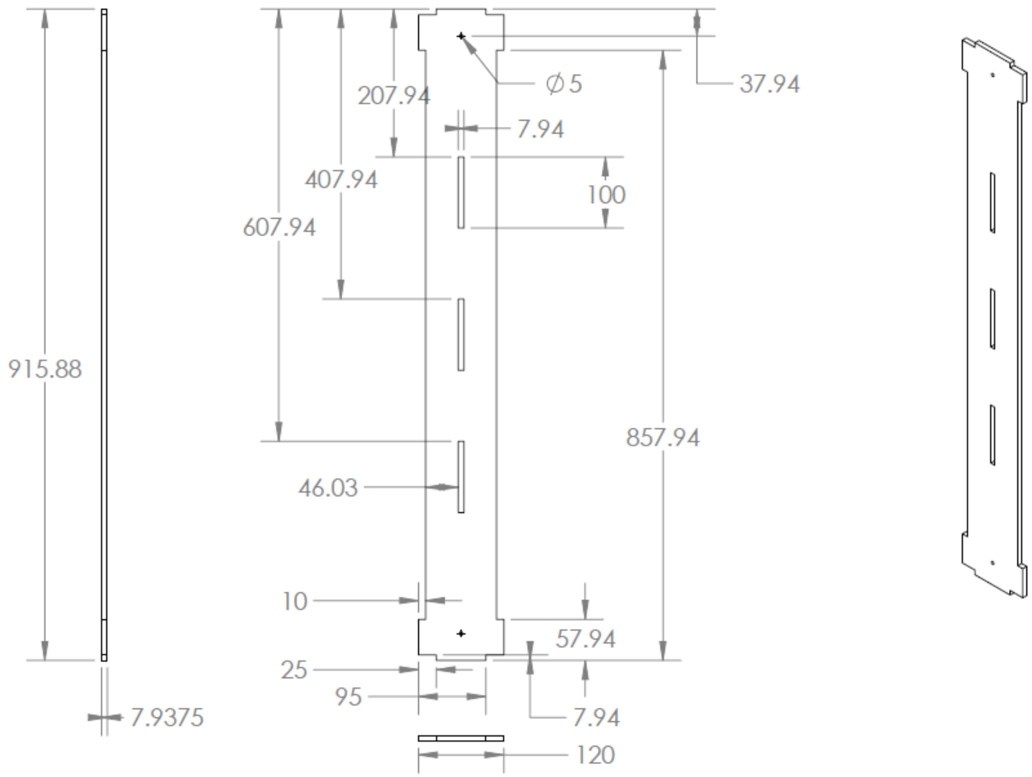

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	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Acrylic Plate	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

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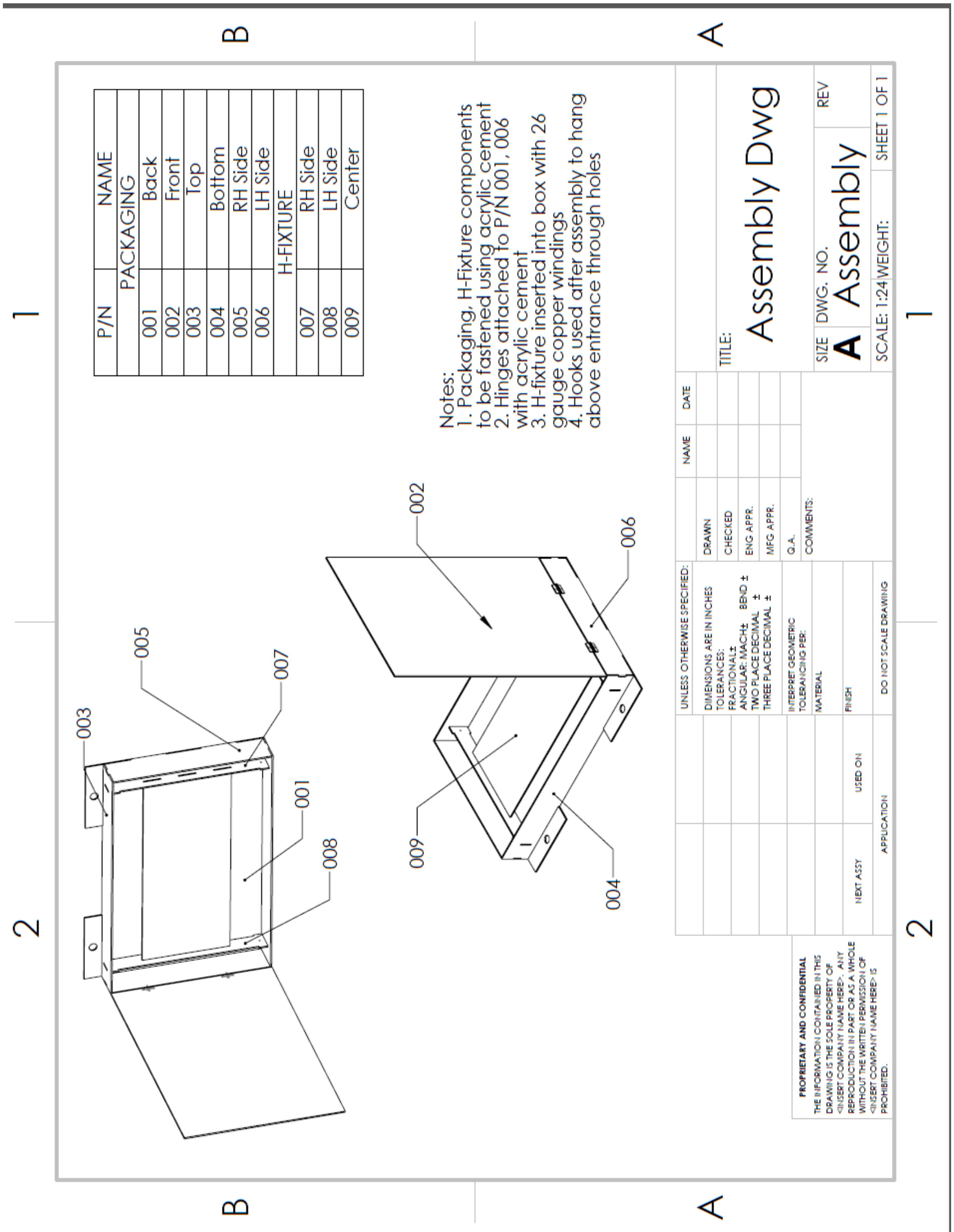
B.2 Assembly Drawing



Appendix C: Bill of Materials

The following table 1C lists a bill of materials for the scaled prototype.

Table 1C: Bill of Materials

#	Description	Manuf. Process	Supplier	Part #	Cost
1	26 Gauge copper	Hand-winding	Moldwin lab	-	-
2	AA batteries	-	Amazon		$7.89
3	Battery holder	-	McMaster-Carr	7712K12	$1.38
4	Arduino Uno	-	Amazon	B008GRTSV6	$19.95
5	Arduino Motor Shield	-	Amazon	B00813HBBO	$8.16
6	5/16" Acrylic plate (Packaging, H-Fixture) (12" x 12")	Laser cutter	McMaster-Carr	8560K591	$19.11
7	5/16" Acrylic plate (Packaging, H-Fixture) (12" x 24")	Laser cutter	McMaster-Carr	8560K591	$33.92
8	2 1/16” Acrylic plate (12” x 24”)	Laser cutter	McMaster-Carr	8560K172	$24.85
9	Acrylic cement	-	McMaster-Carr	7517A1	$9.22
10	2 Hinges	-	McMaster-Carr	11185A190	$2.50
11	2 Steel hooks	-	McMaster-Carr	9580T11	$4.72

Appendix D: Manufacturing Plan

Since this project's main purpose is proof-of-concept, a scaled model (5:1) will be created for demonstration to reduce copper consumption and costs. This scaled model will require only 400 windings compared to the 2000 of the full-scaled. The manufacturing of our prototype consists of two parts: technology and packaging. Plans for each are detailed in the following 2 sub-sections.

D.1 Technology

The main component of manufacturing the ELF technology will be winding the copper wires into the desired rectangular shape. In order to accomplish this task, the wire will be wrapped around a piece of foam with mounted acrylic end pieces by hand (no equipment needed). This copper coil will then be connected to a signal generator, which will utilize an Arduino and Arduino Motor Shield running a C code to create a low frequency square wave and will run on AA batteries. A pro of this process is that that manufacturing can be completed on campus in the AOSS lab. A con is that the wire must be wound by hand.

For mass manufacture, the wire would ideally be wound by a machine. This could be done by using a wire winder with a fixture attached to the chuck. If copper was still used for the mass manufacture, this would be a costly product. The winding equipment would be expensive as well, but only a one-time cost to amortize the tool cost.

D.2 Packaging

Acrylic will be used to create the six faces of the box using a laser cutter to create the appropriate-sized pieces. Five of the six faces will be fastened together into a box shape with an open top using a jigsaw design style of the edges, then glued together with acrylic cement. A hinge will be used to attach the front face to the rest of the box structure, allowing the technology inside the box to be easily accessed when necessary. Other than dimensions, the manufacturing of the full-size prototype is the same. The parts to be purchased for this design include the acrylic sheet, acrylic cement and hinge. A pro of using the laser cutter is that it is simpler to use than a mill, but a con is its lack of precision.

For mass manufacture, there are many low cost-high volume methods that can be utilized to manufacture the packaging. One efficient and cost-effective method is injection molding. Injection molding will eliminate the need for the laser cutting of multiple acrylic pieces and the subsequent gluing process. The cost of materials would not be too expensive, but the tooling costs to amortize the injector molder would be a large one-time cost.

Appendix E: Engineering Change Notices (ECN) Documentation

The following section details changes made to the proof-of-concept.

E.1 Power Source

The option of using either USB to Type M Barrel or Wall Power Adapter to Type M cords was added in addition to the AA batteries. This change will add modularity to our design, since multiple types of connections can be used to power the beacon.

This design change is also informative to future users by offering more than just one energy source. The battery power source is a good option for when power sources are not nearby, but can be wasteful at end-of-life if the batteries are not properly disposed or cannot be recharged. When possible it is better to connect the beacon to a computer or wall outlet, since the energy draw is small and these sources are rechargeable (computer) or already functioning (wall outlet).

E.2 Location of Arduino, Arduino Motor Shield

Only the packaging and copper coil can be scaled to a quarter of the full-size beacon, since the size of the electrical components such as the Arduino, Arduino Motor Shield and connecting cord cannot be scaled. For this reason only the copper coil will be contained inside the packaging and the electrical components (Arduino, Arduino Motor Shield and connecting cord) will be outside.

Appendix F: Validation Protocol

The following sections detail validation protocol for engineering specifications. Table 1F gives a summary of the validation plan and required resources for each component of the design being tested for validation purposes.

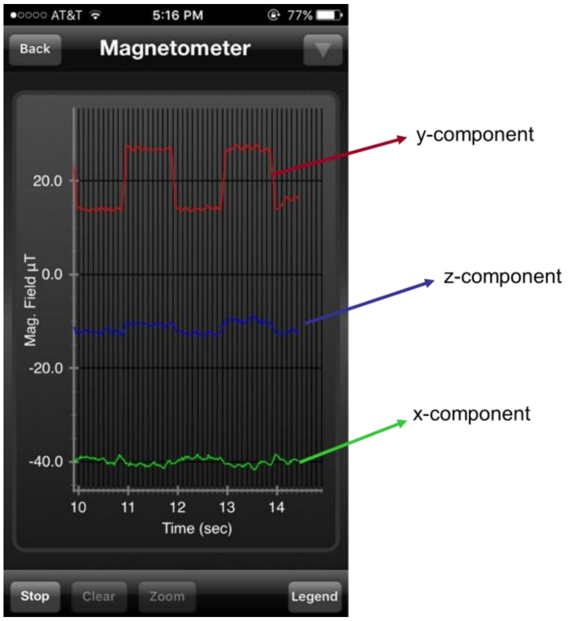
Table 1F: Validation plan for technical specifications

#	Scaled (5:1), Proof-of-Concept	Validation Plan	Required Resources
1	B = 380 nT	Measure using magnetometer	Smart Phone Magnetometer
2	r = 0.5 m	Measure maximum distance at which Smartphone can detect beacon	Smart Phone

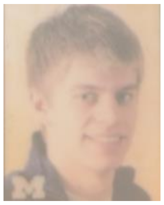
F.1 Magnetic Field Strength, Range

The main validation required for the prototype is for the Magnetic Field Strength. The equipment used was a magnetometer in a smartphone paired with SensorKinetics, a smartphone application used to detect and measure magnetic fields. The test protocol involved exciting the coil through an ELF square wave signal sent through Arduino, Arduino Motor Shield set-up. The requirement for validation was that the magnetic field B is greater than or equal to 300 nT when magnetometer is 0.5 m away. In the testing, the prototype was found to easily achieve this requirement and generated a field strength averaging 20 µT (shown in Figure 1F).

Figure 1F: Target magnetic field strength of 300 nT achieved in y-plane



Authors



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