# WARNING SYSTEM FOR OUTDOOR CONSTRUCTION WORKERS USING HAPTIC COMMUNICATION

A Thesis

by

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ABSTRACT

A construction site is a risky workplace with constant movement of heavy vehicles on ground and cranes overhead, and simultaneous construction work at multiple levels along with significantly high noise levels. Over the past few decades, several efforts have been made to utilize technological advances in order to make the worksite a safer place and yielded positive results. However, the fatal and nonfatal count still remains very high for the construction industry.

This study attempted to test haptic communication as an additional layer of safety for construction workers by developing a prototype to provide haptic feedback for predetermined Geofence zones. A phenomenological research study was conducted with the help of construction professionals to gather industry opinion on the haptic feedback prototypes and to determine the optimal location for the placement of the haptic feedback device. The study found that haptic communication has significant potential to reduce the fatal and non-fatal injuries on construction sites. In addition, the study determined the factors affecting the placement of wearable haptic warning system for outdoor construction workers.

# DEDICATION

I dedicate this thesis to my heroes, my parents. Thank you for understanding me and supporting me in every endeavor.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by Professor Julian H. Kang [committee chair] of the Department of Construction Science, Professor Zofia K. Rybkowski of the Department of Construction Science, and Professor Tracy A. Hammond of Computer Science and Engineering Department, and would not have been possible without their support and guidance. The work was primarily funded by Dr. Kang. All other funding, and work conducted for the thesis was completed by the student independently.

I would also like to acknowledge and express wholehearted gratitude for the contributions made by family, friends, fellow researchers, Department of Construction Science and Texas A&M University.

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# 1. INTRODUCTION

Construction is one of the oldest professions in the world. Humans have been constructing since the start of civilization and as time progressed, construction progressed in scale and complexity. Along with that came the greater risks and dangers to the construction workers. In order to tackle this problem, people have been coming up with various solutions that started with very basic protective gear, such as, boots and hard hats on construction site. This was followed by the introduction of florescent safety vests and other equipment such as safety eye wear, hearing protection and gloves, which provided better visibility, protection and comfort in a construction space.

The latter half of 20$^{th}$ century marked the beginning of Information Technology and the Digital Era. This transformation significantly and positively affected the construction industry introducing advanced ways of ensuring the safety of construction workers. Products such as smart hardhats and safety vests started utilizing location sensors and Radio Frequency (RF) technology for pro-active real-time safety alert system for situations where organizational commitment, supervisory influence, and Personal Protective Equipment (PPE) fails.

Despite these advancements, the fatal and non-fatal count remains significantly high for the construction industry. This study focused on understanding the causes of mishaps on jobsite and exploring the various safety alert systems presently available.

Based on the findings, a new mode of warning construction workers was developed and tested.

## 1.1 Problem Statement

Can wearable haptic technology, on integration with Geofence, be utilized to develop a warning system for outdoor construction workers entering unsupervised or controlled zones?

## 1.2 Research Questions, Hypothesis and Research Objective

Specifically, the research questions of this study were 1) Can haptic technology be a viable mode of communication for construction workers on a job site? 2) What is optimal location for the wearable haptic device from the four predetermined locations – Hardhat, Safety Vest, Neckband and Wristband?

The research hypotheses of this study were, 1) Haptic technology will be a viable mode of communication to alert workers on a construction job site. 2) Wearable haptic neckband will be the optimal position for the placement of haptic device.

The research objective of this study was to answer the research questions by developing a wearable haptic feedback system for outdoor construction workers and determining methods to test the hypothesis mentioned in the previous section.

## 1.3 Limitations and Delimitations

Study Limitations:

The study was limited to outdoor construction environment. The study did not attempt to determine the improvement in safety of construction workers. The Geofence was limited to a circular shape developed around a single point. The study was limited to testing the proof of concept of haptic communication in construction industry and did not attempt to develop or test the scope of haptic communication in the construction industry. The study also limited the Geofence boundary to be predetermined, manually fed and remain constant for each session.

Technology Limitation:

A warning system for outdoor construction workers using haptic communication is not expected to supersede or replace the conscientiousness of the workers. Instead the technology is expected to assist the workers in knowing their safety status and provides alerts based on the haptic feedback zones.

# 2. LITERATURE REVIEW

A typical construction site comprises static materials and equipment in addition to mobile heavy vehicles and manual workforce. They often come in close proximity to each other due to space constraints, and their random and unstructured movement (Sacks et al., 2009). This often results in contact collisions thereby endangering the safety of construction workers.

## 2.1 Need for the Study

### 2.1.1 Injury Statistics Related to Construction

According to the Bureau of Labor Statistics, the construction industry employed over 7.6 million people in 2015. However, the construction industry accounted for one of the largest accident fatality rates per year when compared to other industries in the United States, amounting to 20.5 percent (899 fatalities). A number of these fatal injuries could have been avoided had there been better safety warning system. Furthermore, data extracted from OSHA's fatal occupational injuries by report or exposure 2013-2014 suggest that 15 percent (708 fatalities) of the total fatalities occurred due to contact with objects and equipment. This was further categorized into: struck by object or equipment, struck by falling object or equipment other than powered vehicle, struck by discharged or flying object, caught in or compressed by equipment or objects, caught in running equipment or machinery, and struck, caught, or crushed in collapsing structure, equipment, or material. A recent study on high school students from Texas found that the low wages along with dangerous working conditions are the top two factors that are creating a negative perception towards the construction industry (Ostadalimakhmalbaf et al., 2016). Hence, improving site conditions is extremely important for the construction industry in order to keep its current workforce healthy and safe, and to best reach and attract future generations for careers in construction.

### 2.1.2 Current Safety Practices

Occupational Safety and Health Administration (OSHA) is the regulatory body in establishing construction site safety. It mandated the use of Personal Protective Equipment that includes hard hats, safety vests, work boots, safety eye wear, leather gloves, hearing protection, wet weather gear, face shields, and respirators and filter masks. It has also mandated safety training and education to increase awareness of the workers. These standards are imperative to increase safety in construction, but aren't capable of preventing or warning site workers when they are in risky zones or in close proximity to equipment. There are guidelines for the equipment operators however nothing for the safety of workers who might be involved in contact collisions.

The importance of alerting construction workers for contact collision gains significance because studies have shown that fatigue and task repetition result in lower awareness and loss of focus (Pratt et al., 2001). In addition, technical studies on analytical hierarchy processes and statistical analysis of effective factors on labor productivity have found Labor Safety and Health along with Jobsite Congestion and Disruption as the second most important factors behind Project Planning and Control (Dabirian et al., 2011).

Since all the Personal Protection Equipment (PPE) does not pro-actively generate any warning or feedback to the workers it provides a scope for improvement and innovation. Pratt et al. (2001) and other have noted that construction companies have been slow historically in adapting automated technologies and innovation when compared to other industries. Several case studies from these industries have demonstrated the enhancement in construction worker's safety with the use of emerging technologies (Arif et al., 2014; Teizer et al., 2010a; Choe et al., 2014). Teizer et al., 2010a, explored the safety process that started with administrative policies to effective supervision, enhanced site conditions and safety practices. Technology is widely views as the additional layer of safety protection for construction workers.

According to Ruff (2001), majority of the proximity warning systems may include technologies such as RADAR (Radio Detection and Ranging), sonar, Global Positioning System (GPS), radio transceiver tags, cameras, and combinations of these technologies. But each of these comes with limitations, such as operating range, signal availability, size and weight, and applicability to construction environment. Marks and

Teizer (2012) were referenced to compared the benefits and limitations of the various proximity detection technologies.

There exist several studies that have utilized the aforementioned technologies to alert and warn construction workers. A report of Investigation by Ruff (2007) for NIOSH (National Institute for Occupational Safety and Health) tested proximity detection and alert technology by implementing a magnetic sensing system called HASARD (Hazardous Area Signaling and Ranging Device). HASARD consists of two main components: the magnetic field transmitter mounted on the equipment, and the small receivers or tags that are worn by workers. A low-frequency magnetic field is generated by the transmitter's loop antenna mounted on the front and/or rear of the equipment. The tag measured the strength of the magnetic field and produced an audible and visible alarm if the signal strength reached a threshold that corresponded to the desired detection range.

Teizer et al. (2010a) determined how radio frequency (RF) remote sensing and actuating technology could improve construction safety. Their research focused on alerting workers-on-foot from moving equipment by warning the workers using audio alerts and feeding audio and visual alerts to the equipment operators to avoid a collision. The study also discussed vibration alerts on personal protection units and concluded that they have the drawback to not work well in project locations or regions where workers wear heavy coats that protect from cold weather.

Marks and Teizer (2013) tested proximity detection and alert system for two cases: (1) Static equipment/mobile worker and (2) mobile equipment/mobile worker. Experimental results indicate VHF radio frequency systems can provide alerts in real-time to ground workers, but radio waves are blocked or distorted by components of the construction equipment and varied based on the orientation of PPU.

More recently studies have come up with GPS based solutions to enhance safety of roadside workers. Workers safety vests were equipped with GPS and vehicles with GPS units were used to estimate the trajectory of oncoming traffic, and estimate the likelihood of a collision. The system then alerts the worker and vehicle operator about the collisions and near misses about 5-6 seconds before any potential collision by short-range communication, allowing time for mitigating solutions (Forsyth et al., 2014). According to Martin (2015) the smart E-Vests used auditory (at 490 Hz), vibration (back of neck, front of vest) and visual (LED) alert method. The study measured the reaction time for visual, haptic and auditory alerts and found auditory alerts to be quickest.

In another study spatial- temporal GPS data of ground worker and heavy equipment movements was analyzed to automatically measure the frequency and duration of identified hazardous proximity situations. This was integrated with previous research on blind spots and other safety deficiencies to assist safety managers (Teizer et al., 2015).

In 2015, Redpoint Positioning Corporation came up with a wearable safety alert system for industrial construction sites. Redpoint RTLS (Real Time Location System) interfaces with BIM tools, allowing personnel to dynamically define hazardous areas within the model. The RTLS tags are embedded inside the safety vest and alerts personnel via visual and audible indicators on the vest. It uses a combination of platform, tags, and application software to create an indoor GPS.

Similar to the previous study, Park et al. (2016) used Bluetooth low-energy (BLE)-based location detection technology, building information model (BIM)-based hazard identification, and a cloud-based communication platform. Potential unsafe areas were defined in BIM model, real-time worker locations were acquired to detect incidents where workers were exposed to predefined risks. Then, the safety monitoring results were instantly communicated over the cloud for effective safety management.

### 2.1.3 Noise Level on Construction Site

According to Occupational Safety and Health Administration (OSHA) loud noise can reduce work productivity and also contributes to workplace accidents by making it difficult to hear warning signals. Hearing loss from loud noise can also limit the ability of construction workers to hear high frequencies, understand speech, and reduce their ability to communicate. A study by Laroche and Lefebvre (1998) concluded that there are at least five principle causes for accidents on sites that have sound based warning system: (1) hearing loss among construction workers, (2) high noise levels on some sites,

(3) worker attentional demand or complacency, (4) inadequate placement of alarms, and (5) deficient acoustic features of the alarms.

Although there is little evidence directly linking noise exposure to construction site accidents, noise and hearing loss have been implicated in studies of other industries. For example, noise and hearing loss were found to be accountable for 43% of the injuries in a shipyard setting after controlling for age and job hazard (Charante et al., 1990). Another study by Zwerling et al. (1997) assessed the likelihood of occupational injuries in a large sample of workers drawn from the National Health Interview Survey. These workers had listed themselves as having some kind of pre-existing impairment: visual or hearing impairment, back conditions, upper or lower extremity conditions, diabetes, epilepsy, and arthritis. The authors found that the highest risk of job-related injuries came from workers having sensory impairments with odds ratios for blindness of 3.21, deafness 2.19, hearing impairment 1.55, and visual impairment 1.37. Thereby further reinforcing the fact that the breakdown in visual and audible communication plays a major role in construction fatalities.

Studies have also shown that the noise on a construction site can go up to 125 dBs. In comparison an average human shout or loud alarm is 80-90 dBs whereas the optimal conditions dictate that the sound level of an alarm should exceed the background noise by 10–15 dBs (Suter, 2002). This creates a void and an opportunity to determine a new reliable mode of communication to alert construction workers.

## 2.2 Recent Developments in Other Fields

### 2.2.1 Geofencing

The geofencing technology is a new emerging technology. Geofencing uses the GPS to establish digital boundaries that can be used to control when tools and/or equipment are taken out of those limits. It is increasingly being used to explore the E-C-A (Event/Situation-Condition-Action) approach to define situational fencing and sending out personalized alerts to different users. A 2013 study by Pongpaichet et al. combined personal macro situation, location and weather, with rich personal data to send out situation-based alerts to asthma patents. Geofencing use in autonomous robot control, mapping route navigation and mobile infrastructure inspection have been well documented and recently some construction companies are using the technology to keep track of the whereabouts of construction equipment. Whenever the equipment crosses the boundary and moves to an inappropriate location the manager can receive alerts.

### 2.2.2 Haptic Communication in Navigation

Haptic devices (or haptic interfaces) are mechanical devices that mediate communication between the user and the computer. Haptic devices allow users to touch, feel and manipulate three-dimensional objects in virtual environments and tele-operated systems (Berkley, 2003).

In human-computer interaction, haptic feedback means both tactile and force feedback. Tactile, or touch feedback is the term applied to sensations felt by the skin. Tactile feedback allows users to feel things such as the texture of surfaces, temperature and vibration. Force feedback reproduces directional forces that can result from solid boundaries, the weight of grasped virtual objects, mechanical compliance of an object and inertia. Tactile haptic devices can more easily be wearable.

Haptic communication has already been utilized in multiple fields and various studies have been carried out to test its wide range of possibilities. A study by Elliott et al. (2011) explored the utilization of tactile communication to support dismounted soldier movement, communication, and targeting.

A 2014 study by Prasad et al. tested a wearable tactile navigation vest, HapticGo, which used an android smartphone, while also maintaining users awareness of the environment by detecting approaching obstacles. The study evaluated HapticGo against a mobile tactile navigation app PocketNavigator and found that participants using HaptiGo were successfully able to reach their destinations with significantly lower cognitive load compared to the baseline system. This was consistent with previous studies that concluded that tactile navigation displays outperform visual displays under conditions of high cognitive and visual workload (Elliott et al., 2010).

Haptic alerts have also been used as a navigation tool without any display conditions. Cummings et al. (2012) developed a navigation aid for safety and movement of paratrooper using an interactive application between Android phone application to determine compass bearing and a haptic vest to provide navigation alerts. Similar concept was utilized in developing a turn-by-turn haptic route guidance interface for motorcyclists – HaptiMoto. The study sent tactile signals to the user's rear shoulders through a haptic vest and used a system of tactile pulses where the number of these pulses encoded the relative distance to an upcoming turn, and the duration between pulses and the number of these pulses determined the urgency or nearness to that turn (Prasad et al., 2014).

Recently corporations like Wearable Experiments (We:eX) are commercializing the haptic technology to produce Navigate jacket that feeds direction using LED lights and haptic feedback, and the use of tactile and haptic systems to help people navigate while also focusing on helping visually impaired (Todd and Naylor, 2016).

Other possible uses for wearable haptic system include Physio-therapeutic System for Post-surgery Rehabilitation and Self-care as determined by studying that tested a haptic armband that tracked movement of patient's body part undergoing physiotherapy and delivering alerts when the body parts being tracked were lifted to the required angle of elevations (Rajanna et al., 2015).

Another study by Prasad et al. (2014) developed a user centric model to form tactile codes using shapes and waveforms to convey meaningful information when auditory and visual mediums are saturated or unreliable. The study used two tractors with nine actuators each, arranged in a three-by-three matrix with differing contact areas to represent a total of 511 shapes. The study found that users were able to identify the information provided through tactile code.

As mentioned earlier in this section, multiple attempts have been made over time to enhance the safety of construction workers on a jobsite. Some studies have explored the integration of GPS and Geofencing to provide auditory or visual alert to workers, some studies have tested short-wave warning systems to provide auditory or visual alert whereas one lab tested integration of short-wave communication with haptic alert for roadside workers. However, no study has attempted to develop a haptic warning system for outdoor construction. This study draws inspiration form all the mentioned studies to determine the optimal location for a haptic warning system for construction workers and to test the efficiency of this haptic device on integration with Geofence.

# 3. METHODOLOGY OF THE STUDY

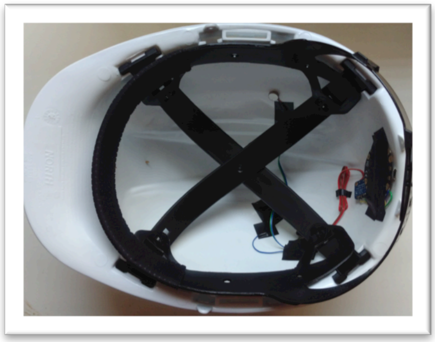
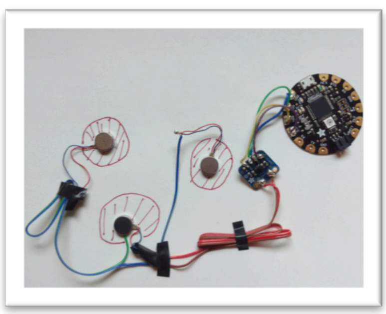
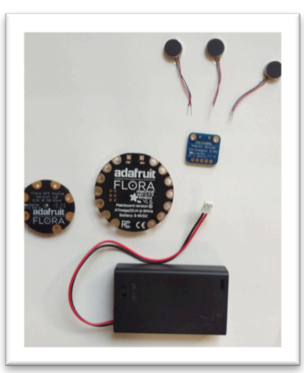
This section outlines the research methodology used in this study. The device development and working have been detailed here along with the inputs on research method, study design, and the population sample.

## 3.1 Research Approach and Design

The study was divided in two parts. First part aimed at developing a prototype and testing the proof of concept of a wearable haptic warning system. The second part focused on testing the haptic warning system and determining the optimal location for construction workers.

For the first part, developing a wearable haptic warning system prototype, literature review was carried out to determine the benefits and limitations of candidates for proximity detection technologies (Marks et al., 2012). GPS was selected to proceed forward due to low initial cost and low infrastructure requirement. Supplementary literature reviews were carried out to determine additional electronics and sensors required for the prototype, along with familiarizing with electric circuit connections and compatible coding language – Arduino. Table 1 discusses the top down approach used to develop a basic Hardhat prototype.

**Table 1: Top Down Product Breakdown Structure for Wearable Haptic Hardhat**

| | | |
|---|---|---|
| 1. |  | Interior View of the wearable haptic warning system |
| 2. |  | Working prototype achieved without compromising structural integrity of the Hardhat |
| 3. |  | Electrical Circuit Diagram of the Assembly |
| 4. |  | Hardware Components of the wearable haptic warning system |

For the second part, a phenomenological research approach was selected. Lester (1999) describes phenomenological research as gathering ‘deep’ information and perceptions through inductive, qualitative methods such as interviews, discussions and participant observation, and representing it from the perspective of the research participant. A phenomenological interviewing design was used. Bevan (2014) described the interview structure for phenomenological interviewing to be a 3-step process. The first step is contextualization approach with descriptive/narrative context questions. The next step involves apprehending the phenomenon through descriptive and structural questions of modes of appearing. And the last step involves clarifying the phenomenon using imaginative variation.

## 3.2 Developing Haptic Fencing Prototype

This study aimed to test a new warning system for outdoor construction workers using haptic communication. Hence as of June 2017, there were no wearable haptic warning systems for construction workers. A new haptic device was developed as part of this research study.

### 3.2.1 Background and Summary

The invention relates generally to a warning system for workers on a construction site. More specifically, the invention relates to a wearable warning system that can be easily mounted as wrist/body strip or as part of personal protective equipment and can provides audible, visual and haptic warnings. These haptic alerts, or a combination of visual, audible and haptic alerts, are mapped to user defined Geofences to convey meaningful information and safety warnings on construction site and similar work environments. The invention relies on user's geo-coordinates received from the gps sensor to convey the warnings and can be powered through a rechargeable electric battery. The GPS sensor enables the processor to check for geofences around the user location and produce corresponding haptic patterns using the haptic controller in harsh construction conditions where audible and visual warning systems might fail.

3.2.2 Components Details

The following table contains the components used for to develop the prototype.

**Table 2: Component Details of the Wearable Haptic Warning System**

| Number | Component | Manufacturer/Vendor | Model No. |
|---|---|---|---|
| 1 | Adafruit Ultimate GPS Breakout | Adafruit Industries | 746 |
| 2 | FLORA - Wearable electronic platform | Adafruit Industries | 659 |
| 3 | Adafruit Haptic Motor Controller | Adafruit Industries | 2305 |
| 4 | Vibrating Mini Motor Disc | Adafruit Industries | 1201 |

The central unit of the prototype, shown in the figure 1, is Adafruit Flora Arduino ATmega32u4 microcontroller.

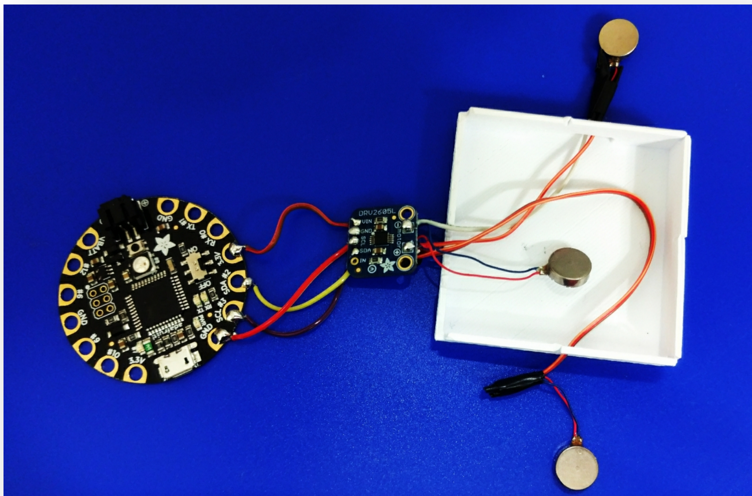



**Figure 1: Electrical Components of the Haptic Prototype**

It has an onboard 3.3v 250mA regulator with a protection diode and can power common 3.3v modules and sensors. It has a USB input of 4.5V-5.5V with 500mA fuse and Clock speed of 8MHz. Conductive wires connect Adafruit Flora to Adafruit DRV2605 Haptic Controller Breakout. Each haptic controller is connected to 3 ERM (Eccentric Rotating Mass) type motors. There are six ROM libraries in the DRV2605 and each contains 123 effects.

**Figure 2: Autodesk Fusion 360 (STV) model of the 3D Printed Case**

Casings were modeled for the haptic devices in Autodesk Fusion 360 and were 3D printed. Five possible locations were determined for haptic alert before the testing began, namely, wristband, neckband, safety vest and hard hat.

3.2.3 Detailed Description

Referring to figure 3, wherein like numerical indicate like or corresponding parts throughout the several views, an exemplary GPS sensor is generally shown at 10 connected to a Microcontroller 14 inside the Body of the haptic warning system, generally indicated at 20. For purposes of illustration and not to be in any way limiting, the following description will make reference to the haptic warning system 20 mounted on a Safety Hat indicated by I. However, it will be appreciated that the invention is equally applicable if it is mounted on any other equipment or piece of clothing.

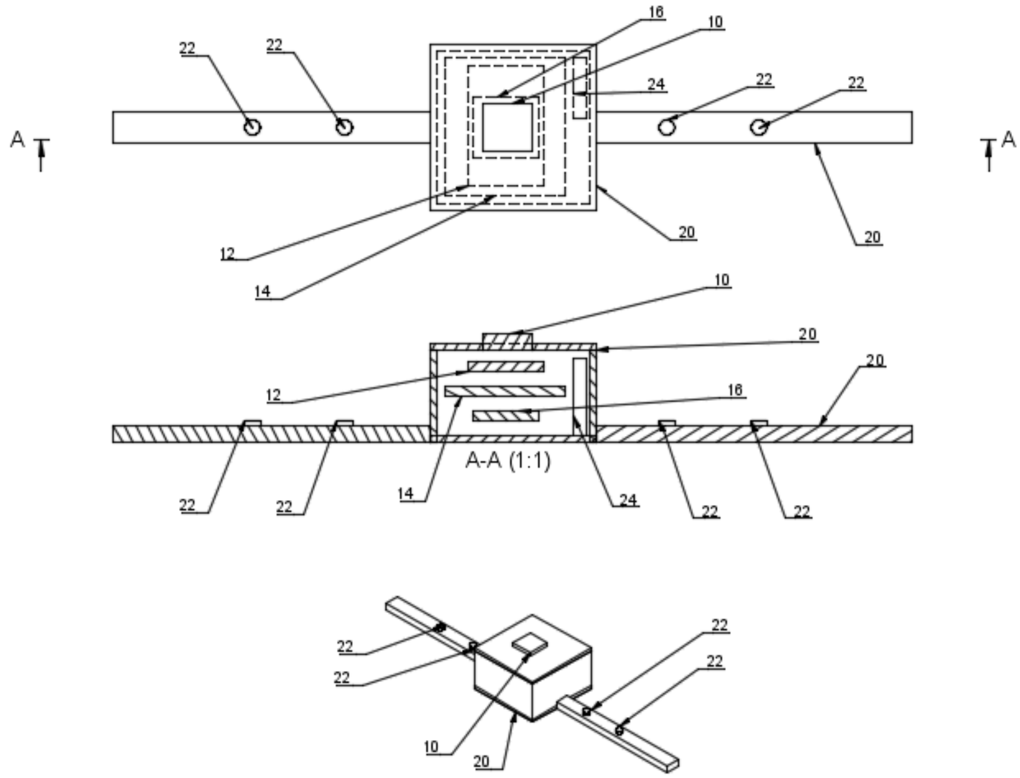



**Figure 3: Projections and Drawings of the Haptic Prototype**

Referring to Figure 3 again, the Microcontroller 14 is connected to the GPS Sensor 10, and the haptic controller indicated by 16. The haptic controller 16 is connected to the vibration motors generally indicated by 22. A Rechargeable Battery, generally shown by 24, powers the whole circuit and the Body of the warning system, indicated at 20, contains the whole circuit while certain parts for instance, and not limited to, the antenna of the GPS Sensor 10 is placed on the exterior.

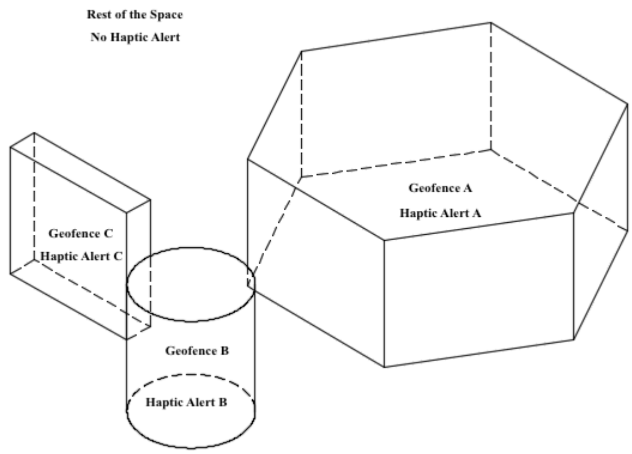



**Figure 4: Simplified View of correspondence between Haptic Alerts and Geofence**

Figure 4 depicts the mapping of Haptic Alerts with Geofence. User is expected to move around the space and at any time will be either inside one of the Geofence or outside all of the Geofence. An exemplary Geofence shown in the discussed figure, Geofence B, is a cylindrical space defined by mathematical algorithms for instance the Haversine Formula. Geofence B is mapped to a specific wave function defined by the Haptic Controller 16 to produce corresponding Haptic Alert B. Each Haptic Alert can communicate warnings such as moving overhead cranes or emergency situations.

### 3.3 Phenomenological Research

The phenomenological interviewing was carried out at CIR Building Construction Site on Texas A&M University campus. Eleven (11) English-speaking construction workers were randomly selected to be part of the study and included representatives from a General Contractors and various sub contractors.

The study began with a brief description about the scope of haptic feedback in construction industry and an introduction on the working of the haptic device. Participants were informed about the research questions and a round of discussion followed this. Later, the participants tried haptic prototypes and their inputs were gathered to know more about each prototype location. The last step involved imaginative variations and hence participants were asked to come up with suggestions on other possible locations for a wearable haptic device on a construction environment. Transcripts of the discussion were prepared and analyzed, and are discussed in detail in the next chapter.

The haptic alerts were timed to run for sixty (60 seconds and the code has been included in the appendix. During the first 30 seconds, the haptic function was a combination of 117 different waveforms activated every 50 milliseconds and ran 5 times during the 30 seconds period. This was followed by the second haptic function which was a combination of 3 different waveforms activated every 100 milliseconds and ran 85 times during the next 30 seconds.

Haptic Prototypes for the four predetermined location – Hard Hat, Safety Vest, Wristband and Neckband are shown in Figure 5 below.

**Figure 5: Haptic Prototypes for four predetermined locations**

# 4. PRESENTATION, INTERPRETATION AND ANALYSIS OF THE STUDY

This section presents the phenomenological study details, along with the interpretation and analysis to help answer the research question and determine the optimal location for a wearable construction device. The transcript of the study has been included in the appendix. This chapter also highlights the ideas and cautions of the using haptic feedback on construction site discussed during the phenomenological interview.

The objective of the study was to determine answer to the research questions posed in previous sections. The first section of the phenomenological study involved explaining the objectives behind developing the prototypes and discussed possible scenarios like assigning a Geofence to Crane's swing radius to correspond to haptic feedback, through which the technology is expected to impact the current construction scenario. Practical hands on session followed this where participants were encouraged to wear and experience the current prototypes to determine if haptic communication is a viable mode of communication on construction site.

All the participants – Eleven (11) out of Eleven (11) responded positively towards the viability of integrating haptic communication with Geofence to set up haptic feedback zones on outdoor construction sites.

The third section of the phenomenological study involved imaginative variance where participants were asked to consider and suggest locations for the wearable haptic warning system apart from the four discussed prototypes. The participants suggested and discussed new possible locations that are mentioned in table 2 along with the four predetermined location. The suggestions from participants included incorporating the haptic warning system in Sunglasses and as an attachable/detachable Safety Vest add-on.

Based on data from the phenomenological study, hardhat was preferred by seven (7) out of eleven (11) participants (63.6 %) and four (4) out of eleven (11) participants (36.4%) responded that they would prefer wearable haptic sunglasses.

**Table 3: Factors Affecting Placement of Wearable Haptic Warning System**

| | Weatherproof | Recharging Ease | Safety Clearance | Traceability | Social Acceptance |
|---|---|---|---|---|---|
| Hardhat | Green | Red | Green | Green | Green |
| Safety Vest | Red | Green | Green | Green | Green |
| Wristband | Green | Green | Red | Green | Green |
| Neckband | Red | Green | Green | Green | Red |
| Safety Vest Add-on | Red | Green | Green | Red | Green |
| Sunglasses | Green | Red | Green | Red | Green |
| Ankle band | Red | Green | Red | Green | Red |

The above table shows various location options for wearable haptic fencing and their feasibility based on mentioned criteria. A corresponding green circle implies that the location has one of the following implications:

- Weatherproof: Location is a suitable fit when considering harsh weather conditions like extreme heat leading to excessive sweat etc. and is not rotated as part of seasonal wear.
- Recharging Ease: Green dot would represent that the particular location is relatively better when considering the ease to recharge the device. Easily detachable locations have preference over locations like Hardhat since industry workers are more particular about their individual hardhats.
- Safety Clearance: The location is presumably safe for the wearable device and will likely avoid accidental physical hazards such as getting stuck in equipment, tools etc.
- Traceability: The wearable device at the discussed location is relatively easier to account for and is not likely to be lost or misplaced.
- Social Acceptance: The wearable device at this location meets the regional social norms and will not make the users uncomfortable morally, sexually or physically.

In the discussed table 2, the red circles denotes the scenarios where above standards were not met by that particular location. In addition to this, the responses were used to determine the order of priority for factors affecting the location of the wearable haptic warning system for construction workers.

The results are represented in Figure 6 where Safety clearance holds the highest priority for determining location of the wearable device followed by other factors in the following order - Weatherproof, Social Acceptance, Traceability and Recharging ease.

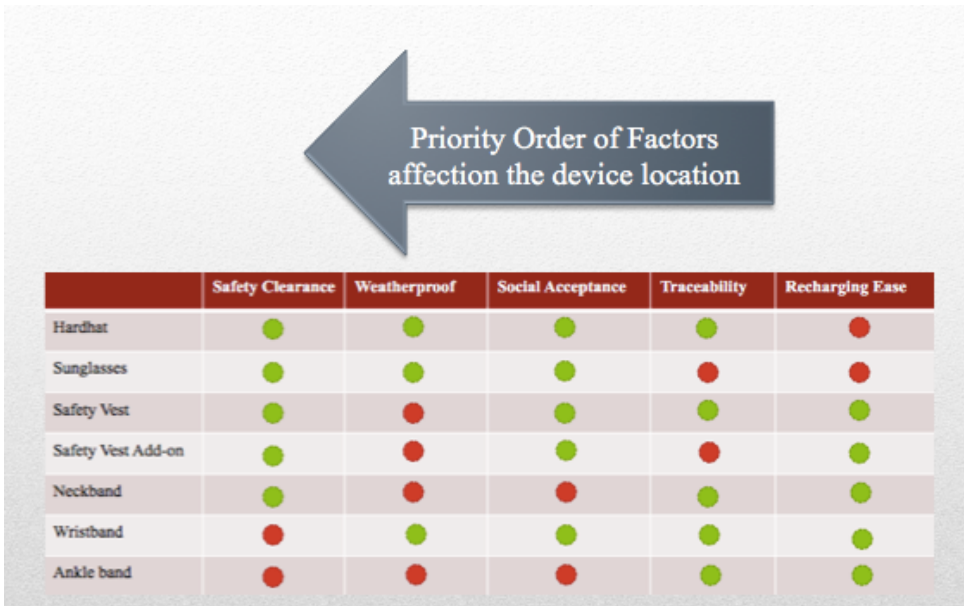



**Figure 6: Priority Order of factors affecting placement of wearable Haptic Prototype**

# 5. CONCLUSION AND RECCOMENDATIONS

Current safety practices have shown considerable improvement in creating safer construction work environments and are saving multiple lives everyday. However they still error-prone, rely heavily on manual, audio and visual based warning systems and have not been sufficient in completely preventing work fatalities on a daily basis. With accessibility to enhanced and economical technology, this study has shown positive results towards an automated haptic feedback approach on a construction site to assist the onsite personnel know their safety status and warns them using a new mode of communication in construction scenario – Touch.

This study tested the proof of concept of a wearable haptic feedback warning system for outdoor construction workers and was substantiated by the positive viewpoint of the construction industry professionals during the phenomenological interview. In addition, a majority of the interview participants validated that a Hardhat would be the best possible location for a wearable haptic feedback system on a construction site, followed by Sunglasses/ Smartglasses, thereby answering the research questions that motivated this study.

The study found that while considering a wearable haptic feedback system, construction workers prioritized the location according to the following preference – Safety Clearance, Weatherproof, Social Acceptance, Traceability, and Recharging Ease.

Continuation of this research is prudent, and the study should be replicated with a more samples to validate the outcomes. The results are geographical based and the preference criteria for the location of wearable haptic system might vary accordingly. Future scope for the study is significant. Enhanced centimeter-level location precision of GPS System is anticipated partly due to expected replacement of microwave atomic clocks with significantly better optical clock technology in the near future.

In the meanwhile, future studies should focus on developing a framework for a wearable haptic feedback system on a construction jobsite. The objective should be to ensure that haptic feedback does not increase the risk of injury in what is already one of the most fatal work environments. Haptic feedback zones and haptic alert language needs to be defined and sensitive areas such as working at heights or wielding zones need to be considered.

Alternate sets of studies are required to enhance the software of the device to expand the scope to define the functions in real time using Building Information Model (BIM). Improvements are required in the software algorithm to define the Haptic Fencing function in BIM, include irregular boundaries, and assign haptic feedbacks to corresponding work zones as based on recommendations from the framework study.

The device can also be improved to include data logging capabilities that can be used to improve the positioning of workers and equipment to assist in the development of new safety concepts. Figure 7 provides a roadmap towards integrating the haptic prototype as an Add-on or Extension for currently used BIM Software.

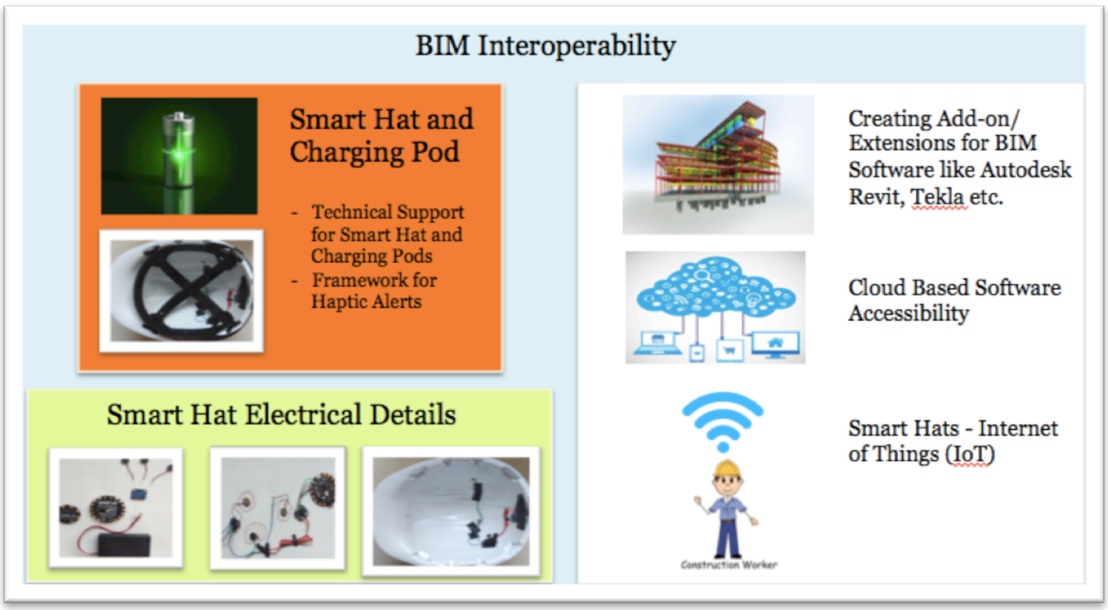



**Figure 7: Future Scope for Integrating Haptic Prototype with BIM**

In summation, this study involved developing a wearable haptic communication device, and conducting a phenomenological interview study to identify an optimal location for the haptic device. It showed positive signs that it has potential to be instrumental in reducing the fatal and non-fatal injuries on construction jobsite. The study recommends further research to develop a framework for a wearable haptic feedback system for the construction industry, and to improve the haptic device software to address some of the safety concerns explored in the study.

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APPENDIX A

ARDUINO CODE FOR PHENOMENOLOGICAL STUDY

The current code is enhanced version of ‘Adafruit_DRV2605.h’ library and ‘Adafruit_GPS.h’ library available under MIT Open Source license.

```
/*******************************************************************
*    Title: Adafruit DRV2605L Library basic.ino Code
*    Author: Limor Fried/Ladyada for Adafruit Industries
*    Date Retrieved : 11th June 2017
*    Code version: 1.0.3
*    Availability: https://github.com/adafruit/Adafruit_DRV2605_Library
*******************************************************************/

#include <Wire.h>
#include "Adafruit_DRV2605.h"

Adafruit_DRV2605 drv;

void setup()
{
  Serial.begin(9600);
  Serial.println("Haptic Test I");
  drv.begin();
  drv.selectLibrary(1);
  drv.setMode(DRV2605_MODE_INTTRIG);
}

uint8_t effect = 1;
int i = 0;
int j = 0;
```

```
void loop()
{
 if (i <6) // First Haptic pattern runs 6 times for i = 0 to i =5.   30 seconds < Total run
time < 35 seconds
  {
   Serial.print("i #"); Serial.println(i);
   Serial.print("   Haptic Pattern 01: Effect #"); Serial.println(effect);

   drv.setWaveform(0, effect);  // play effect
   drv.setWaveform(1, 0);       // end waveform
   drv.go();

   delay(50);

   effect++;
       {if (effect > 117) effect = 1;
        if (effect == 1) i++;
       }
  }
 if (i>5 && j <85) // Second Haptic pattern runs 85 times. Carried out after the first
pattern is complete.   25 seconds < Total run time < 30 seconds
  {
   Serial.print("j #"); Serial.println(j);
   Serial.print(" Haptic Pattern 02: Effect #"); Serial.println(effect);

   drv.setWaveform(0, effect);  // play effect
   drv.setWaveform(1, 0);       // end waveform
   drv.go();

   delay(100);

   effect++;
       {if (effect > 3) effect = 1;
        if (effect == 1) j++;
       }
          }
}
```

//Arduino Code for Haptic Fencing

```
/*********************************************************************

*    Title: GPS_HardwareSerial_Parsing.ino Code

*    Author: Adafruit Industries (2012)

*    Date Retrieved : June 2017

*    Code version: 1.0.3

*    Availability: https://github.com/adafruit/Adafruit_GPS

*********************************************************************/

#include <Adafruit_GPS.h>
#include <math.h>
#include <Wire.h>
#include "Adafruit_DRV2605.h"
Adafruit_DRV2605 drv;

double PointLat = 30.619062;   // Latitude of Point A
double PointLon = 96.351020;   // Longitude of Point A
double R = 6372.729;           // Radius of Earth at Latitude 30.61812 and Altitude 105m
above sea level. Corresponding to Architecture Quad

double lat1, lon1;
double latR1, latR2, lonR1, lonR2, dlon, dlat;
double a, e, d;

#define GPSSerial Serial1  // Name of the hardware serial port
Adafruit_GPS GPS(&GPSSerial); // Connect to the GPS on the hardware port
#define GPSECHO false  // 'true' if required to debug and listen to the raw GPS
sentences

uint32_t timer = millis();
uint8_t effect = 1;

void setup()
{
```

```
  Serial.begin(115200); // connect at 115200 so we can read the GPS fast enough and
echo without dropping chars
  GPS.begin(9600);  // 9600 NMEA is the default baud rate for Adafruit MTK GPS's

  GPS.sendCommand(PMTK_SET_NMEA_OUTPUT_RMCGGA);
  GPS.sendCommand(PMTK_SET_NMEA_UPDATE_1HZ); // 1 Hz update rate
  GPS.sendCommand(PGCMD_ANTENNA); // Request updates on antenna status

  drv.begin(); // Haptic Library
  drv.selectLibrary(1);
  drv.setMode(DRV2605_MODE_INTTRIG);

  delay(1000);

  GPSSerial.println(PMTK_Q_RELEASE); // Ask for firmware version
  drv.begin();
  drv.selectLibrary(1);
  drv.setMode(DRV2605_MODE_INTTRIG);  // default, internal trigger when sending
GO command

}

void loop() // Runs over and over again
{
  char c = GPS.read(); // read data from the GPS in the 'main loop'
  if (GPSECHO)
    if (c) Serial.print(c);

  if (GPS.newNMEAreceived())
  {
    Serial.println(GPS.lastNMEA()); // this also sets the newNMEAreceived() flag to
false
    if (!GPS.parse(GPS.lastNMEA())) // this also sets the newNMEAreceived() flag to
false
      return; // If fail to parse a sentence, wait for another

  }

  if (timer > millis()) timer = millis(); // Resetting if millis() or timer wraps around

  if (millis() - timer > 100) // Run every 100  milliseconds
  {
    timer = millis(); // reset the timer
    Serial.print("\nTime: ");
```

```
Serial.print(GPS.hour, DEC); Serial.print(':');
Serial.print(GPS.minute, DEC); Serial.print(':');
Serial.print(GPS.seconds, DEC); Serial.print('.');
Serial.println(GPS.milliseconds);
Serial.print("Date: ");
Serial.print(GPS.day, DEC); Serial.print('/');
Serial.print(GPS.month, DEC); Serial.print("/20");
Serial.println(GPS.year, DEC);
Serial.print("Fix: "); Serial.print((int)GPS.fix);
Serial.print(" quality: "); Serial.println((int)GPS.fixquality);

if (GPS.fix)
{
  Serial.print("Location: ");
  Serial.print(GPS.latitude, 6); Serial.print(GPS.lat);
  Serial.print(", ");
  Serial.print(GPS.longitude, 6); Serial.println(GPS.lon);
  Serial.print("Location (in degrees, works with Google Maps): ");
  Serial.print(GPS.latitudeDegrees, 6);
  Serial.print(", ");
  Serial.println(GPS.longitudeDegrees, 6);

  Serial.print("Speed (knots): "); Serial.println(GPS.speed);
  Serial.print("Angle: "); Serial.println(GPS.angle);
  Serial.print("Altitude: "); Serial.println(GPS.altitude);
  Serial.print("Satellites: "); Serial.println((int)GPS.satellites);

   if( calcDist() <= 10.0) // Start the Haptic function if inside the Geofence
   {
        Serial.println("You are inside the Geofence. Kindly GET OUT asap!");
        drv.setWaveform(0, effect);  // play effect
        drv.setWaveform(1, 0);       // end waveform
        drv.go();

        delay(10);

         effect++;
         if (effect > 3) effect = 1;
    }
 }
}
}
// **Geofence Calculations**
```

```
double convertDegMinToDecDeg (float degMin)  // Converting lat/long from degree-
minute format to decimal-degrees
{
  double min = 0.0;
  double decDeg = 0.0;

  min = fmod((double)degMin, 100.0);

  degMin = (int) ( degMin / 100 );  //Rebuilding coordinates in decimal degrees
  decDeg = degMin + ( min / 60 );

  return decDeg;
}

double calcDist()  // Haversine based distance calculation formula
{
  lon1 = convertDegMinToDecDeg(GPS.longitude);
  lat1 = convertDegMinToDecDeg(GPS.latitude);

  lonR1 = lon1*(PI/180);    // Converting the current GPS coords from decDegrees to
Radians
  lonR2 = PointLon*(PI/180);
  latR1 = lat1*(PI/180);
  latR2 = PointLat*(PI/180);

  dlon = lonR2 - lonR1;
  dlat = latR2 - latR1;

  a = (sq(sin(dlat/2))) + cos(latR1) * cos(latR2) * (sq(sin(dlon/2)));   // Haversine
Formula. Result in meters.
  e = 2 * atan2(sqrt(a), sqrt(1-a)) ;
  d = R * e * 1000;

  Serial.println();
  Serial.print("Distance to the Point(M): ");
  Serial.println(d, 6);
  Serial.println();
  return d;

}
```

# APPENDIX B

## PHENOMENOLOGICAL INTERVIEW TRANSCRIPT

### Descriptive Context

This is about safety. When we have people working out there they do unnecessary things or silly things and when we notice that we try to shout out to them " Hey, stop! That's not the right thing to do", but you can't do that sometimes because of the construction noise in the background. What you would really like to do if possible is to physically disturb them and say, "Hey, watch out something is coming that way." So touch is a new way of communication that is coming to the industry as Haptic Device. He came up with a small haptic device that you can attach to your hat or neck or wrist that you want your people to wear and anytime you want to give any warning sign to those people you can push a button and the system will kick up automatically to give them some buzz. When you get some vibration around your neck, hardhat, wrist etc. then people may say, "Hey something wrong might be happening, I need to watch out. I need to be more careful!". That is the thing we want to do with that device.

What we do not know yet? Among many places that you can attach this device to, we don't know which location might be the most effective and most effectively convey the vibration to you (the industry users). For example if we put something on your jeans or vest then people may not feel the vibration since they are busy working on the jobsite. If you put something on your forehead then it might be easy for you guys to feel the vibration but this is not the right place because you will be sweating all the time and so this may not be the right location. What about the neck, hand? So there are many places you guys can talk about. So what we want to know today from listening to you all and by having the chance to wear some of the prototypes, we want to know which location, which part of the gear will be the best location to place the haptic device.

We are trying to test a new mode of communication here and trying to determine if we can convey meaningful information through haptic alerts. For example- the swing radius of a construction crane can be defined using a virtual fence and whenever the construction workers enter or exit the boundary, the haptic system will alert them about the crane overhead. Administrators will be able to setup multiple virtual zones throughout the site and assign relevant haptic alerts to convey warnings. As the workers walk through the jobsite, different haptic alerts will provide information like overhead cranes, electrical power lines or heavy vehicles. This is an additional layer of warning system that the construction industry can utilize. However it is not meant to replace or make up for the consciousness of workers on site. Currently we have made 4 prototypes – hard hat, safety vest, neck band and wrist band, and work with a rechargeable battery.

The prototypes were passed around the room for the participants to experience and critique. Figures were used to better explain the working and possible uses of the haptic device.

Discussion: Please note that for this section all the inputs from the 11 participants is denoted by P, and inputs from Mr. Yadav are denoted with Y.

Questions of Modes of Appearing

Y: What we want to know is if the haptic vibrations produced by the 4 prototypes significant enough to alert the construction workers.

P: So, for general stuff like this, walking into a zone you will get the warning through the haptic vibration, is good but not while inside the building someone could activate it right. The thing is if somebody is 60 feet up on a ladder, you get a haptic vibration and you are startled. You don't want to startle anybody who is working at a height and in dangerous enclosed space.

Y: It is possible to manage the haptic feedback with altitude.

P: For general area, Yes! Walking into a haptic feedback vibration zone to let someone to know or increase their safety by watching out for certain things I can see it being very good but if somebody is at heights or some sort of enclosed space or using wielding tool or something that they have to be on job about haptic feedback or vibration can startle them if its not the right way. Make sure that's not an issue.

Y: That's good point. It may increase the risk, because the vibration might startle the workers. What we would like to hear from you guys today is if you feel the haptic feedback from the device, and what according to you is the optimal location.

Y: How about the neckband and the Wristband?

P: Lot of worker will not wear a neckband because it will be uncomfortable due to sweat and will give the impression of a necklace.

P: Wristband might not work as it gets sweaty plus daily work like moving equipment or using construction tools might become more dangerous as the device might get stuck in equipment or we might put your wrist into an equipment etc.

Imaginative Variation

Y: Do not worry about the size of the prototype, it will get much smaller and where according to you is the best place to put it.

Y: That's good point. It may increase the risk, because the vibration might startle the workers. What we would like to hear from you guys today is if you feel the haptic feedback from the device, and what according to you is the optimal location.

P: I think the hard hat is the best. You always have to wear it. It is always got to be on.

P: Most vests have a spot on the shoulder, and you can clip something to it. Also it will be easier to charge the device.

Y: Our concern is that it might not be the most sensitive spot in our body. Feeling the vibration or not.

P: Safety Vest is not worn all the time. Might differ depending on the season – Might wear florescent T shirts in summer etc. Might not wear them in flammable conditions etc.

P: We got to have the safety glasses at all the time. We can add the device over the ears. (They need to have safety glasses all the time). Easiest way to lose it – This can be a problem if the initial cost is high.

Y: Can we have a show of hands to note the preference?

Hard Hat: 7/11, Safety Vest: 0/11, Wristband: 0/11, Neckband: 0/11, Belt: 0/11, Sunglasses: 4/11, Clip on the Safety Vest: 0/11, Ankleband: 0/11 , Workboot: 0/11