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Development of a Real-Time Vibrator Tracking System for Intelligent Concrete Consolidation

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16. Abstract

Proper consolidation of concrete is critical to the long-term strength of concrete bridge structures. Vibration is a commonly used method to make concrete flowable and to remove the excessive entrapped air, therefore contributing to proper concrete consolidation. To introduce vibrations to freshly placed concrete, various tools such as internal vibrators are widely used in the construction industry. Producing a dense concrete without segregation with these tools requires an experienced vibrator operator. Inexperienced vibrator operators tend to over-consolidate or under-consolidate concrete. Many of these quality problems have their roots in the lack of quality control methods that can provide real-time feedback on the quality of concrete consolidation to vibrator operators. The proposed research developed a real-time wireless sensing-based internal vibrator tip tracking system to support intelligent concrete consolidation operations. The research team explored the use of an Ultra Wideband (UWB) tracking system to realize precise localization of the tip of an internal vibrator. A series of indoor and outdoor experiments are conducted to validate and model the tracking accuracy. A visualization program was developed to visualize operators' vibration effort in real-time. More specifically, the program is capable of displaying vibration location and time in real-time. A vibrator operator can leverage such information to visualize the distribution of his vibration effort, and spot areas that may need mitigation actions. The new concrete consolidation tool will allow contractors to proactively address concrete consolidation issues, a problem common to many concrete construction projects.

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DESCRIPTION OF THE PROBLEM

Proper consolidation of concrete is critical to the long-term strength of concrete bridge structures. Concrete being placed in forms should be placed in layers, with each layer being vibrated when it is placed. Placing too much concrete at any one area at a time, or failing to vibrate concrete adequately can result in incomplete consolidation, causing a honeycomb pattern (Figure 1).

Figure 1 Honeycomb defects in concrete caused by improper consolidation

There are two main types of methods employed in concrete consolidation process. They are manual and mechanical methods.

1) Manual methods:

When concrete is placed in thin layers, each layer is carefully rammed or tamped. This is an effective consolidation method, but laborious and costly. The manual consolidation methods are generally only used on smaller nonstructural concrete placement.

2) Mechanical methods:

Mechanical methods represent the most widely used concrete consolidation method. Its essential mechanism is vibration. Vibration may be either internal, external, or both.

To introduce vibrations to freshly placed concrete, various mechanical vibrators can be used. Among them, the most commonly used are internal vibrators (Figure 2). Producing a dense concrete without segregation with internal vibrators requires an experienced vibrator operator. Inexperienced vibrator operators tend to over-consolidate or under-consolidate concrete, both can lead to honeycomb and segregation defects in concrete. Many of these quality problems have their roots in the lack of quality control methods that can provide real-time feedback on the quality of concrete consolidation to vibrator operators. It is ideal to have a way to determine if an area of concrete has been vibrated properly. Currently, judging consolidation adequacy may be one of the most difficult jobs in concrete construction as the vibrator operator can only see the surface of the concrete during vibration and limits his observation only to the exposed surface.

Figure 2 Internal Concrete Vibration (Image Source - Wkipedia.org)

Recently, thermal imaging technology has been shown to be a possible solution to determining the adequacy of vibration as a hot vibrator can provide local heating to the concrete it touches, leaving a persistent “thermal signature” (Burlingame 2004). It is reported that this thermal signature can be detected using infrared imaging after the vibration operation is completed. This allows an inspector to return to an area of fresh concrete and observe the remaining heat signature up to 20 minutes after vibration was completed. However, this approach may not be feasible for layered concrete placement as the thermal signature can be quickly covered during the construction process. Furthermore, the heat signature only can provide information on where a vibrator has been inserted. Other crucial information such as vibration duration and vibration depth cannot be determined through the thermal imaging method.

Therefore, it is reasonable to conclude that a device to measure the adequacy of consolidation of concrete in-situ does not exist and the judgment of adequacy is often a myth to vibrator operators and inspectors as basic but essential information including vibration location, vibration duration, and vibration depth is seldom recorded. There is a need for methods that can reliably and rapidly record these kinds of information and use them as real-time feedback for guiding operators to conduct proper vibration of freshly placed concrete.

The purpose of this research is to develop a real-time vibrator tracking based intelligent concrete consolidation system. Our vision is to develop a system that incorporates tracking elements, or "tags", attached on internal vibrators, which precisely track the location of vibrator tips in a three-dimensional space. Therefore, the vibration procedure can be monitored in great detail and in real-time. The tracked vibration location, duration, and depth can be used to pro-actively identify and mitigate consolidation issues, therefore preventing over-consolidation and under-consolidation. The new system would significantly improve concrete consolidation quality control practices.

APPROACH

Compaction of earth or pavement once shared the similar problem as faced by concrete consolidation. Improper compaction often leads to foundation problems. This has led to the development and wide adoption of intelligent compaction methods. An essential component in these intelligent compaction methods is GPS-based location tracking. The basic principle of these methods is that once the position of compaction equipment can be tracked in real-time, such information can be used to monitor compaction procedures and provide real-time feedback to operators. In this study, we extended this approach to monitoring concrete vibration procedures. The purpose of this research is to develop and test a real-time vibrator tip tracking based intelligent concrete consolidation system. More specifically, once the movement of the tips of internal vibrators can be precisely tracked in a three-dimensional space, information of vibration location, vibration duration, and vibration depth can be automatically derived and used by vibrator operators to proactively mitigate consolidation issues, therefore preventing over-consolidation and under-consolidation.

The difference between this proposed approach and the intelligent compaction approach is that instead of using GPS as a tracking mechanism, we use Ultra Wideband (UWB) as the positioning and tracking technology. Internal concrete vibrators have a very small footprint when compared to the footprint of a compaction equipment. This requires a better positioning accuracy than what is needed in earth or pavement compaction operations. In addition, many concrete operations happen in an environment with considerable obstructions, which can cause degraded GPS performances. To understand alternative technologies that can be used to track the small footprint of an internal concrete vibrator, the research team reviewed relevant studies. The following provides a short summary of these studies.

Literature Review

Overview of RTLS Technology

Recently, Real-Time Locating Systems (RTLS) have been widely studied by the Architecture, Engineering, and Construction (AEC) industry. These systems include, but are not limited to, GPS, Radio Frequency Identification (RFID), RuBee, Infrared, Bluetooth, Ultra-Wideband, Wi-Fi, Cellular, ZigBee, and vision sensors. Most, if not all, these methods rely on one of the following methods to calculate real-time locations of tracked objects:

- Angle of Arrival (AOA)
- Received Signal Strength Indication (RSSI)
- Round Trip Time (RTT)

- Time of Arrival (TOA)
- Time Difference of Arrival (TDOA)
- Triangulation/Trilateration
- RF Fingerprinting
- Proximity to several points

A brief overview of the RTLS systems is provided as follows:

GPS. GPS is a space-based satellite navigation system that was developed by the United States. It provides location and time information in all weather conditions. A GPS receiver calculates its position by precisely timing the signals sent by GPS satellites high above the Earth. In a nutshell, a GPS receiver uses the messages it receives from GPS satellites to determine the transit time of each message and computes the distance to each satellite using the speed of light. A triangulation process is often used to eventually pinpoint the GPS receiver position. Recently, similar satellite navigation systems have been under development in or deployed by Russia (GLONASS), China (Compass), and Europe Union (Galileo).

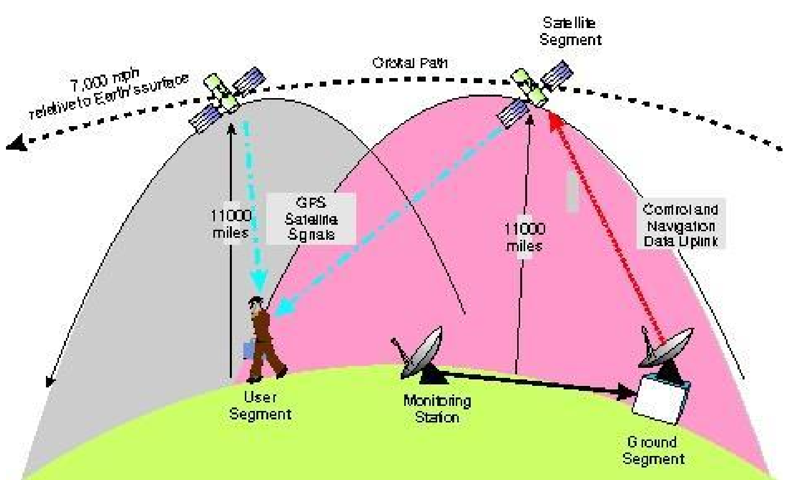

Figure 3 The Principle of GPS Positioning

RFID. Radio Frequency Identification represents a way of identifying, locating, and tracking objects or assets and people using radio waves, and it presents several advantages over some other traditional identification technologies in that its operation does not require physical contact, line-of-sight, or clean environments devoid of noise, contaminants, glare and dirt. Current RFID systems are comprised of three main components (Figure 2): 1) RFID tag, or transponder that is attached to the object to be identified and is the data carrier in the RFID system; 2) RFID reader, or interrogator that is a fixed or mobile device that reads and may write data to the tag though RF wireless communication when tags come within its read range (varying from one inch to 300 feet or more); 3) a data processing subsystem including software and infrastructures that utilizes the data obtained from the transceiver in some useful manner such as enterprise integration.

Figure 4 RFID System Components (Winthrop 2006)

RFID tags vary in many specifications, such as power source, carrier frequency, read range and rates, data storage capacity, memory type, size, operational life, and cost. Since their power source dictates other characteristics directly or indirectly, RFID tags are primarily classified as passive or active, depending on the manner in which they derive operating power to run the digital logic on the chip and transmit the stored data to the reader (Sarma 2003). Passive tags have no power supply built in and derive their power from the RF energy transmitted from a reader that allows it to transmit its information back. Because of the limited supply of power, the transmission of passive tags is limited in both data content -- typically no more than an ID number -- and range of broadcast, usually shorter than 32 feet (10 m). Active tags have an on-board power source (usually a battery) that is used not only to power the logic, but also to transmit the stored data to the reader. With an independent power supply, active tags allow long read range and other improved capabilities compared with passive tags, and are typically read/write – the read range is also constrained by power available at the reader and operating frequency bands. The trade-off is a finite lifetime (optimally, eight to ten years), and greater size and cost. Depending on the mode of energy savings, active tags also can be further classified into wake-up tag systems or awake tag (beacon) systems. Wake-up tag systems are deactivated or asleep until activated by a coded message from a reader. Awake tag or beacon systems are responsive to interrogation without requiring a coded message to switch the tag from an energy conservation mode.

RuBee. RuBee is an emerging RTLS technology, which uses IEEE 1902.1 and is expected to provide an alternative to RFID technology by overcoming some of the key issues facing the RFID systems. These issues include battery consumption and security. RuBee uses low frequency and consumes very low power.

Infrared. Infrared has wavelength longer than visible light but shorter than RF. Infared-based RTLS typically uses diffused IR, which eliminates the line of sight issues, to achieve room-level locating. Infrared RTLS is low cost and safe, but it has the limitation of short reading range and low locating accuracy.

Wi-Fi (Wireless Fidelity). Wi-Fi based RTLS relies on 802.11 networking for real-time locating. Its main principle is Radio Signal Strength Information (RSSI) and Time Difference of Arrival (TDOA). In general, Wi-Fi based RTLS can provide locating accuracy up to 1 m. The issue with Wi-Fi-based RTLS is that it requires significant infrastructure – Wireless Local Area Network (WLAN), which is normally difficult to set up in an outdoor environment.

Bluetooth. Bluetooth operates in the 2.4 GHz band as same as Wi-Fi. In a general Bluetooth based RTLS framework, Bluetooth access points are installed at a regular distance, and Bluetooth-capable devices act as tags. The location engine uses the tag's

RSSI to calculate tag locations based on trilateration, fingerprinting, or proximity.

ZigBee. ZigBee-based RTLS operates based on the IEEE 802.15.4 standard. ZigBee can support large number of nodes providing a low cost global network. ZigBee operates at a slower data rate than Wi-Fi does, therefore consuming less power.

UWB. UWB is an emerging sensing technology that is capable of determining three-dimensional resource location information in object-cluttered environments in real time. In general, an Ultra-Wide-Band (UWB) system is composed of active tags and mounted receivers which use angle-of-arrival and time-of-arrival of the UWB signals to determine a tags position. The tags send UWB pulses, which are short and have low repetition rates (about 1-100 mega pulses per second). A typical UWB system is shown in Figure 3.

Figure 5 Typical Components in a UWB system (Ubisense 2013)

Cellular. As mobile devices become ubiquitous, the interest of using cellular devices as a RTLS system is rising. Cellular devices use the Ultra High Frequency (UHF) portion of the radio frequency spectrum. In the simplest term, the cellular-based RTLS relies on resolving the position of the mobile devise by indicating the cell with which the mobile device is registered (Figure 4). In addition, when the receiving cells provide RSSI for mobile devices, the location granularity over the cell of original can be improved.

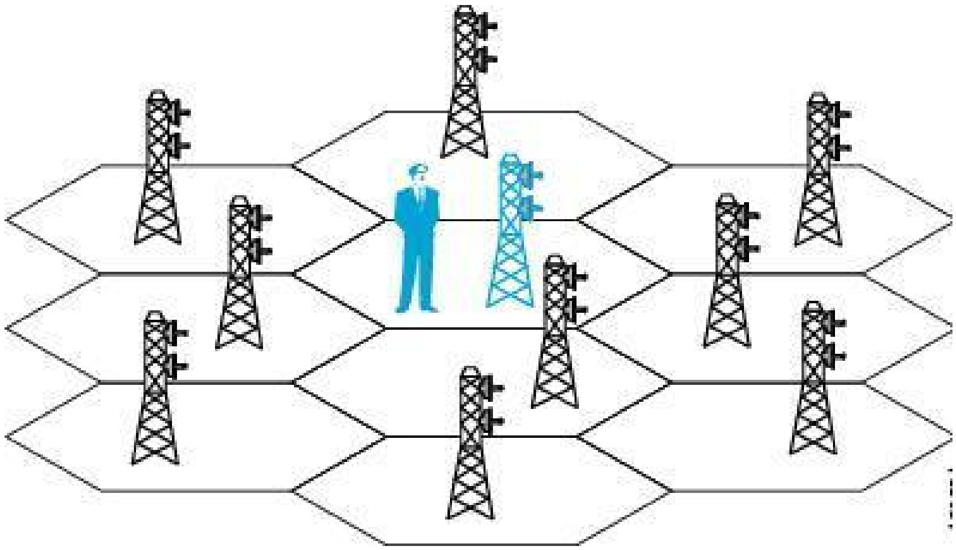

Figure 6 A Cellular-based RTLS System (Credit: www.cisco.com)

Vision-based Systems. Vision-based systems, such as digital cameras and range sensors, are typically used as a locating and tracking system when it is not possible to attach a tag to the asset or person needed to be located. The principle of vision-based RTLS systems is to use computer vision methods to process image data obtained using live cameras. To compare these various RTLS technologies, their key characteristics are summarized in Table 1.

Table 1. RTLS System Comparison

RTLS Technology	Common Frequency	Reading Range	Accuracy
GPS	1.2276 GHz 1.57542 GHz		0.01m with differential GPS 2-5m others
RFID	Low frequency – 30 kHz – 300 kHz High frequency – 3 MHz – 30 MHz Ultrahigh frequency – 300 MHz – 915 MHz	Passive 10m Active 100m	1-3m
RuBee	131.072 KHz	15m	
Infrared (IR)		10m	5 – 10m
Wi-Fi	2.45 GHz, 5 GHz	100m	1-5m
Zigbee	2.4 GHz	10 – 100m	1m
Ultra-Wideband (UWB)	3.1 – 10.6 GHz	30m	0.01m
Cellular RTLS	800MHz, 1.9 GHz		50-200m

Related Studies

Asset location data have long been considered as a critical type of information for developing business intelligence. In construction, the availability of location data provides opportunities to understand many aspects of construction operations as well as to develop intelligent construction monitoring applications. To date, RTLS systems have been studied in the construction field on their potential for construction productivity monitoring, construction safety, construction equipment automation, construction quality monitoring, logistics and material and tool management, and Building and infrastructure asset management. In addition, many studies have focused on assessing the performance of various RTLS systems or developing dedicated locating methods. This is a field with a vast amount of relevant studies. Table 2 shows the distribution of these studies across two variables: (1) the technologies used; and (2) the targeted applications. It also can be noted from Table 2 that there are limited studies on using RTLS systems for construction quality monitoring. This study focuses on this gap by develop a RTLS system for monitoring concrete vibration procedures.

In this research, the primary goal is to test the applicability of real-time location systems for monitoring concrete vibration procedures. In order to track the tip of a vibrator, a RTLS system should have the following capabilities: (1) high position accuracy; (2) high data update rate; and (3) resistant to interference. Based on the above review, the research team selected the UWB system as the potential technology that can meet these requirements.

Table 2 An Overview of RTLS Studies in the Construction Field

	GPS	RFID	Ultra Wide Band	Visual Sensing	W
Construction Productivity Monitoring	Nipesh and Jochen (2013); Navon (2005); Hildreth et al. (2005)	Su and Liu (2007)	Cheng et al. (2013); Teizer et al. (2013); Teizer et al. (2007)	Gong and Caldas (2009); Gong et al. (2011); Navon (2007);	
Construction Safety	Oloufa et al. (2003)	Chae and Yoshida (2010); Teizer et al. (2010); Lee et al. (2011); Wu et al. (2010)	Carbonari et al. (2011); Cheng et al. (2012); Giretti et al. (2009); Hwang (2012); Teizer et al. (2013)	Teizer et al. (2007); Chi and Caldas(2011); Cho et al. (2011)	Wu et al. (2010); Shen et al. (2008)
Construction equipment automation	Anderegg and Kaufmann (2004); Ming et al. (2007)	Moon and Yang (2009)	Albahnassi and Hammad (2011); Cheng et al. (2011); Zheng et al. (2011)	Cho and Gai (2013); Gong and Caldas (2007); Beliveau et al. (1996)	
Construction Quality Monitoring	Navon (2005)	Wang (2008)			
Logistics, material and tool management	Song et al. (2006)	Grau and Caldas (2009); Grau et al. (2010); Goodrum et al. (2006); Tzeng et al. (2008); Ergen et al. (2007); Ki (2010)			Jang and Skibnieswki (2008); Kim et al. (2010);
Building and infrastructure asset management		Ergen et al. (2007); Li et al. (2012); Donath, M. (2006);			
System Performance Evaluation	Peyret et al. (2000)	Li and Burcin (2011); Luo et al. (2011); Pradhan et al. (2009)	Cheng et al. (2011); Cho et al. (2010); Khoury and Kamat (2009); Maalek and Sadeghpour (2013); Saidi et al. (2011)	Teizer and Vela (2009); Park et al. (2011);	Khoury and Kamat (2009); Li and Burcin (2012); Park et al. (2011); Skibnieswki (2009)
Positioning and Tracking Method Development	Razavi and Haas (2010); Behzadan et al. (2008)	Razavi and Haas (2010); Razavi and Haas (2011); Razavi and Moselhi (2012); Song et al. (2006); Song et al. (2007)	Razavi and Haas (2010); Shahi et al. (2012); Teizer et al. (2008)	Brilakis et al. (2011); Yang et al. (2010)	Behzadan et al. (2008)

METHODOLOGY

The proposed methodology consists of two major components: (1) real-time vibrator tip position tracking; and (2) real-time visualization of vibration effort. The first component involves system assembling and validation of tracking accuracy through experiments. The second component focuses on the development of a visualization method that can display the spatial distribution of vibration effort in real-time. The following sections provide detailed description of the research tasks accomplished in each of the components.

Real-Time Vibrator Position Tracking

System Calibration

The Ubisense Real-Time Location System consists of sensors, tags and Ubisense software platform running on a PC. The sensor is a precision ultra-wideband (UWB) measurement device that contains an array of antennas and UWB radio receivers. It detects UWB pulses from the tags, allowing the Ubisense location system to find the tags' positions. The sensors are connected to a PC via Ethernet cable. In addition, sensors are connected among themselves with Ethernet cables that serve as timing cables (Ubisense Location Log Ubisense Manual). The tag transmits UWB radio pulses, which are detected by sensors; each sensor measures angle of arrival (AoA) and time difference of arrival (TDoA) of the in- coming signal and this information is used to determine tag's location (Ubisense Research Network2007) . The system operates on 6 – 8 GHz radio frequency range. In addition, 2.4 GHz channel is used for sending telemetry commands to the tags (such as when to emit a pulse). The advertised operating range (in open conditions) is up to 160 m with achievable accuracy better than 30 cm. The angles of a sensor coverage are 120° horizontally and 100° vertically. The Ubisense system is relatively easy to set up. The entire setup process requires 45 minutes to an hour. The majority of the setup time is due to system calibration, which is key to achieve high accuracy positioning. The overall process for system setup includes:

1) Install a sensor cell
2) Measure the sensor positions
3) Start the location engine software

4) Add or import sensors
5) Configure the cell plan
6) Configure tag range
7) Boot sensors
8) Calibrate the sensors thresholds
9) Wake up tags
10) Calibrate orientation and cable offsets
11) Check the operation

In term of measuring sensor positions, the recommended practice is to use a laser surveying instrument and fiducial marks that can be found on sensors' front sides if the cover is removed. Known sensor positions are prerequisite for the orientation and cable offset calibration using the methods built in the Ubisense software. There are three ways of performing orientation and cable offset calibration. They include full calibration, dual calibration, and orientation calibration.

For full calibration, multiple measurements from five or more survey points with known and fixed Z coordinate are used to determine both orientation and cable offsets for all sensors. In dual calibration, multiple measurements from a single survey point with known X, Y and Z coordinates are used to determine orientation and cable offsets for a pair of sensors. The third option is to use orientation calibration and cable calibration which determine orientation (pitch and yaw; roll is assumed to be zero) and cable offset, respectively. Both methods need to be performed on each sensor, and they both require multiple measurements from a single survey point with known X, Y and Z coordinates. The sensors after calibration are adjusted for noise reduction due to external factors. The thresholds are set way below to accommodate for noise reduction. Once the system is set up and the tags are successfully tracked, Ubisense provides a 3D environment for visualizing the positions of tags (Figure 7).

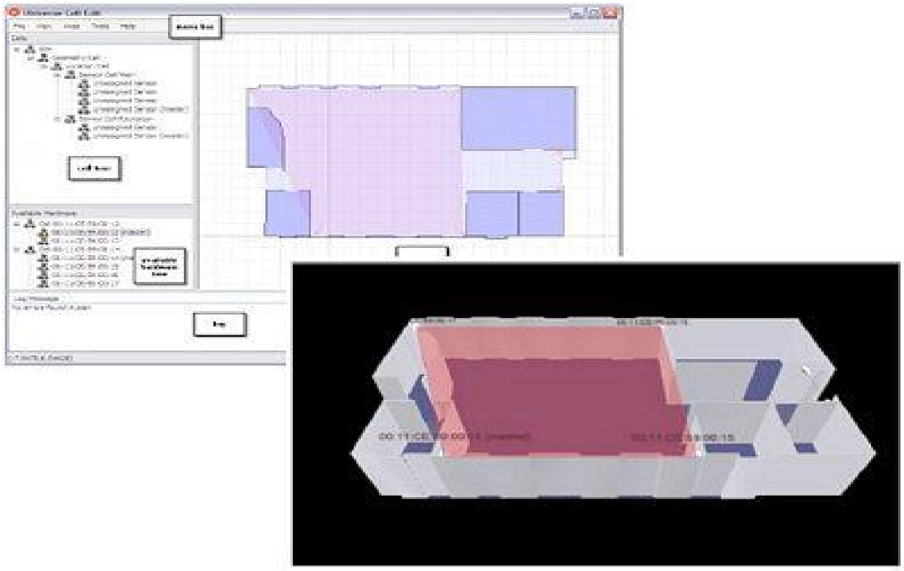

Figure 7 Ubisense Visualization Platform

Experiment and Data Analysis

Indoor and outdoor experiments were conducted to evaluate the accuracy of the system in terms of tracking vibrator tips. The indoor experiment is further divided into two types of experiments to determine the tag positioning accuracy. The first type of experiments focused on determining the accuracy of the tags on the Ground Profile. And the second type of experiments focused on determining the accuracy of the tags once they were attached to the vibrator.

Two types of experiments were conducted to determine the tag positioning accuracy. The first type of experiments focused on determining the accuracy of the tags on the Ground Profile. And the second type of experiments focused on determining the accuracy of the tags once they were attached to the vibrator.

Experiment 1:

In this experiment, the Ubisense system was set up in an indoor rectangular space. The geometry of the indoor space was shown Figure 5. The UWB sensors were set up as a triangular arrangement covering the entire profile of the room. The positions of the UWB sensors in relative to the indoor space are shown in Figure 6.

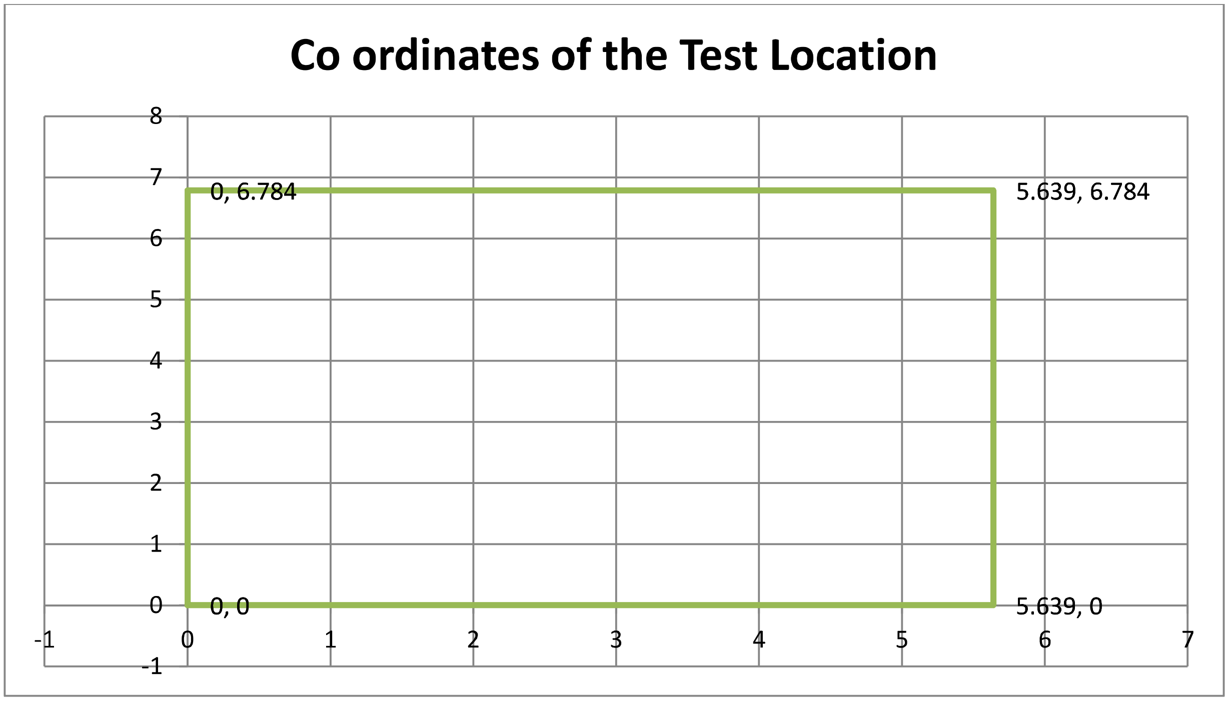

Figure 8 The Indoor Experiment Site Layout

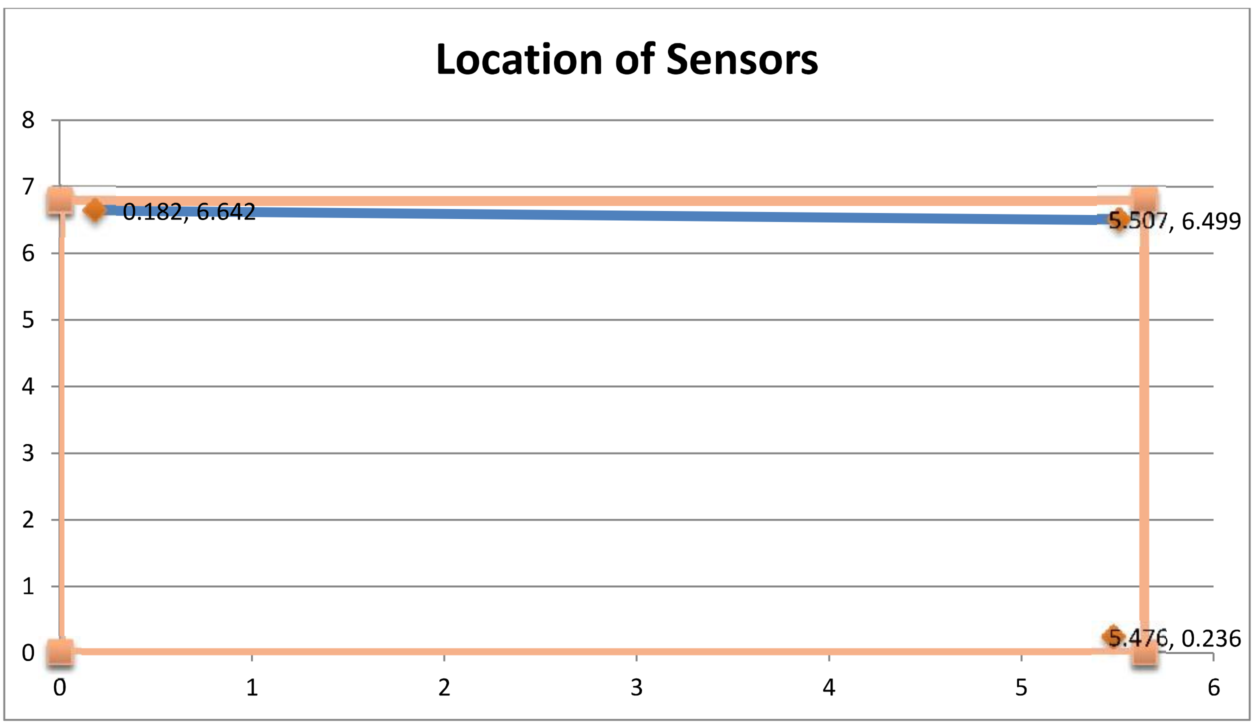

Figure 9 The Layout of UWB Sensors

In order to validate the UWB positioning accuracy, 20 points in the indoor space were randomly picked and their positions were measured using a terrestrial laser scanner (Figure 7). The measured positions of these points are recorded in Table 3.

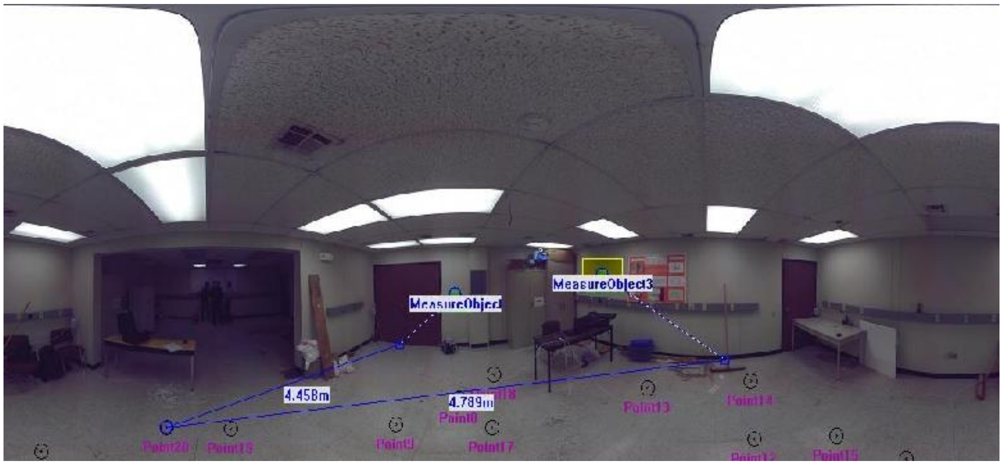

Figure 10 The Benchmark Points in the Testing Sites

Table 3 Tracking Performance Summary

	Ground Truth Points			Ubisense Tracking Results		
	X (m)	Y(m)	Z (m)	X (m)	Y (m)	Z (m)
Point1	4.791	0.8	0	4.7912949	0.798906	0.00715
Point2	4.794	2.937	0	4.7939563	2.8977458	0.001215
Point3	4.797	5.376	0	4.797456352	5.36879657	0.005215
Point4	3.278	6	0	3.2678966	5.99678596	0.007897
Point5	1.752	5.386	0	1.751547896	5.38589961	0.001299
Point6	1.74	2.94	0	1.745874	2.9398647	0.008548
Point7	3.261	0.805	0	3.2596366	0.80499636	0.001548
Point8	3.258	2.017	0	3.2574859	2.0189633	0.007459
Point9	3.873	2.631	0	3.8727489	2.6304789	0.001459
Point10	4.0019	2.0165	0	3.99064	2.01582	0.002548
Point11	2.959	5.078	0	2.947899	5.077899	0.002489
Point12	2.045	4.469	0	2.044696	4.45963214	0.002548
Point13	1.129	3.254	0	1.1112369	3.236987	0.00279
Point14	0.828	4.776	0	0.792912	4.764695	0.007895
Point15	2.35	5.077	0	3.868985	5.0965214	0.004896
Point16	3.879	5.072	0	3.854789	5.07196854	0.001456
Point17	2.956	2.637	0	2.95548693	2.6214587	0.005237
Point18	2.647	1.412	0	2.6312148	1.4100125	0.005412
Point19	4.79	3.848	0	4.762879	3.84425699	0.004713
Point20	4.789	4.458	0	4.7745699	4.454789633	0.005236

Once these points were measured using laser scanning, UWB tags were placed on these points. The coordinates of these points as determined by the UWB system are shown in Table 4. It should be noted that both measurements, laser scanning based and UWB-based, used the same coordinate system. Figure 11 shows the comparison between positions calculated by Ubisense and the ground truth positions. It can be determined that the average distance error between the position measured by the terrestrial laser scan and the position measured by the UWB system is 0.089 meter with a standard deviation of 0.337. Therefore, the results suggest that the position accuracy of this UWB system is well within 15 cm, which is stated accuracy by the manufacturer of the system.

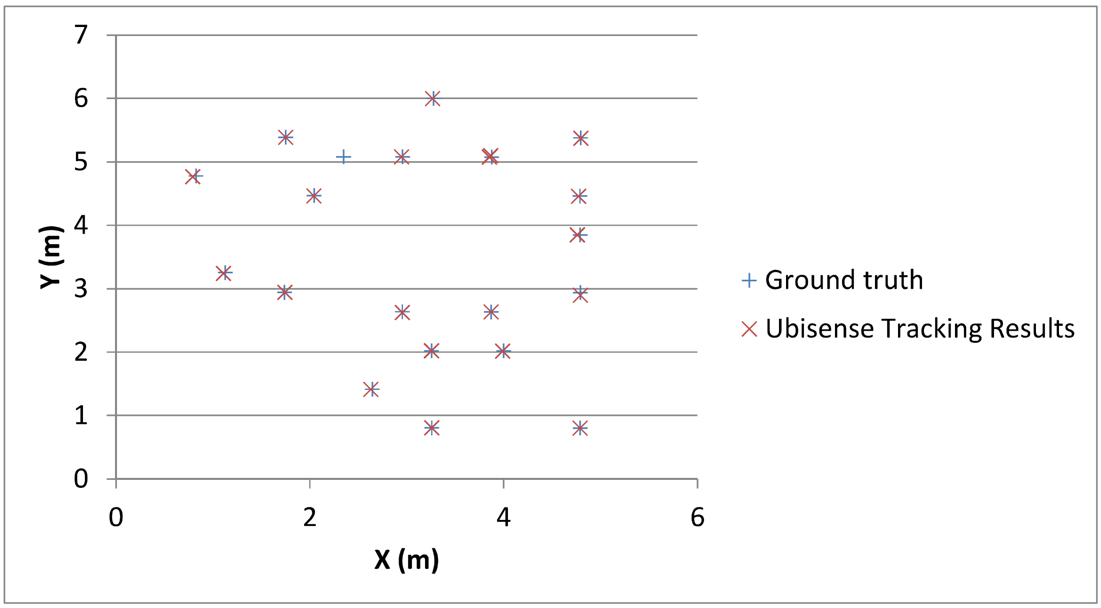

Figure 11 Experiment Positioning Accuracy

Experiment 2:

In experiment 2, a RFID tag was attached to a concrete vibrator. The tag was placed at a distance of 1 foot from the vibrator tip (Figure 13). After the tag was attached, we simulated the scenario of using the vibrator vibrating the area as shown in Figure 14. More specifically, we navigated the tip of the vibrator around the room, and in particular, navigating over the various points, which were set up in the first experiment. Therefore, these points can be used to quantitatively measure the position tracking accuracy.

Figure 12 A Concrete Vibrator with an Attached UWB Tag

The UWB system was set up to run at certain update rates. During this experiment, in each second, the UWB system will update the position of the tag. These position updates were recorded, and Figure 30 shows the trace of the position of the vibrator tip during the execution of the experiment.

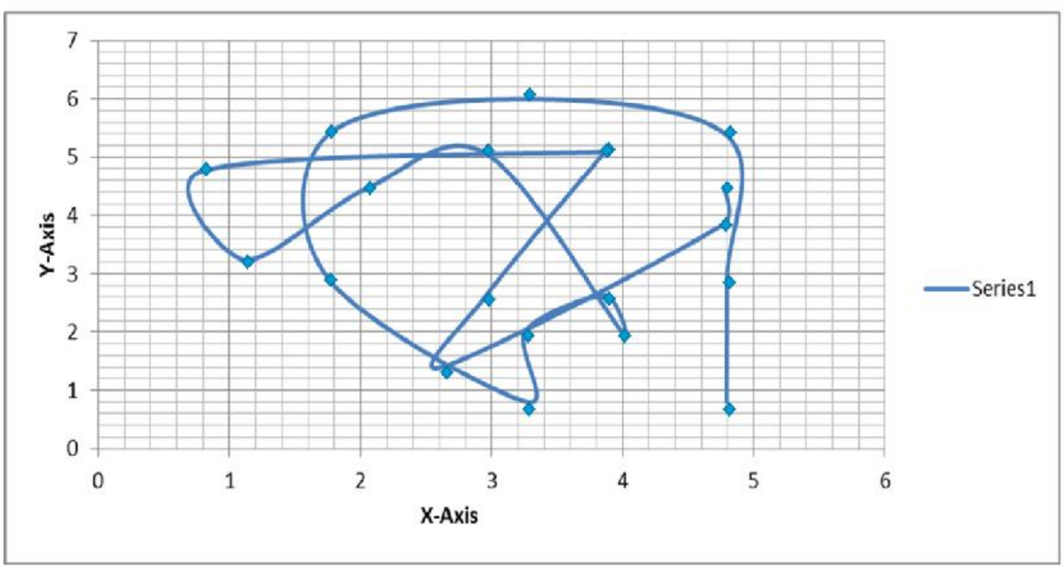

Figure 13 Ground Truth Points and the Traced Vibrator Path

Real-Time Visualization of Vibration Effort

Software Development

The benefit of using RTLS systems to track concrete vibration performance can be maximized when the vibration effort can be visualized in real-time. A vibrator operator can leverage such information to visualize the distribution of his vibration effort, and spot areas that may need mitigation actions. To this end, a computer program was developed using the C# language to track tags, to infer vibrator poses, and to visualize operators' vibration effort in real-time.

Figure 14 shows the interface of the program. The program records the position of vibrator tips in predefined time intervals, and displays the position of vibrator tips over time in various graphical charts. The core of the program is two computer threads that run independent of each other, one for fetching position data from UWB sensors; and the other for plotting graphics. Each time when new position data is fetched, the plotting thread is notified and uses the new position data to update the graph. In this way, these two threads work asynchronously to keep the program responsive under most conditions. The program also provides capability for saving the position data into text files on the computer as a project record. The text file can be plotted into a graph again for inspectors as quality checking tools.

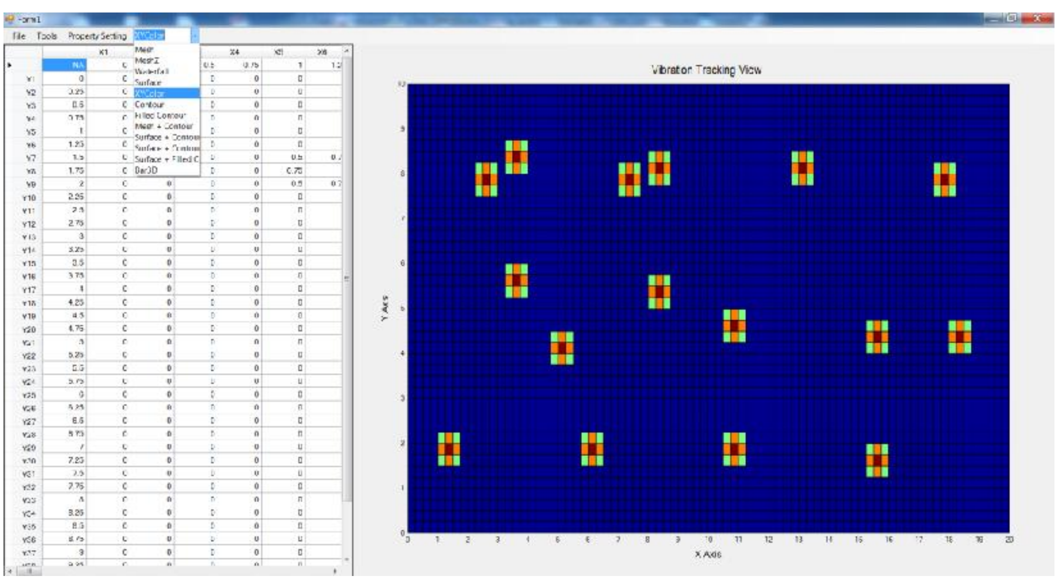

Figure 14 The Interface of the Vibration Effort Tracking System

The essence of the program is to use the concept of occupancy grid to record vibrator insertion points. In other words, the concrete work area was first discretized into a grid of cells with a specified size. The initial value in each cell is set to zero. Each time when the position of the vibrator tip is updated, the program quickly determines the grid cell where the vibrator is inserted, and increments the value stored in the cell by one. Since the position update rate can be specified, it becomes a straightforward process to calculate the actual length of time each cell was vibrated. One limitation to this approach is that it is unrealistic to assume that the vibration effort of each insertion is constrained to a cell, in particular, when a small cell size is used. A more reasonable approach is correlating the number of cells to be updated to the vibration influence zone as specified by the vibrator manufacturer. It is also important to consider the attenuation effects when the vibration energy propagates through concrete. Therefore, the values in cells surrounding an insertion point needs to be incremented non-uniformly. The further the cell is from the center cell (where the vibrator is inserted), the less increment value should be used.

To test the program, we used a schema as shown in Figure 15 to update the cells. A cell size of 0.25 meter was used in this particular case. Figures 16 and 17 showed the results of using the software to visualize vibration efforts with the updating schema as shown in Figure 15. It is important to note that these results were showing in real-time. Therefore, the vibrator operator can use it to immediately identify areas that are less or over vibrated.

0.5	0.75	0.5
0.75	1	0.75
0.5	0.75	0.5

Figure 15 An Example Cell Update Schema

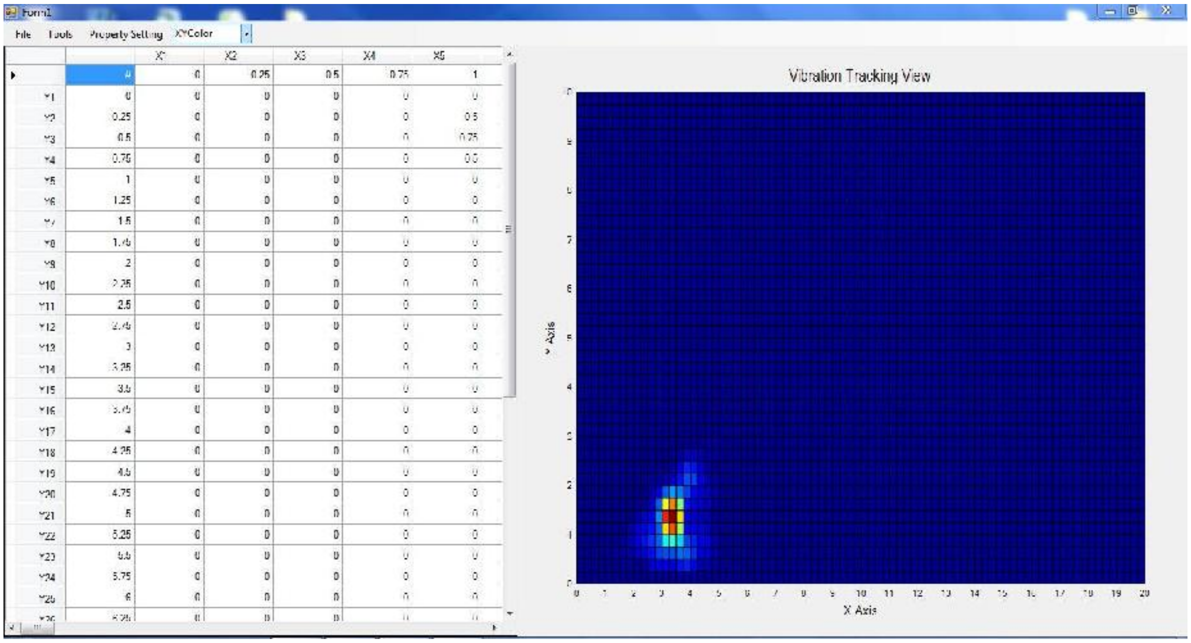

Figure 16 Vibration Effort Visualization with A Color Map

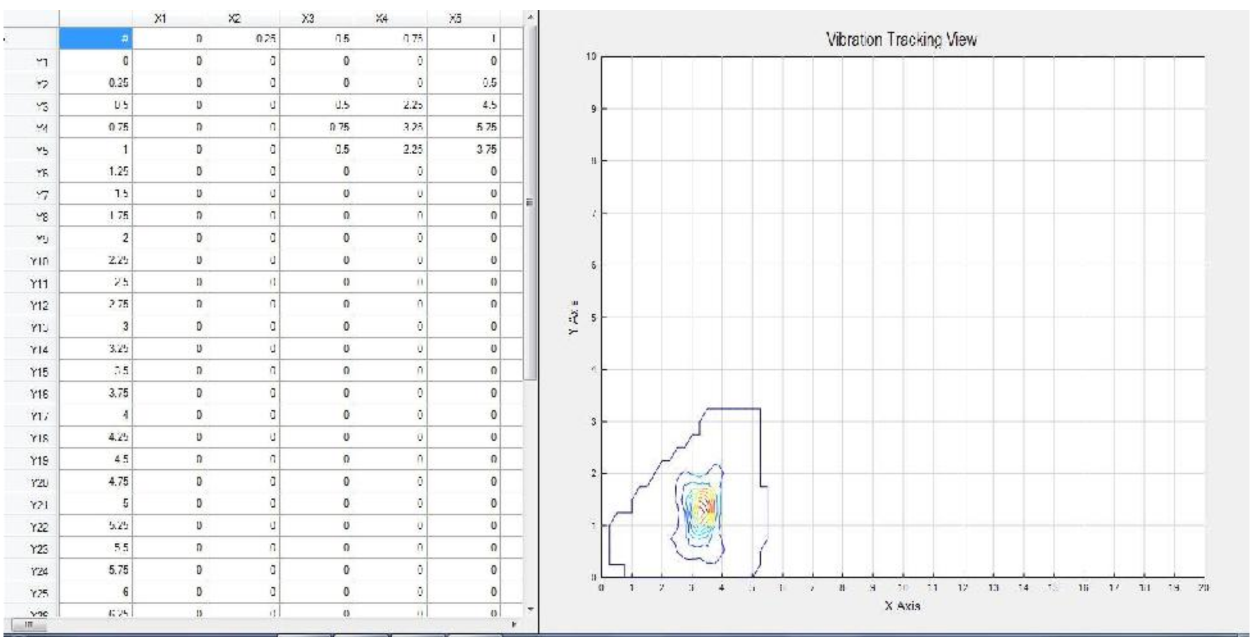

Figure 17 Vibration Effort Visualization with A Contour Chart

Experimental Validation

To validate the effectiveness of the developed program, an outdoor experiment was conducted. More precisely, the experiment served two purposes. First, it is to validate tracking accuracy in an outdoor environment. Second, it is to test the program's performance in terms of providing real-time feedback to vibrator operators. As a part of the experiment, a layout plan as shown in Figure 18 was designed. The layout plan specifies the positions of reference points for tracking accuracy validation and the paths along which the vibrator is supposed to follow. The grid is laid out in the field with the assistance of a laser scanner. Figure 19 shows the outdoor environment and the planned reference point position. On top of this grid design, vibration zones are also specified in order to evaluate whether the program can clearly show the temporal distribution of vibration effort (Figure 20).

During the experiment, the following settings are used: (1) The vibrator is used twice one when the device is on and the other when the device is off to check the feasibility of the tag; (2) The Tags are set to a frequency where a reading is possible for every one second; and (3) The sensors and tags are adjusted to cover maximum range.

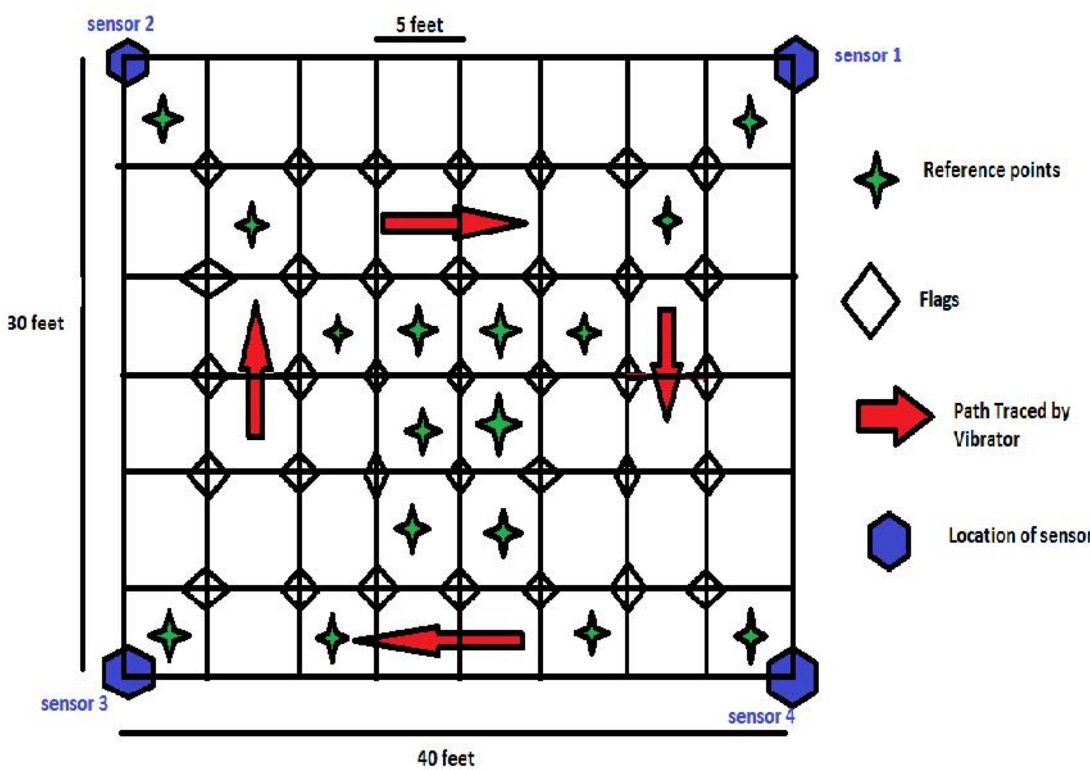

Figure 18 Design of Experiment Layout

Figure 19 Planned Reference Point Positions

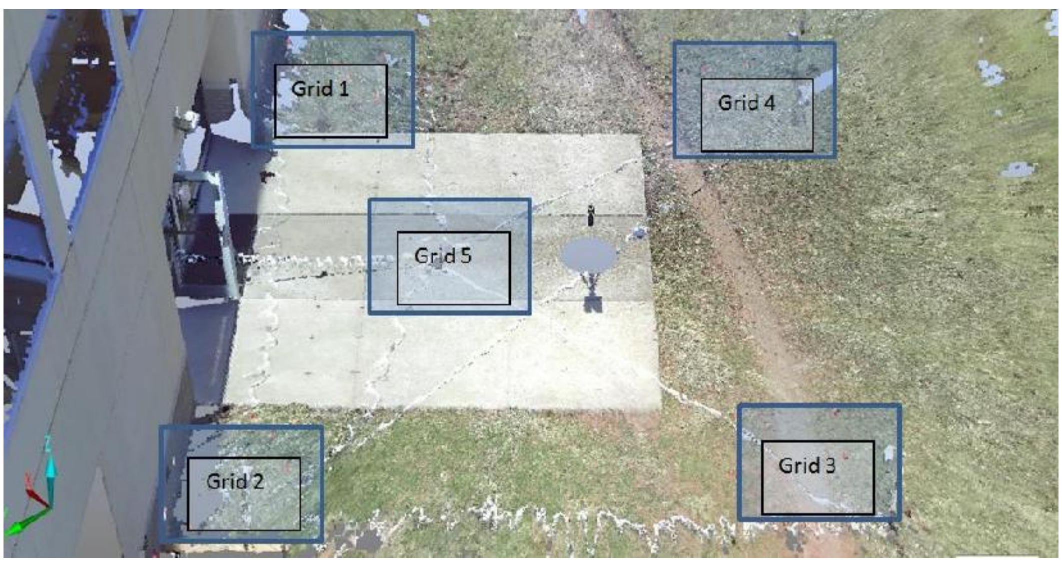

Figure 20 Planned Vibration Zones Overlaid on the 3D Point Cloud

Detailed steps for the experiment are explained as follows:

1. First we set up a rectangular grid 30 feet by 25 feet subject to the length of the cables attached to the sensors.
2. The four sensors are established at the four corners and their location is determined using laser scan data.
3. The reference points using flags or markers are set up as shown in the figure
4. The flags are then placed in the intersection of the 5*5 feet grids.

5. The laser scan is commenced and the location of all the flags and the reference points are determined.
6. The RFID tag is placed on the vibrator at a distance of one foot from the tip of the vibrator (Figure 21)
7. The Vibrator is traced along the path of the flag such that it forms a square pattern
8. The vibrator is now operational and the vibrator is traced along the reference points diagonally in both directions.
9. Once the data from the vibrator is recorded along with the visualization pattern that indicates the intensity of vibration, the data is referenced with laser scan data to check for accuracy.

Figure 21 A Vibrator with Tags Attached

Multiple vibration scenarios are designed in order to emulate various vibration problems. The purpose is to test whether the visualization program can be used to identify these defective vibration operations. By Vibrating along different grids respectively the contour map obtained will give an indication of the points vibrated and not vibrated. The vibration time is noted from the Real time logging data and the corresponding image obtained from the visualization software will give the areas vibrated along with the extent of vibration.

Vibration Effort Tracking Validation Scenario 1 (Figure 22)

Case 1- Grid 1 and Grids 3 will be vibrated whereas Grids 2,4 and 5 will not be vibrated this will give a clear distinction of the different areas vibrated.

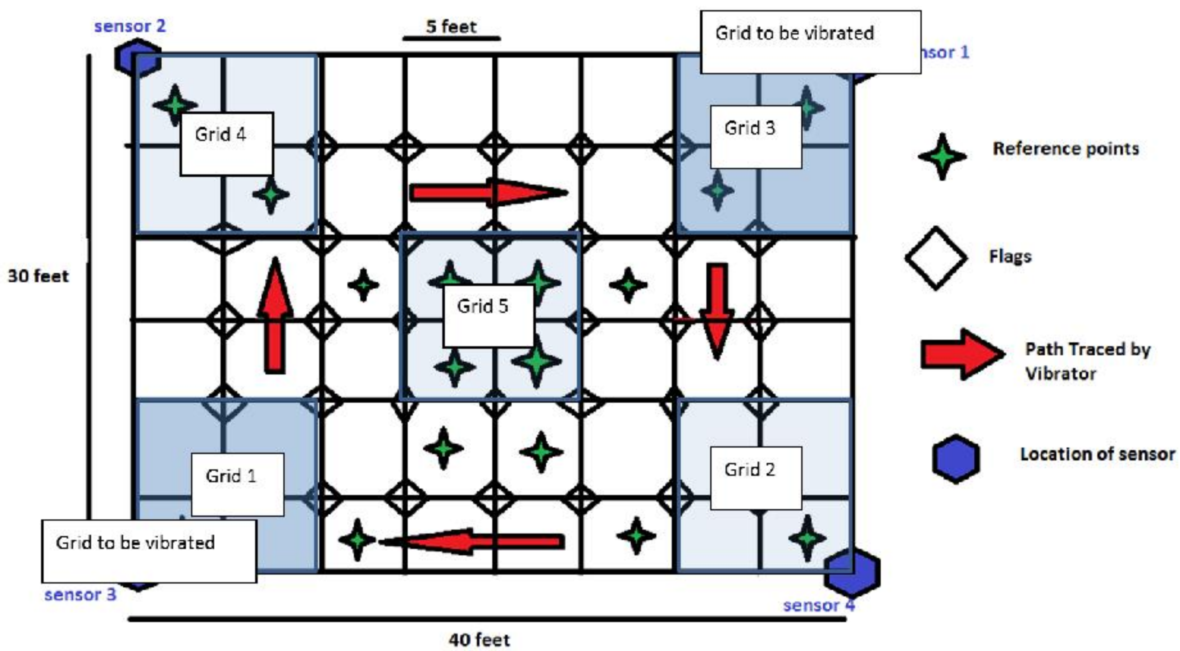

Figure 22 Vibration Scenario 1

Accordingly, Figure 23 shows the results from vibrator tracking and visualization. It is clear that the visualization is effective in terms of demonstrating where has been vibrated and for how long. In addition, as the vibrator stays at these two regions longer and longer, the vibration pattern also clearly shows the pattern that the area has been over vibrated (Figure 24), which is the other concern in concrete vibration.

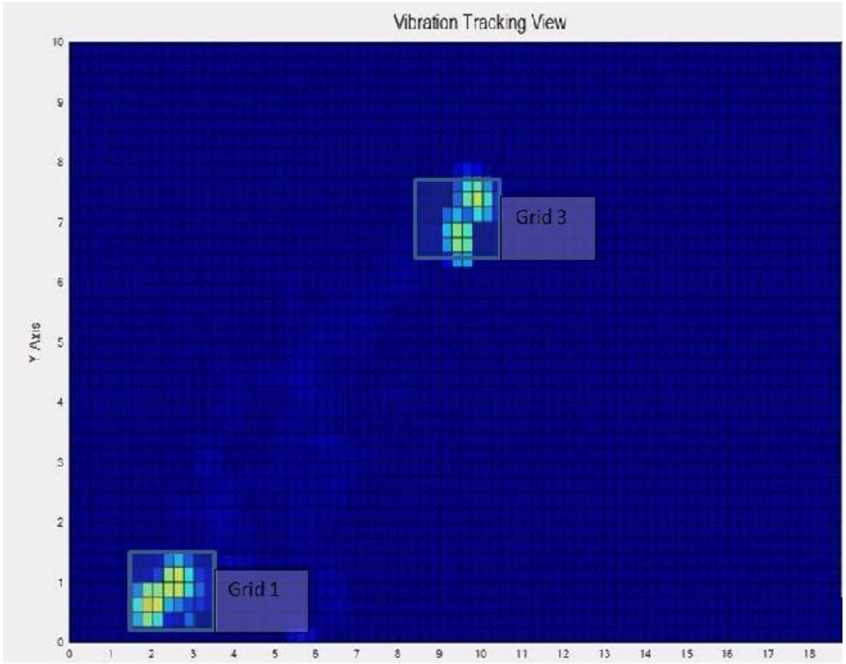

Figure 23 Vibration Effort Visualization for Scenario 1 (Mild Vibration Effort)

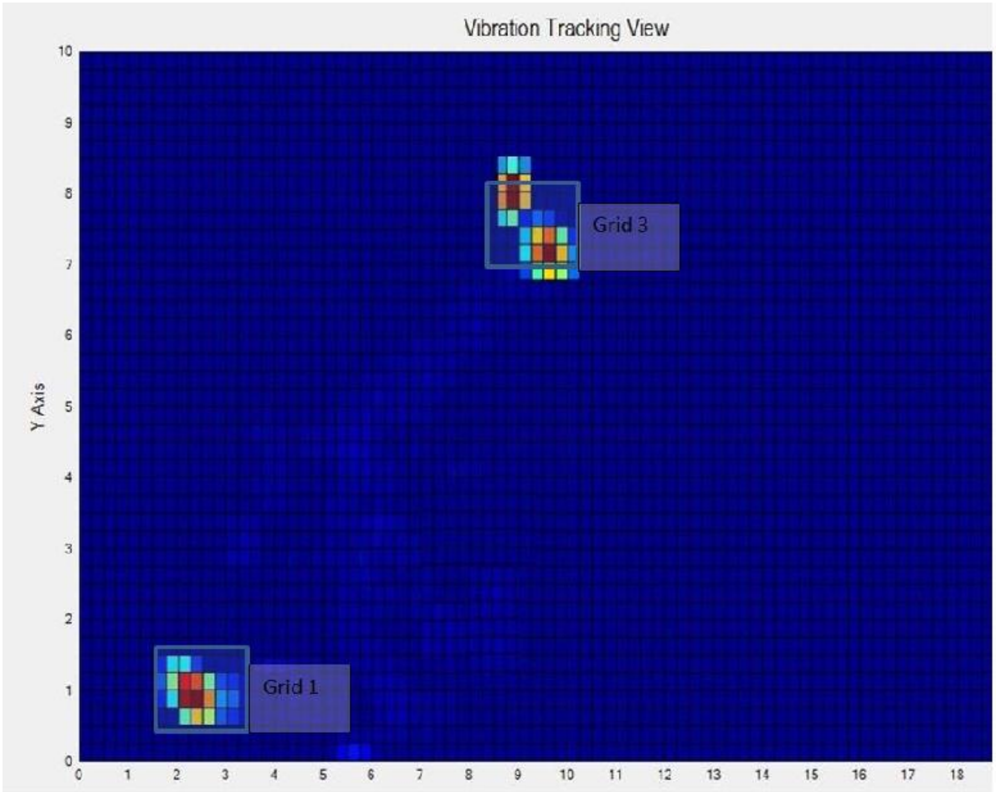

Figure 24 Patterns Showing the Potential of Over-Vibration

Case 2- Grids 2 and 4 will be vibrated (Figure 25)

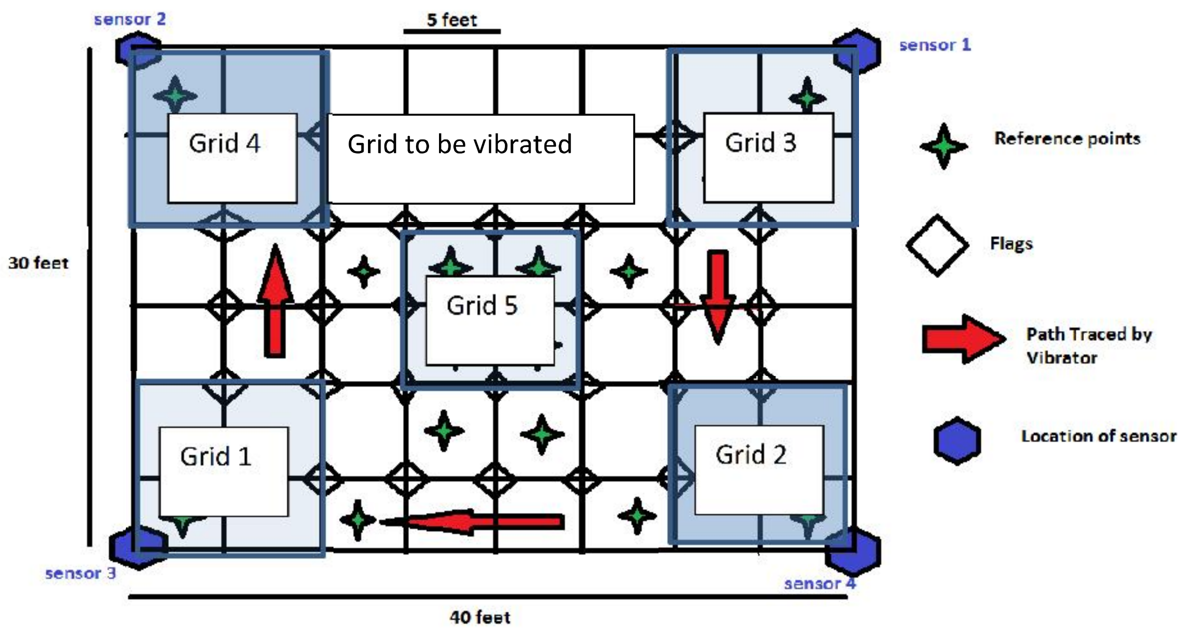

Figure 25 Vibration Scenario 2

Similarly, as the result of vibration tracking, Figure 27 clearly shows where has been vibrated and where has been not. Figure 27 gives the indication of over-vibration as the time goes on.

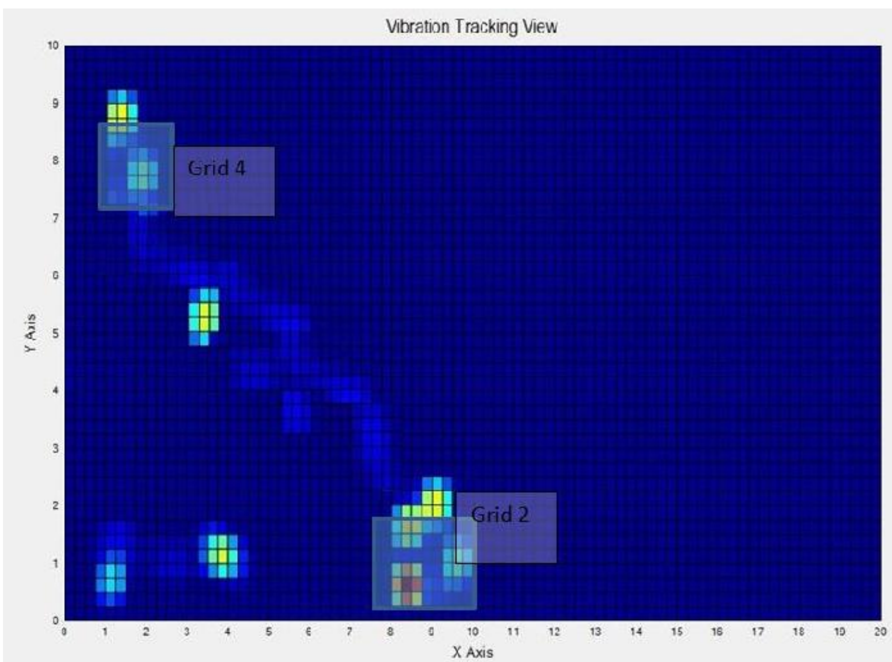

Figure 26 Vibration Scenario 2: Visualization of Vibration Effort (Even Vibration)

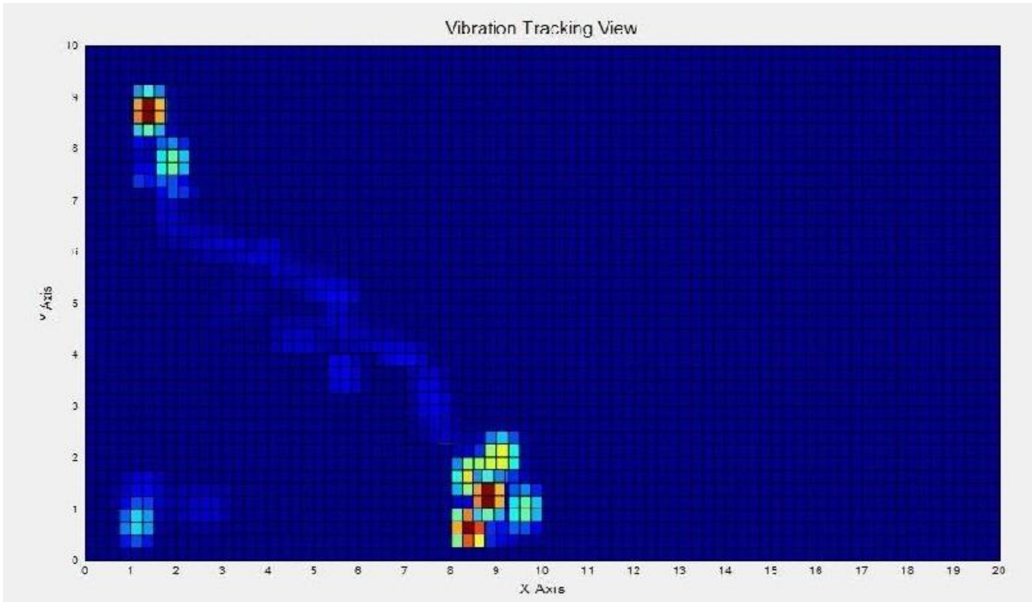

Figure 27 Vibration Scenario 2: Visualization of Vibration Effort (Over-Vibration)

Case 3 – Grids 1, 2, 3, 4, 5 will be vibrated (Figure 28)

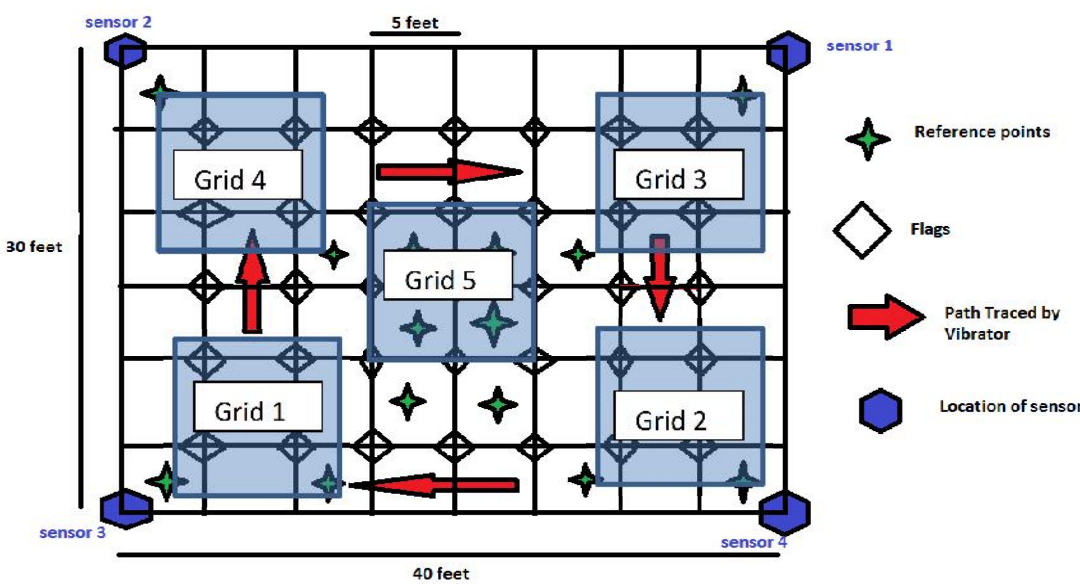

Figure 28 Vibration Scenario 3

The vibration tracking results are shown in Figures 31 and 32.

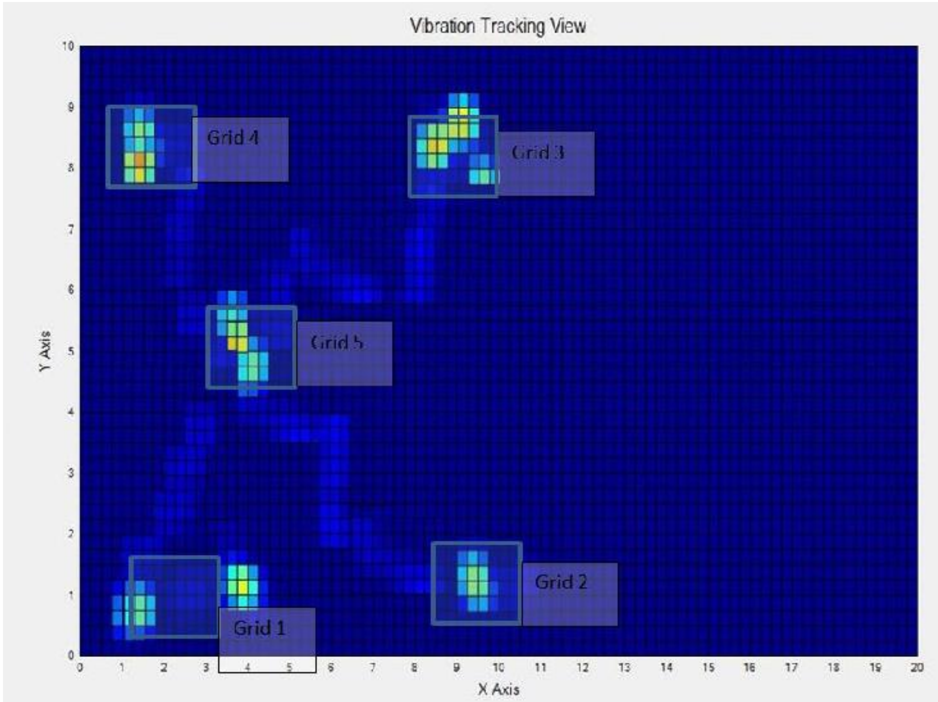

Figure 29 Vibration Tracking Results for Scenario 3 (Even Vibration)

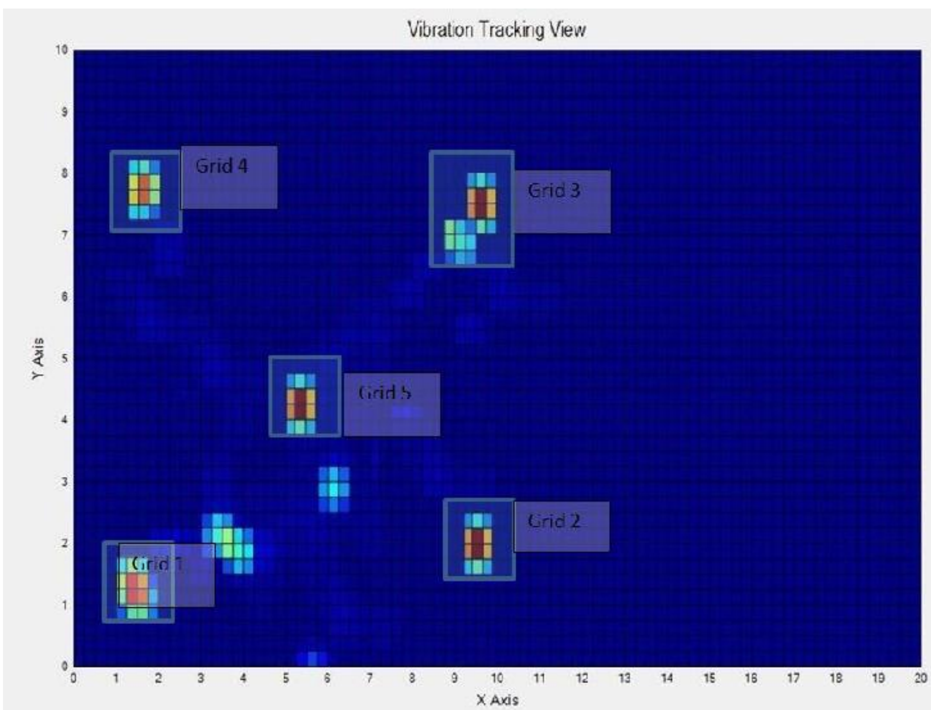

Figure 30 Vibration Tracking Results for Scenario 3 (Over-Vibration)

Tracking Position Accuracy. To further evaluate the tracking accuracy, the tracked positions were logged for the purpose of conducting statistical analysis (Table . The ground truth positions of the reference points are shown in Figure 31.

Table 4 Comparison between Tracked Positions and Ground Truth Positions

	Ground Truth Positions			Positions Calculated by Ubisense		
Point	**X**	**Y**	**Z**	**X1**	**Y1**	**Z1**
1	5.659	2.522	0.304	5.599656	2.496332	0.295118
2	4.913	2.521	0.304	4.926636	2.499685	0.305448
3	5.023	3.343	0.304	5.02124	3.385566	0.29926734
4	5.679	3.313	0.304	5.678895	3.312963	0.2937695
5	4.194	1.363	0.304	4.189632	1.359687	0.2948996
6	3.566	1.336	0.304	3.565966	1.33588	0.2951472
7	2.906	1.342	0.304	2.912364	1.342566	0.2963488
8	2.957	1.974	0.304	2.956987	1.973966	0.2973452
9	3.62	1.991	0.304	3.619865	2.00015	0.29798145
10	4.193	1.988	0.304	4.192586	1.97996	0.296915
11	6.804	1.965	0.304	6.80004	1.9654	0.2976198
12	7.419	1.967	0.304	7.420056	1.964558	0.29147917
13	8.03	1.965	0.304	8.02965	1.96496	0.2938364
14	8.003	1.345	0.304	7.9596	1.34	0.29429198
15	7.403	1.336	0.304	7.40125	1.35	0.29456323
16	6.781	1.36	0.304	6.78451	1.35963	0.29468161
17	4.135	4.685	0.304	4.13449	4.68599	0.2923016
18	3.555	4.725	0.304	3.56001	4.7226	0.293799
19	3.006	4.726	0.304	3.000125	4.72546	0.296612
20	4.174	5.29	0.304	4.175	5.28799	0.30348
21	3.572	5.302	0.304	3.57214	5.3	0.3010372
22	2.996	5.304	0.304	2.99965	5.3	0.3017042
23	4.205	5.898	0.304	4.20566	5.89663	0.3025412
24	3.583	5.911	0.304	3.5891	5.91452	0.3024139
25	2.995	5.905	0.304	2.98996	5.90112	0.3024309
26	8.002	4.672	0.304	8	4.6785	0.3019898
27	7.394	4.759	0.304	7.34526	4.76	0.3017
28	6.799	4.794	0.304	6.78012	4.794321	0.3021825
29	8.053	5.284	0.304	8.0621	5.284015	0.3013867
30	7.414	5.283	0.304	7.4201	5.29	0.30172675
31	6.825	5.276	0.304	6.821456	5.27789	0.30162606
32	8.065	5.885	0.304	8.0751	5.885479	0.30155394
33	7.457	5.888	0.304	7.45144	5.921	0.30152947
34	6.834	5.882	0.304	6.832146	5.88912	0.30150002
35	1.814	7.098	0.304	1.814566	7.093216	0.30148865
36	0.849	7.0124	0.304	0.850123	7.016216	0.3014782
37	1.903	7.979	0.304	1.87205	7.98	0.30151814
38	1.152	8.011	0.304	1.1489	8.011256	0.30155394
39	9.3	6.917	0.304	9.2569	6.92015	0.2966616
40	8.518	6.964	0.304	8.51456	6.96359	0.2961929
41	9.434	7.611	0.304	9.43048	7.610969	0.2962765
42	8.671	7.486	0.304	8.67096	7.48599	0.2962922
43	9.018	7.347	0.304	9.01756	7.3478	0.2961567
44	10.019	1.086	0.304	10.01856	1.379599	0.2950453
45	8.704	1.069	0.304	8.69396	1.069	0.2946232
46	8.701	1.898	0.304	8.699	1.90012	0.2951666
47	9.597	1.929	0.304	9.596989	1.93	0.298967
48	9.25	1.409	0.304	9.25012	1.400989	0.29610438
49	1.749	0.874	0.304	1.749	0.874003	0.29124435
50	1.091	0.873	0.304	1.091	0.87296	0.29130449
51	0.936	1.381	0.304	0.93569	1.38099	0.30226087
52	1.658	1.407	0.304	1.65796	1.40689	0.30173547
53	1.412	1.141	0.304	1.410054	1.39123	0.3032709

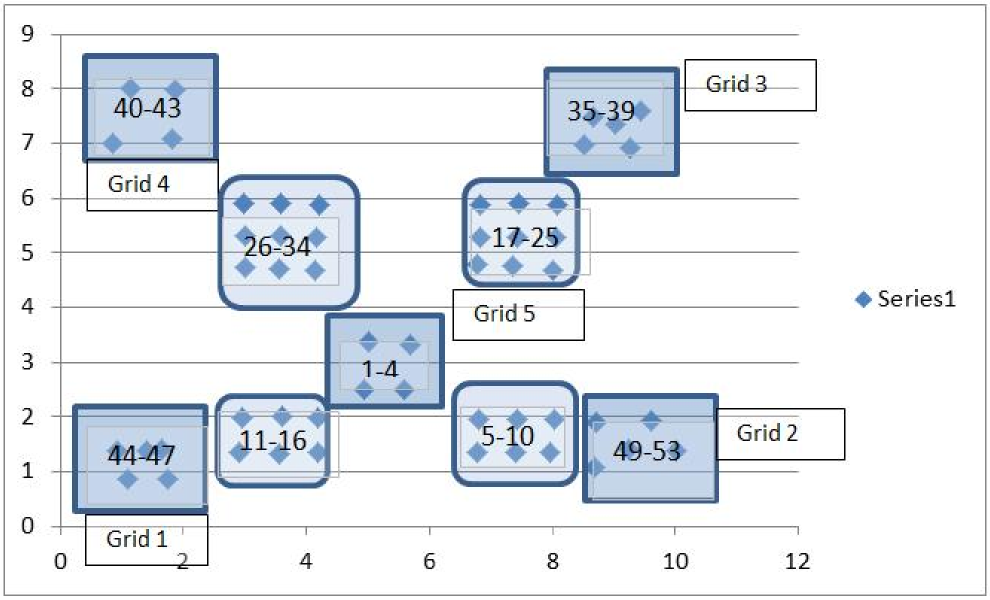

Figure 31 The Ground Truth Positions of Reference Points

A statistical analysis was conducted to determine the tracking accuracy. The results are summarized as follows:

Average Difference in X value= 0.002265853

Average Difference in Y value= 0.01207246

Standard Deviation= .014603725

It can be concluded that the tracking results are very accurate.

FINDINGS

The proposed research provided a much needed concrete consolidation effort visualization system to support intelligent concrete consolidation. The tuned hardware system and the developed software can be packaged into a product for wide adoption in the construction industry. The system will potentially reshape the existing concrete vibrating procedures and provide valuable information to inspectors to verify concrete consolidation procedures. DOT personnel can be trained on the deployment of the developed system on future job sites. The new system may also bring changes to the existing bridge construction quality control methods.

CONCLUSIONS

This study investigated the feasibility of using wireless tracking methods, more specifically Ultra-Wide Band tracking, to track concrete vibration effort in real-time. The objective is to ensure proper concrete consolidation.

A series of experiments were conducted to validate the accuracy of Ultra-Wide Band technologies, especially when the tags are attached to concrete vibrators. Our experiment indicated that the tip of concrete vibrator can be reliably and accurately tracked with the proposed technology. A real-time vibration effort visualization program was developed in this research for testing the concept of intelligent concrete consolidation with wireless tracking methods. Our outdoor experiment results suggested that the developed program along with the tracking devices is capable of accurately displaying the vibration effort in real-time. The research outcome will contribute to the improvement of concrete consolidation quality assurance methods. Future research can be conducted along the following directions:

1) The vibration factor has to be attributed to the mix design of the Concrete Structure
2) The Vibration spatial distribution effort can be further studied and the effort can be analyzed specifically to the frequency of the Vibrator.
3) The phenomena of optimum Vibration can be more researched and this can be factored to vibration visualization effort.

RECOMMENDATIONS

The results of this research suggest:

1) The usage of ultra wide band technology helps to increase the productivity of construction as it helps in monitoring and precise location of vibrator tip where no other technology exists to measure this particular process.
2) The developed system provides a much needed concrete consolidation effort visualization system to support intelligent concrete consolidation.
3) It is encouraged that concrete contractors begin to implement such technology into their existing workflow to ensure higher quality concrete.

4) Construction inspectors may consider using the developed tools as a new way of proactively monitoring concrete construction quality.

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