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Real-time tracking of concrete vibration effort for intelligent concrete consolidation

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A B S T R A C T

Proper consolidation of concrete is critical to the long-term strength of concrete 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. A real-time wireless sensing-based internal vibrator tip tracking system was developed and validated in this research to support intelligent concrete consolidation operations. More specifically, the research 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 novel visualization program was developed to visualize operators' vibration effort in real-time. 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. This also provides an innovative construction inspection practice to owners and resident engineers. The new concrete consolidation tool will allow contractors to proactively address concrete consolidation issues, a problem common to many concrete construction projects.

1. Introduction

Cast-in place concrete structures, whether they are piers, columns, or slabs, are one of the most common types of structures used in civil infrastructure and buildings. Vibration is introduced during concrete casting to ensure proper concrete consolidation. It is well understood that proper consolidation of concrete is critical to the long-term strength of concrete structures [1]. Despite this knowledge, vibration is a common source of problems in concrete construction. In many occasions, inexperienced construction crews tend to under-vibrate or over-vibrate the freshly placed concrete. Under-vibration can cause problems including honeycombing, excessive entrapped air, sand streak, cold joints, and subsidence cracking; while over-vibration can be the culprit for causing segregation, sand streaks, loss of entrapped air, form deflection, form damage or failure, and an excess buildup of paste/mortar at the surface [2].

There are currently 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 but laborious consolidation method. The manual consolidation methods are generally only used on smaller nonstructural concrete placement; and 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 [3,4].

Among various mechanical vibration methods, internal vibrators are the most common ones used to introduce vibrations to freshly placed concrete. Construction specifications and manuals, such as ACI Materials Journal, typically specify how vibration should be done in order to produce a dense concrete without segregation. Nevertheless, with exceptions to certain automated concrete operations in heavy construction activities (pavement and dam construction), there are few, if not none, methods that can be used to monitor the process on how vibration has been applied to the freshly placed concrete. After the placement of concrete, there is virtually no record of when and where a concrete vibrator has been inserted and for what duration. This leaves the quality control of concrete vibration to the subjective interpretation of

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Table 1
Comparison of RTLS system performances.

RTLS	Description	Reading range	Accuracy
GPS	A space-based satellite navigation system that allows a GPS receiver to calculate its position by precisely timing the signals sent by GPS satellites high above the Earth.		0.01 m with differential GPS 2–5 m others
RFID	A technology that uses radio waves as a way of identifying, locating, and tracking objects.	Passive 10 m Active 100 m	1–3 m
RuBee	A radio frequency identification based technology that uses the IEEE 1902.1 standard and provides better security and battery consumption performance.	15 m	
Infrared (IR)	A technology uses diffused IR to achieve room-level locating.	10 m	5–10 m
Wi-Fi	A technology relies on 802.11 networking for real-time locating.	100 m	1–5 m
Zigbee	A technology operates based on the IEEE 802.15.4 standard for localization.	10–100 m	1 m
UWB	A technology uses radio waves with large band widths to track radio tags.	30 m	0.01 m
Cellular RTLS	The cellular-based RTLS relies on resolving the position of the mobile devise by indicating the cell with which the mobile device is registered.		50–200 m

Table 2
An overview of RTLS studies in the construction field.

	GPS	RFID	UWB	Visual sensing	Wireless
Construction productivity monitoring	[8–10]	[11]	[12–14]	[15–17]	
Construction safety	[18]	[19–22]	[12,23–26]	[13,27,28]	[22,29]
Construction equipment automation	[30,31]	[32]	[33–35]	[36–38]	
Construction quality monitoring	[9,73]	[39]			
Logistics, material and tool management	[40]	[41–47]			[48,49]
Building and infrastructure asset management		[44–46,50]			
System performance evaluation	[51]	[52–54]	[55–59]	[60,61]	[57,61,62,71]
Positioning and tracking method development	[63,72]	[39,63–66]	[63,67,68]	[69,70]	[72]

construction inspectors. Yet this kind of subjective evaluation is in common use today [5]. The problems associated with improper concrete vibration are often hidden from the plain sight of construction inspectors and owners, but will be visible after formworks are removed or will eventually surface as a concrete structure starts to display accelerated deterioration. 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.

This research addresses this gap by developing an ultra wide-band (UWB)-based intelligent concrete consolidation method that can reliably and accurately monitor and document concrete vibration procedure such that concrete vibration effort can be quantitatively assessed for monitoring concrete vibration quality and for proactively mitigating potential concrete quality problems. The UWB technology is a wireless sensing based system for real-time localization of moving objects. The contribution of this research includes the development of a novel approach for monitoring concrete vibration procedures and providing an innovative construction inspection tool. The approach allows real-time 3D visualization of the spatial and temporal distribution of vibration effort, therefore it can be used to prevent over-consolidation and under-consolidation. Considering almost every construction project involves certain types of concrete work, the developed intelligent concrete consolidation method will significantly improve concrete consolidation quality control practices.

2. Literature review

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 the intelligent compaction methods is GPS-based location tracking. One 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 concept to monitor concrete vibration procedures. More specifically, the central idea of our proposed vibration effort tracking method is to track the location and duration of insertion points of concrete vibrators during concrete placement. This requires the tip of a concrete vibrator to be precisely

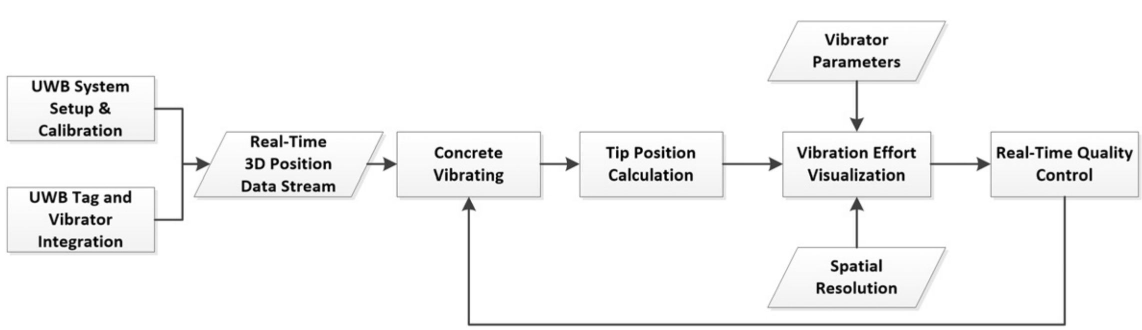

Fig. 1. Proposed system for UWB-based vibration effort visualization.