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A Smart Construction Object (SCO)-Enabled Proactive Data Management System for Construction Equipment Management

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Abstract

The importance of efficient construction equipment management can never be over emphasized. However, in current practices, construction equipment management is reportedly inefficient. It is largely based on rule-of-thumb rather than scientific evidence derived from solid data analytics. It faces challenges such as 'small', erratic data. Building on previous studies on smart construction objects (SCOs), this paper aims to develop a SCO-enabled proactive big data management system to facilitate the data collection, data visualization and data analysis for construction equipment management. It does so by first analyzing the problems of data management in prevailing construction equipment management practices. Then, the architecture of the proposed system is presented, which consists of two key components. The first one is a highly customizable smart chip that integrates various sensing and communication modules for proactively collecting and exchanging big data with volume, velocity, and verity inflowing from daily equipment operations. The second one is the data analytics platform for data storage, visualization and analytics. The pilot of the system has just been started in a central police station renovation project in Hong Kong. Fruitful datasets and analytics are expected from the pilot application of the proposed system. It is envisaged that the proposed system can supplement the existing construction equipment management with more comprehensive and concurrent decision-making information.

Background

The importance of efficient construction equipment management can never be over-emphasized. Construction projects range widely for developing the built environment of a city, including civil works and high-rise buildings, and thus often involve plant-extensive activities such as excavation, earth moving, rebar bending, concrete mixing, and hoisting. In the cost elements of construction projects, the cost associated with construction equipment accounts for a significant proportion. It has been reported that the equipment-related cost may range from 5% to 10% of total cost for a building project, and could account for 40% or above the total cost for a civil work (Siddharth et al., 2015. As the expenditures of construction projects are prodigious all around the world (e.g., the Hong Kong government has projected public expenditure on capital works to reach HK$70 billion for the fiscal year of 2016), a slight improvement in construction equipment management represents a significant saving to project clients and contractors involved.

For construction equipment management, data management and proactive strategies derived from dataset are becoming increasingly important for decision-making when big data has rapidly become the "heart of the talk" of this era across a wide array of areas (Nirmala, 2015). The accumulated data from machine operations, maintenance, and purchases/disposals has largely been ignored before but suddenly it is uncovered like a gold mine, by mining which hidden patterns, unknown correlations and other useful information can be extracted to provide better prediction and decision-making. With the increasing promotion of data mining and data management, rather than passively waiting for the data being generated, proactive data strategies have been adopted to capture, store, process and analyze big data with a view to harnessing its value. This is particularly opportune nowadays when data acquisition and communication technologies such as Auto-ID, laser scanner, and sensor networks, and unit data processing cost are becoming increasingly accessible.

Unfortunately, prevailing construction equipment management practices is highly dependent on individual experiences instead of hard data and facts. The data on construction equipment operations is recorded by contractors sporadically, if at all. The limited data is stored in different cost centers such as a project site or a fleet, forming the so-called isolated "information islands" that are further failed being communicated and known by other decision-makers outside an "information island". More reliable, comprehensive data sets that can cover the target population to account for the totality of construction equipment operations are highly demanded by fleet or project managers, or the top executive of a construction company. Furthermore, existing studies on construction equipment management only use limited types of data (e.g., Vorster, 2005; Edwards and Holt, 2009; Fan and Fan, 2015). Thus, it is urgent to improve construction equipment management derived from reliable and comprehensive data analytics.

The paper aims to develop a SCO-enabled proactive data management system for construction equipment management, with a view to informing better decision-making. The reminder of the paper comprises four sections. Next section briefly introduces the current practice and the limitations to manage the data related with construction equipment. Afterwards, by introducing smart construction objects and the main aspect of construction equipment management, the system architecture is proposed. Two major parts, the data collection part and the data analytics part with their subsystems are explained in details. The methodology for the pilot of this system and the current development status are presented in Section 4. The value and innovation of the proposed system are briefly discussed in sections 5 and conclusions are drawn.

Current solutions and opportunities

Currently, data related to construction equipment operation (e.g. operation time) is written on paper form, which is far from meaningful to derive some actionable information (e.g. break-down prediction and efficient monitoring). As shown in Table 1, a possible solution to derive more data sets would be hiring a site personal to record the operations on an *ad-hoc* basis. Hiring someone to record the data from 7:00am to 7:00pm is not only tedious and error-prone, but also extremely expensive. Statistics from Hong Kong Census and Statistics Department show that the average daily wage of a general worker in June 2016 is around HK$945.7. This is particularly financially burdensome given the fact that there is a myriad of equipment on a construction site to be monitored. Installing a webcam to record the operation of all equipment would appear a clever solution but video streams are not directly computable irrespective of some software claiming to do so. Construction equipment giants such as Caterpillar® or Sony® would record operation data in their recent equipment, e.g. their ready-mixed concrete vehicles are able to record locations and daily volume of supplies. However, these data services are yet to be applied to existing plants. Practitioners in the construction industry have also tried to use Auto-ID technologies to collect operation data of equipment. However, scanning the Auto-IDs is highly disruptive to ongoing construction processes. To sum up, the current methods are far from satisfactory in collecting data on construction equipment operation. It is expected that data related to all aspects of equipment operation can be collected in a more automatic and effective manner.

Table 1 Existing solutions for collecting construction equipment operation data

Existing solutions	Strength	Weakness
Manual recording	Easy to learn and operate	Tedious, error-prone, costly
Webcam	Full operation recording	Incomputable data
Existing construction equipment giants	Tailor made, specialized system	State-of-the-art and big equipment only
Auto-ID	Accelerating data collection, cheap tags	Manual scanning, interruptive

The SCO-enabled construction equipment management system

Smart construction objects (SCOs) are defined as *'construction resources (e.g., machinery, tools, device, materials, components, and even temporary or permanent structures) that are made smart by augmenting them with sensing, processing, and communication abilities so that they have autonomy and awareness, and can interact with the vicinity to enable better decision making'* (Niu et al. 2015). In addition to some basic properties such as dimensions, materials, and manufacturers, a SCO must have three core properties, namely, awareness, communicativeness, and autonomy. *Awareness* denotes SCOs' ability to sense and log their real-time condition and that of the surrounding environment; *Communicativeness* means the ability of a SCO to output information it has obtained through its awareness; and *Autonomy* refers to the ability of a SCO to take self-directed action or alert people for further action based on preset rules. While these SCOs are still providing decision-making information to human decision makers, what makes them different from conventional construction objects is that they can talk to each other directly. In doing so, some routine or clearly rule-based decisions can be made by SCOs autonomously without necessarily involving human decision makers in the loop (Niu et al., 2015).

By making pre-fabricated components into SCOs, Niu et al. (2016) have proposed and tested a SCO-enabled logistics and supply chain management system to facilitate decision-making, which demonstrated potentials for achieving process and information concurrence. As a result, more informed decisions could be made. Similarly, SCOs could be used to facilitate data collection and informed decision-making in the construction equipment management while more attentions should be paid to the volume and variety of data source. A SCO-enabled proactive data management for construction equipment is thus proposed with additional considerations and designs for data storage, data warehouse, and data visualization subsystems. Here, construction equipment management may include, but not confined to, the aspects as elaborated in Table 2, which is summarized from existing literature and demands from the construction practitioners.

To understand all these aspects, one needs to have reliable, comprehensive data collected from real-life job sites and to analyze in a systematic manner.

Table 2. Main aspects of construction equipment management

Aspect	Detail
Equipment usage patterns	To understand whether it is a seasonal, sloping stair, step up, spike, or other pattern as a starting point for many other construction equipment management inquires.
Efficiency and productivity	To understand whether the equipment is operating or idling by linking to the job done.
Fuel consumption	Nominal fuel consumption and actual fuel consumption
Carbon emission	Nominal carbon emission, and real-time actual measurement of emission of carbon dioxide (CO2), nitrogen oxides (NOx), hydrocarbon, to derive emission rates.
Safe and authorized operations of equipment	Auto-check equipment maintenance records, Personal protective equipment (PPE), and qualification to operate the equipment.
Regular or preventive maintenance	Good maintenance will minimize maintenance and repair costs and maximize production and profit, with the greatest impact on profits. It helps control costs and service intervals, lengthens equipment life, minimizes downtime and adds resale value. Regular inspections and adhering to recommended maintenance schedules are the keys. Preventive maintenance is to treat the problem proactively before it becomes a catastrophic failure.
Repair or replacement	A major repair can change the depreciable equipment value due to an extension in service life, while a minor repair is normal maintenance. When it is not worthwhile to have a minor or major repair, replacement is desired.
Operating cost	Fuel cost, tire lifecycle and cost, preventative maintenance, repairs, operator wages, and other additional costs.
Buy or lease	It is a classic dilemma in construction equipment management. Each option has its own advantages and disadvantages, which are changing from one period of time to another, and from one company to another.
Depreciation and disposal	It is not only about financial accounting manipulation, but also strategic decisions relating to a company's major asset.
Fleet configuration/optimization	Project managers reshuffle their equipment fleet on a regular basis for resource allocation (Fan et al., 2008).
Fleet tracking	Modern construction equipment is tracked using GPS and other locationing technologies for multiple purposes, e.g. security, usage pattern analysis, efficiency analysis, etc.

In order to collected data from which the information in Table 1 can be possibly derived or deducted, the system architecture of the SCO-enabled proactive data management system is proposed as Figure 1. The system has two major parts, (A) SCOs for proactive data collection; (B) data analytics for construction equipment management. For part A, existing construction equipment are augmented into SCOs by a hardware end-point called *i*-Core. Encapsulating the smartness of SCOs, i-Core denotes a standalone, programmable, and extendable integrated chip that can be implanted to construction machinery, device, and components. *i*-Core turns dead-weight construction equipment into SCOs using customizable sensors and communicating modules. Sensors for capturing various types of data will be selected and tested for achieving the functions of vibration detection, motion detection, real-time location detection and wireless data transmission. With the sensors tested, selected and integrated, prototypes of *i*-Core will be manufactured for lab testing and field trials. These prototypes will be attached, mounted or embedded to the construction equipment in real-practice for data sensing and communications.

As displayed in the construction equipment layer, different types of construction equipment will be incorporated into the system including the mobile plant such as mixer truck, static plant with motions such as tower crane, and static plant such as scaffolding. Three series of *i*-Core are developed. The location-focused series is mainly designed for locationing of mobile equipment. Motion-focused *i*-Core is designed to monitor the frequently moving parts of equipment such as the jib of the tower crane and cherry picker. Condition-focused series are designed for monitoring the environmental factors that may have influence on the operation life of the equipment. The SCOs with these customized *i*-Cores would form data network for possible data exchange.

Part B consists of three major subsystems, which are the data warehouse subsystem to store data, the data management subsystem to process data and the visualization subsystem to present the data. Data captured by SCOs will be transferred into the data warehouse. These data serve as the training data input for the built-in machine learning algorithm. The real-time status of the equipment will be displayed through the 3D model animations in the user interface. These animations can be replayed anytime when review of the equipment operation is needed. Meanwhile, data about the fleet operation status such as moving, idling, and off-line will be visualized in graphs and diagrams in the user interface as well. The analysis results, such as the optimum usage rate, depreciation rate, carbon emission rate and other potential insights from the data will also be presented in the user interface to facilitate prediction and decision making.

The data warehouse subsystem

The data warehouse subsystem is one of the key subsystems in this system, aiming to warehouse various types of data from both *i*-Core networks and external data sources. Recent development of open source and commercial big data software have successfully paved a way to store and manage the gigantic amount of data observed from the complex actions and interactions of construction equipment. In the proposed system, a set of libraries will be employed such as Hadoop, Cassandra, Hive, and Spark with. The libraries will form the software infrastructure of the data warehouse. In addition, conventional relational database such as MySQL and lightweight formats such as JSON will also be incorporated.

The data management subsystem

The data management subsystem consists of a series of data operations on the data warehouse through structured data pipelines (e.g. SQL), aiming to provide a toolkit of data management to ensure the quality, consistency, and useful statistics for the data stored in the warehouse. Three main modules are included in this subsystem, which are data cleansing module, data fusion module, and applied statistics module. The data cleansing module is a software-based process for data quality control, as a complementary process to the hardware controls. In comparison to the hardware filters, the software data cleansing allows sophisticated rules and expressions which are collected from the construction practitioners. The data fusion module aims to resolve inconsistency of multi-faceted and multi-source data. In comparison to the noise data removal of the data cleansing module, the data fusion aims to consolidate valid but different data. The aim of the applied statistics module is to provide fundamental indices for data storage in the warehouse. In this system, a set of value-added statistical analytics will be developed to index equipment's various representations, including the activities, efficiencies, the site safety and behaviors, the maintenance and operational status, the environmental impacts, and the possible risks of machine failures and operation failures. These indices can provide references for data cleansing and data fusion, and also provide basic evidences to managers at construction companies.

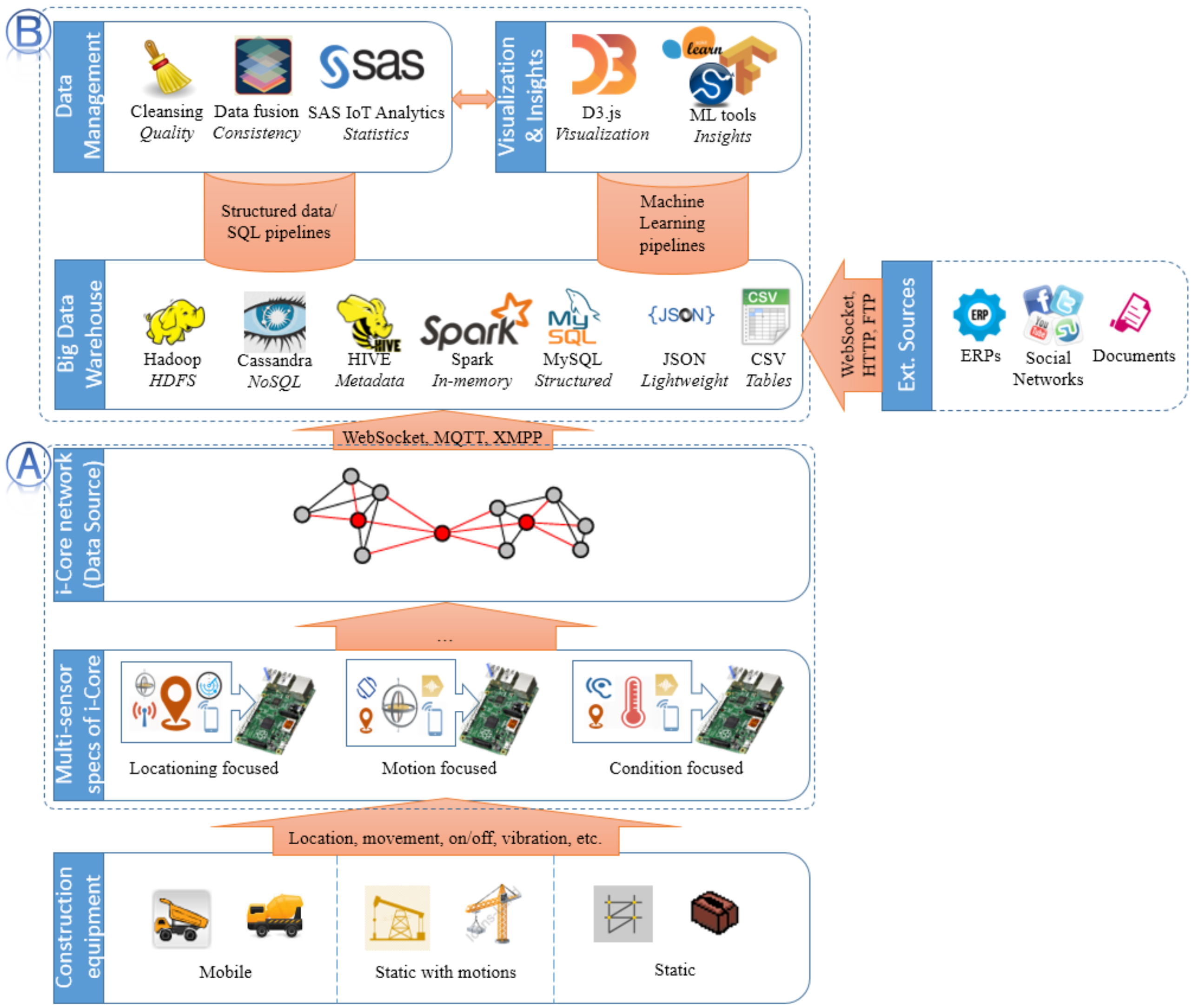

Figure 1. The architecture of the proposed system

The visualization and insights subsystem

The visualization and insights subsystem could help discover the patterns and value sunk in the data ocean. Data visualization is a representation of data in a pictorial or graphical format. This module aims to reorganize the data in some more intuitive ways. For managers, visualized data is much convenient to uncover hidden patterns, unknown correlations and other useful information, to provide better business prediction and decision making. For equipment operators, visualized formats are also valuable in terms of safety (wider awareness, visualized semantic regions on site), efficiency (knowing equipment's physical status better, computer-aided planning), and collaboration (awareness of other equipment and their needs). Some research and development-friendly visualization libraries such as D3.js will be incorporated to accelerate the development of this deliverable.

The methodology of the system pilot

This study will also make good use of a "living lab" that has been established by the research team over the past year with Hong Kong Housing Authority, local contractors and some cross-border suppliers. According to Bergvall-Kareborn and Stahlbrost (2009), a living lab represents a user-centric research methodology for sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts. The living lab process, which integrates both user-centered research and open innovation, is based on a maturity spiral concurrently involving a multidisciplinary team in the following four main activities, including co-creation, exploration, experimentation, and finally, evaluation.

An i-Core prototype has been developed to remotely control generator switch on site. When i-Core is connected to the generator switch, managers/foremen could use text massage to remotely control the generator switch. The bi-directional transmission between the i-Core and the data analytics platform is achieved in the pilot test, serving as a solid base for other equipment. Currently, the pilot of the SCO-enabled construction equipment management system just starts in a central police station renovation project in Hong Kong, in collaboration with a big local contractor in Hong Kong. In the initial stage, one i-Core is connected with an electricity switch while a few i-Cores are expected to be installed for water pumps and tower cranes. A preliminary data analytic system has also been set up based on the serves and databases in the 'living lab'. It is expected the data collected in the pilot could not only supply the management decisions but also provide insights to improve the further development of the system. By comparing and cross-checking the data collected in the pilot with the desired data types derived from Table 2, the pilot could help confirms the types of data needed for construction equipment management and possibly identify new data types with decision-making implications.

Discussions and conclusion

Facing the fragmented and data deficient construction equipment management, this study proposes a SCO-enabled proactive data management system for construction equipment management that could proactively collect data and systematically analyze the data. By turning the existing construction equipment into SCOs using *i*-Core, this system represents a novel thinking that using SCOs will cause the least disruption to ongoing construction processes instead of making radical changes to the existing construction operations. In fact, there are extant studies focusing on how can innovations be accepted and well implemented (e.g. Rogers 1983; Roumboutsos and Saussier 2014). A common agreement has been arrived that a technological system of newness would be more easily accepted when the side-effects of such system on system users become lower. The proposed system does so by augmenting the existing equipment with sensing and communicating abilities without compensate their original functions and appearances.

The system architecture and each of the subsystem are introduced in details in this study. An ongoing pilot of the system is conducted in a 'living lab' following a co-production methodology. In the initial pilot stage, *i*-Core is planned to be embedded to critical electricity switches, generators, and tower cranes first. The setting-up is still in process. With the proposed system, all data that might have cost implications, environment-protection implications, safety implications and other possible use will be continuously collected by *i*-Core, while advanced big data analytics will be applied to process and visualize the collected data. Unlike conventional construction equipment management methods which are heavily relied on fragmented paper-based documents, the results generated by system-supported data analytics will be much more comprehensive to support informed decision-making.

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