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Advanced Virtual Reality Applications and Intelligent Agents for Construction Process Optimisation and Defect Prevention

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Abstract

Defects and errors in new or recently completed construction work continually pervade the industry. Whilst inspection and monitoring processes are established vehicles for their 'control', the procedures involved are often process driven, time consuming, and resource intensive. Paradoxically therefore, they can impinge upon the broader aspects of project time, cost and quality outcomes. Acknowledging this means appreciating concatenation effects such as the potential for litigation, impact on other processes and influence on stakeholders' perceptions—that in turn, can impede progress and stifle opportunities for process optimisation or innovation. That is, opportunities relating to for example, logistics, carbon reduction, health and safety, efficiency, asset underutilisation and efficient labour distribution. This study evaluates these kinds of challenge from a time, cost and quality perspective, with a focus on identifying opportunities for process innovation and optimisation. It reviews—within the construction domain—state of the art technologies that support optimal use of artificial intelligence, cybernetics and complex adaptive systems. From this, conceptual framework is proposed for development of real-time intelligent observational platform supported by advanced intelligent agents, presented for discussion. This platform actively, autonomously and seamlessly manages intelligent agents (Virtual Reality cameras, Radio-Frequency Identification RFID scanners, remote sensors, etc.) in order to identify, report and document 'high risk' defects. Findings underpin a new ontological model that supports ongoing development of a dynamic, self-organised sensor (agent) network, for capturing and reporting real-time construction site data. The model is a 'stepping stone' for advancement of independent intelligent agents, embracing sensory and computational support, able to perform complicated (previously manual) tasks that provide optimal, dynamic, and autonomous management functions.

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Keywords: Intelligent agent; Virtual Reality; Process Innovation; ICT; Sensors; Optimisation.

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1. Introduction

Defects and errors in new or recently completed construction work continually pervade the industry. Whilst inspection and monitoring processes are established vehicles for their 'control', the procedures involved are often process driven, time consuming, and resource intensive. Paradoxically therefore, they can impinge upon the broader aspects of project time, cost and quality outcomes. In recent years, the trade-off between the increasing needs for non-stop inspections during construction projects and the issues associated with these has made a great attention to the value of systematic and innovative methods of monitoring operations of construction sites as oppose to the conventional inspector based methods. Much research has been done and many systems have been introduced by different scholars with regards to automation of capturing, processing and sharing project data among project team and stakeholders. These systems have been proven for improving various aspects of construction projects, e.g. logistics, carbon reduction, health and safety, efficiency, asset underutilisation and efficient labour distribution. However, unlike other industries, construction sector has not been quite successful in adopting such automated monitoring systems in small and medium scale projects [1], due to dynamicity of construction products [2], unsafety and unsuitability of construction sites for high-tech monitoring systems [3], disintegration of construction project teams [4], and slow and error prone construction project data collection systems [5]. Therefore, majority of construction projects are still retaining their slow and inaccurate traditional inspector reliant control systems. This leads to lack of as-built information of construction projects [5] which ends up with various of disorganisation of projects in terms of controlling schedule, cost, and workforce [6]. As such, this study evaluates the existing challenges with current technologies from a time, cost and quality perspective, with a focus on identifying opportunities for introduction of hybrid and low cost systems for ensuring project optimisation and innovation within ordinary construction projects such as, Virtual Reality, sensors, tracking devices and etc.

2. Virtual Reality (VR) in Construction

The Virtual environment (VE) Due to the dynamic 3D presentation capability on 2D screens, offer unique opportunities enabling users to experience real-time interactive objects and environments. Research has addressed the VE in relation to users' spatial cognitive factors [7]. Technologies such as 3D modelling and BIM are already being widely implemented in the industry, in particular, the UK has already issued BIM Level 2 mandate for public projects from 2016 [8]. The AEC industry is striving to increase the level of interoperability between the different professional disciplines directly involved in the execution of the project, therefore, architects, engineers and contractors are beginning to align and coordinate the tools and technologies they use in their fields of work. At the same time, however, clients and consultants who are not directly involved in the technical planning and execution often have a limited or incomplete understanding of the process and the expected outcome. Although BIM offers a myriad of conventions to facilitate and accelerate the planning and construction of a project for professionals, it provides a limited ability to interrogate space, form and atmosphere from the point of view of a non-AEC professional. The potential of VR lies in bridging this gap between clients and building industry personnel by leveraging the data already compiled in the BIM models.

The ability to experience together in virtual space the same place that does not exist physically while the participants are actually in different geographical locations brings forward a revolution in perception rather than in technology within the AEC sector. The design reviews of BIM models are further enhance by the VR technology so as to identify problems early on in the design stage and avoid subsequent delays.

The capability to visualise technical information, accurately represent ideas and perform simulations can potentially increase the awareness of the client of the exact final form of the built asset. People untrained in the AEC disciplines often have difficulty in getting an accurate sense of space just by reading orthogonal drawings or trying to determine how renders relate to them. Additionally, traditional renderings often provide a misrepresentation of form, colour and lighting due to skewed perspective or unrealistic points of view while the VR environment immerses the user so that they can experience it for themselves. This sense of presence also ensures stakeholders of the worth of their investment. Additionally, clients can leverage the VR environment for marketing purposes or training of staff. The research conducted by Heydarian [9], emphasise the need for the involvement of the end-user and their input early on in the design development so as to increase their confidence in their investments and ensure satisfaction at the close out and also produce better design with regard to performance. These results can be further enhanced by the use of the VR environments in the post-construction stages of the project and in the facility management of the building.

The VR simulations present an opportunity to create accurate and comprehensive reference of the possibilities for prefabrication. Additionally, as construction is a high-risk industry, the ability to estimate and prevent hazards in the execution of the design is a primary goal of the sector. One of the first stages of achieving this goal is sharing the available data among all the sectors involved from the design and concept stage to construction and throughout the project.

3. Sensing Technologies in Construction

The integration of sensor technologies into BIM would shift its focus to the construction field. Investment in the IoT sensing technologies is going to result in major cost and time savings as well as in providing greater control and safety. Improvement in productivity levels is achieved by greater control over the manufacturing process. Major technologies are already part of the manufacturing method and are enabled through the Internet of Things.

3.1. The Internet of Things

The Internet of Things, IoT, consists of sensors and actuators, which share information across platforms in order to develop a common operating picture (COP) [10]. The devices connect over the internet, which enables them to have a real-time communication not only with the human operators but also with each other. The manufacturing industry is mainly utilised for organisation of tools, machines and people, as well as for real-life tracking of their position [11]. In general, the IoT is enabling easier coordination of large commercial building projects which rely on off-site manufacturing and prefabrication. Prefabrication is becoming an increasingly more often chosen method for creating quicker, more cost effective, and less wasteful in terms of material, energy, and workload buildings. Overall, there are three main application of the Internet of Things in off-site manufacturing - supply chains, factories, and products. The integration of sensors, middleware, software, and cloud data storage brings a greater visibility and transparency in the operation and assets of companies. Big Data integration into the Industrial Internet of Things allows data sets to be controlled and examined online by the utilisation of cloud-hosted advanced analytics at wire speed. Current sensor technologies are not only precise, but also self-aware, self-predict, and self-compare. They are also able to compare their expected optimal level with their actual current configuration and environment settings [12].

3.2. Big Data

Big Data is providing the historical, predictive, and prescriptive analysis needed by IIoT for the transparency of the machine operation and process, huge amount of data streams are analysed in the online space by cloud-hosted advanced analytics when Big Data is utilised into IIoT systems. Therefore, Big Data and advanced analytics are increasing the productive service of sensors, while lowering the need for extra maintenance, thus lowering expenses. The collected data is collected from numerous different sources including and not restricted to texts, forms, web blogs, comments, videos, photographs, telemetry, GPS trails, IM chats, and news feeds. Cloud computing provides a low cost solution for Big Data storage and makes companies to be able to gather and manage greater amounts of data than in the past [12].

3.3. Current Stage of Technology

The current stage of innovation is focusing on enabling intelligent devices such as sensors, machines, components, and even the human body. The goal of these devices is to deal with data flow "from device to the data store, to the analytic systems, to the data scientists, to the process, and then back to the device" [12]. The goal of IIoT in the industry sector, especially in manufacturing, is to bring the focus to the actual need of the customer rather than simply the product that they have ordered [12]. Currently one of the major limitations in production is the lack of traceability throughout the entire value chain and manufacturing process. There is a great amount of data which is lost or corrupted since sensors do not communicate between each other. A project going by the name of MEGAFiT is leading an operation towards dealing with the above mentioned current issues with sensor technologies. Major brands have invested into this program aiming to manufacture first time right, error-free sensing technologies, which would reduce cost, material, and energy consumption [13]. In the next five years it is expected that the global sensor market is going to grow by more than $39 billion since 2015 [14].

The future of manufacturing lies into the shift of the supply chain to the forefront of production Through the IoT, corrections and redirection are going to be possible instantly, thus bringing the desired in-transit transparency [14]. Cloud-based GPS working along with Radio Frequency Identification (RFID) chip technologies are going to enable the demanded visibility between the manufacturer, the suppliers, the distribution centre, the retailer, and the customer. These two devices are the backbone of IoT when it comes to the supply chain [15].

3.4. GPS

Cloud-based GPS technologies are used during the logistics stage of the offsite manufacturing, or in other words during its arrangement and management. A major drawback of GPS tracking applications is that they are able to send location data once every hour. This means that it utilises only a small amount of data and does so not so frequently [12].

3.5. RFID

Radio Frequency Identification devices are identification sensing technologies relying on radio waves, thus not requiring direct visual sight in order to read any data. These sensors are operating at minimum ultra-high frequency, UHF, when it comes to supply chains, with the next step being the ultra-wide band, a.k.a. UWB. The higher the frequency, the greater bandwidth, data exchange, and most of all – level of communication. The system relies on a RFID reader and a tag. RFID tags are the chips, which are placed within shipments and are tracked by the readers. With the increasing demand for customised building parts in the picture, the complexity of the supply chain increases, which in turn is simplified by the accurate tracking information provided by the RFID [16].

4. Products

4.1. SMARTROCK2

One of the most invested technologies in current technologies is the incorporation of wireless humidity sensors into building materials such as concrete. Concrete is a material, which exhibits different electromagnetic properties at different humidity conditions [17]. SmartRock2™ is the current level of such sensing technology reporting real-time data about the temperature and maturity monitoring of concrete. This waterproof sensor is placed within 5 cm depth into the concrete formwork before pouring. Wireless Bluetooth technology allows monitoring of the data through an app. The device accurately predicts the strength of concrete and tries to eliminate concrete cylinder break tests [12]. This method is useful both in offsite manufacturing such as concrete 3D printing technologies and real-time on-site building and construction.

4.2. SPECIALIS*ED HEADSETS: Smart Helmet*™ - DAQRI (hard hat of the future)

Tablets, general applications and head mounted devices designed for the general consumers are oftentimes inept at fully encompassing the needs of the people working on a construction site. Therefore, the Los Angeles based company DAQRI has attempted at tackling the problems of heavy industry settings through their specifically tailored hard hat enabled with a number of sensors and devices. The DAQRI Smart Helmet brings together safety and immersion into augmented reality, in addition to preventing injury from falling objects, it provides workers with an additional informatics layer superimposed on what they already see in their physical environment.

This futuristic hard hat is equipped with an anti-reflective, scratch-resistant visor and also a 4D HUD (Heads up Display) - a transparent augmented reality display which in this case is designed to meet the needs of the construction industry. Additionally, the helmet is fitted with four cameras - two mounted to the front and two to the rear in order to create a 360-degree view [18]. The cameras can take both images and video which also allows for 2D target recognition and objects tracking. The recordings taken by the wearer can be shared in real-time thus transforming the regular worker into a live presenter from the construction site. A software called Intellitack, which captures and displays data about the setting of the user, supports the camera. Also, it provides information on the location of the user and does not rely on GPS, Bluetooth and Wi-Fi [19]. The tracking devices built in the helmet create a mapping of the environment and can serve as a basis for a 3D reconstruction of the facility. Furthermore, in a factory situation, instead of monitoring data separately at a control room and then going on to examine the problem. DAQRI helmet allows the user to look directly at control panels on the wall and determine if there are irregularities. Additionally, through the capabilities of a thermal camera, the helmet allow the user to see temperature readings and detect if an object is overheated [20]. An additional laser-based 3D depth-sensing camera is used to look and take photos through poorly lit or hazy conditions.

The helmet's compatibly with BIM technology further facilitates communication between workers and coordination of plans and information as multiple users can share the information directly from the same BIM model. Workforce can further be provided with direct instructions and visual simulations allowing them to understand more quickly the tasks they are required to perform. Through this augmented reality state of interaction with the construction site, it becomes more interactive, accessible and easier to interpret which then increase efficiency and improves communication.

5. VR Tracking Devices

Sensing In terms of sensing tracking devices related to Virtual Reality technologies, there is currently an increasing interest in Leap Motion Controllers, Myo, Nimble VR and PrioVR.

5.1. Leap Motion Controller

The Leap Motion Controller is a hand and finger motion sensing device, which is used both in Virtual Reality as well as in Augmented Reality. The sensor converts the movements into 3D input while maintaining an accuracy of up to parts of the millimetre. It operates without the need of any handheld accessories, thus allowing the most natural-like interaction with virtual objects. The Leap Motion Controller allows all kinds of gesture control from the user – from movement of objects, panning and zooming, to creation of shapes. The devices operates with different 3D Autodesk software [21]. The technology is based on 2 cameras and three infrared LEDs, which are able to track 200 frames per second providing a 150° field of view. The greatest disadvantage is that is able to track a relatively small amount of interactive 3D space – around 8 cubic feet, thus allowing small hand gestures such as swiping, grabbing, pinching, and punching. The objects that are directly under the LED light, as well as incandescent light bulbs, halogens, or even daylight are the ones that are going to be visible in the scene. The shown data is a grayscale stereo image, which does not always refer directly to the lightness of the materials in real life. The device does not produce an in-depth map but rather applies advanced algorithms to the raw sensor data [22].

5.2. Myo

The second rising sensing technology related to VR is Myo. Myo is also tracking finger and hand gesture but it is rather based on muscle activity. The device is worn as an armband and it works on the basis of a combination of medical grade EMG sensors, highly sensitive nine-axis IMU containing three-axis gyroscope, three-axis accelerometer, three-axis magnetometer. The electrical activity in the forearm muscles of the user is correlated to his or hers muscle movement, which in turn allows control over software by the user's hand and finger gestures. The application of this sensor extends not only to construction sites, but also to laboratories, control over robotics, equipment, as well as digital presentations [21]. LED lights on the 93- gram device are informing the user for its current state and possible errors. The current gestures that it is able to detect are position movement of the hand, spreading of the hand, squeeze of the fist, waving to the left and to the right, rotating the fist, and finger/thumb tapping [23].

5.3. Nimble VR

Another hand tracking sensing technology is Nimble VR. This device is currently in cooperation with the Oculus technologies in order to achieve an even more immersive Virtual Reality experience. Nimble VR consists of a sensing camera incorporated into the headset of the Oculus allowing it to work without any additional hand devices, thus allowing more natural hand and finger interaction of the user [21]. The device is different from the Leap Motion Controller mainly since it is utilising 'time-of-flight' depth sensing technology. The devices works based on an infrared laser, which generates a pulse of invisible light illuminating the 110 degree field of view environment. The sensor detects the infrared light bouncing from the environment and calculates the distance to specific points in the environment The skeletal hand-tracking allows bringing the user's hands into the VR and performs best from 10 to 70 cm distance in front of the user. The device detects gestures such as grabbing object and moving them, opening menus, pushing buttons, and general movements [24].

5.4. PrioVR

A further development of motion capture is present in the sensing technology PrioVR currently used mainly in gaming technologies, film, animation, as well as scientific studies. The device is used predominantly in real time interactive environments and consists of an infrared sensor and an infrared camera. It involves movement actions such as building, demolishment of structures, movement of cranes, as well as simple actions such as opening doors into Virtual Reality. PrioVR is a full-body motion sensing suit, which imports motion data wirelessly into the PrioVR wireless space station, which in turn sends it into the VR software real-time. The device allows 360 degrees of real-time motion capture of not only one but multiple suit-equipped users since it utilises a spread spectrum [21]. The joysticks allow movement in the Virtual Reality without actual walking. It is the most expensive option from the previously discussed sensing VR technologies, allowing full-body interaction, reaching 1200 US dollars [25].

6. Future Expectations

Overall, the primary focus at the moment is on the development of supply chains and virtual reality sensing devices, since these areas would result in major cost reductions, risk minimisation, and increase of quality of products. In an ideal future manufacturers are going to be linked to several factories and suppliers, thus data would be shared instantly [14]. The ability to perform 4k resolution in VR would be several times better than the current stage of the technology. One of the main technologies, which is expected to reach this level of visual quality is the Oculus Rift [24]. The combination of offsite manufacturing with additive manufacturing and robotic assembly is the near reality [28].

It is postulated to address these challenges, by employing methods from artificial intelligence, cybernetics and complex adaptive systems in order to support novel arrangements of independent intelligent pieces of equipment (as smart agents) with basic sensory and computational resources to preform complicated tasks of dynamic data collection and analysis within construction projects. In such a network, agents could be any device, which is capable of collecting and communicating site data, such as still time-lapse or video cameras, RFID tags, GPS receivers, range sensors , or other type of sensors capable of local surroundings sensing. In developing such a system a specific consideration should be given to optimisation of inter-agent communication and collaboration schemas possibly in a form of a dynamic autonomous management tool. Such system could have wide scope of possible applications including: identification, reporting, and documentation of defects and errors within a construction environment; monitoring of the construction progress; creation, maintaining and updating of the construction-site materials repository or optimisation and monitoring of workforce deployment.

It is envisaged that the architecture of such a system would rely on a network of dynamic, self-organised sensors (agents) for capturing and reporting construction site data in semi real-time. The network could consist of a set of multiple autonomous sensing agents (including intelligent cameras with a "clip on", easily attached to different structures – engaging "pick & drop" a sensor concept). The key in the proposed system would be the exceptionally low cost of individual sensing devices to a level at which they can be treated as disposable units. As one of the most expensive and the least reliable subsystems of the robotic agent is propulsion mechanism, the mobility of the device would depend on the cooperation from the construction workforce. It is envisaged that a device will indicate a request to be moved by audio-visual signalling (e.g. flushing LED). The assumption is that a passing by site worker would pick it up and carry till the unit signals that it should be dropped (clipped to a nearest safe structure). It is assumed that that the worker would not be directed to the target destination instead simply proceed with the task he/she is currently engaged in. The unit will estimated its own position with respect to the construction side topology and the target destination and plan the optimal randomised moves to approximately reach this destination in a finite number of pick & drop steps. The key enabling low cost technology making this possible is combination of off the shelf GPS systems and Structure from Motion (SfM) and Simultaneous Localisation and Mapping (SLAM) [26] computer vision algorithms.

Another more expensive option would be to manage sensors arrangements with the help of autonomous UAVs. As before this will engage pick-up agents - to send out signals, indicating when a change of position is needed, and then dropping them in a new position when prompted by the agents of the system.

A set of software agents to address multiple data analysis tasks, including: i) vision based object recognition for non-obtrusive inventory, ii) tracking and action recognition for onsite personnel management, iii) site map building (using intelligent SLAM algorithm) for construction progress monitoring.

A set of optimisation agents for managing project resources; e.g. delivery of just in time logistics, distribution and management of material, labour allocation across the construction site etc. Such a system should actively embed the model of Invisible Hand theory [27], whilst also taking into account concomitant human factors engaged in site-related activities. A conceptual model of this architecture is presented in Figure 1.

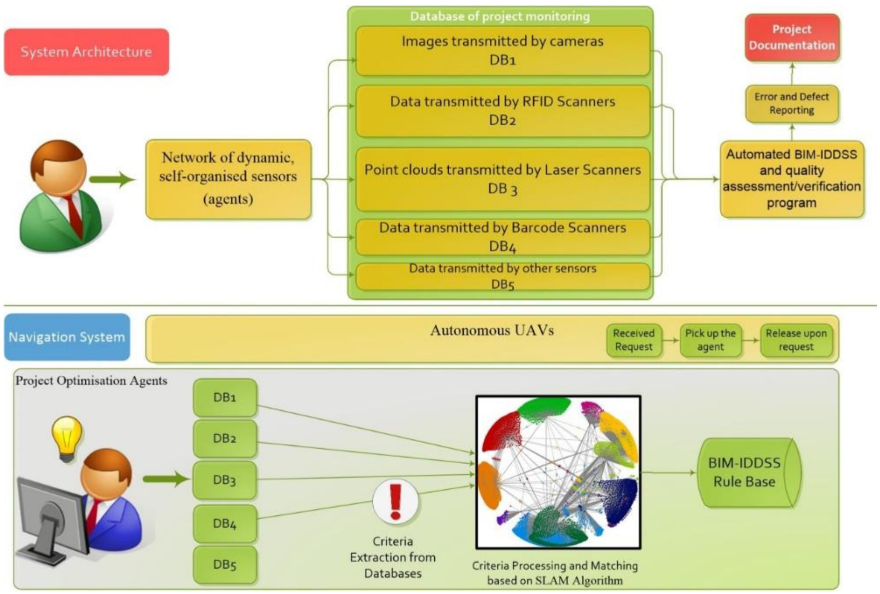

Figure 1: Conceptual model of the architecture of the proposed intelligent project monitoring system

7. Conclusion

This study was motivated by the needs for automated project monitoring and control systems for optimisation of day-to-day activities within ordinary construction projects. This paper presented a review of state of the art technologies that facilitates systematic project monitoring within the construction domain. In order to address the issues with the existing systems, the paper proposed relying on optimal use of artificial intelligence, cybernetics and complex adaptive systems. From this, a conceptual framework for development of a real-time intelligent observational platform supported by advanced intelligent agents was presented. It was argued that the proposed platform can actively, autonomously and seamlessly manage intelligent agents (cameras, RFID scanners, remote sensors, etc.) in order to identify, report and document 'high risk' defects. Findings underpin a new ontological model that supports ongoing development of a dynamic, self-organised sensor (agent) network, for capturing and reporting real-time construction site data. The model is a 'stepping stone' for advancement of independent intelligent agents, embracing sensory and computational support, able to perform complicated (previously manual) tasks that provide optimal, dynamic, and autonomous management functions.

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