Components of a Technology Roadmap for Automated Excavation

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Abstract
In the construction industry, especially in earthmoving equipment, automation has received a great deal of attention. Fully environmentally friendly automatic construction equipment, such as excavators, are perceived as vital for safe, productive, and resilient future construction sites. However, there is much uncertainty about the technologies which need to be adopted and developed in order to effectively achieve this end and provide the industry with strategic direction. This paper explores current academic thinking about technology roadmaps and technological innovations of excavation operations, in order to identify the components for automated excavation technology roadmaps. Literature in well-established databases are identified using robust search strategies. Text mining, a quantitative approach, was used to analyse and organise findings. Three main technology innovation categories were identified: 1) real time positioning systems; 2) technologies to detect over ground objects, 3) technologies to detect below underground objects. In addition, multi-sensory data fusion methods are identified as an essential and vital requirement for construction automation.

Keywords: Automated excavation, roadmap, technology innovation, sensors, data fusion.

1. Introduction
1.1 Research background and motivations
In a globally competitive business environment, technological innovation has significant effects on firms’ short-term performance and long-term viability. Therefore, technology choices are crucial to competitive advantage. When there is uncertainty about the future direction of the technology, appropriate technology strategies should be developed to support the firm’s future technology expansion plans [1]. These strategies must be aligned with industrial agreement on transformation, and for the construction industry, automation, and in the future connectivity, will motivate technology investment, toward safe, productive, and resilient future construction sites.

The academic literature has strongly argued the importance of technology roadmaps which enable two major ambitions: first it is a planning tool for strategic decision making, second it facilitates communication [2]. A technology roadmap has a time-oriented association, and the dependencies over time are bounded by technologies and products. These dependencies extend through relationships with the market, and to responsible organizations for transfer of technologies and products [3].

A technology roadmap represents both management theory and practice [4] and is beneficial at three levels: 1) national research and development: policies that guide technology, science, economics, and innovation prospects; 2) industries and sectors: boosting collaboration and coordination in special technological areas; 3) specific technological routes [5].

Currently, there are no technology roadmaps available for automation of construction nor for excavation. The construction industry focuses on three goals: safety, performance, and resilience. Automation is expected to achieve these goals without the need for manual intervention on a construction site. The safety of personnel, construction equipment and on-site assets is of primary importance; automation aims to avoid strikes, which also improves resilience, and to avoid construction outages, which also helps productivity. Performance improves through operational optimization which can be automated, whilst resilience is increased through greater site awareness and toward zero recovery needs.

The automated excavation technology roadmap would present how emerging technologies can facilitate the emergence of new products and services in the construction industry to achieve the safety, performance and resilience of excavation.

The objectives of this research are as follows:
(1) Identify the components required for an automated excavation technology roadmap.
(2) Explore existing and emerging technologies for intelligent excavation.
The methodology is discussed in Section 2. A brief description of relevant theoretical issues follows, including technological innovation, automation and organisation needs. After that, results are discussed in two main subsections: (1) technology roadmaps (2) technology and automation. Finally, the conclusion section identifies limitations and recommendations for further research.

2. Method

2.1 Data collection and data analysis

To identify the components required for the technology roadmap for automated excavation, various search strategies with different search strings were used in the ScienceDirect and Google Scholar databases. The search strings are shown in Table 1. The Boolean operator “OR” was used as an inclusive technique and the Boolean operator “AND” was used as an exclusive technique to target relevant literature, identifying relevant literature while excluding irrelevant ones. Nevertheless irrelevant literature was eliminated after reviewing titles, the literature was reduced to 58 articles, then further reduced to 25 highly relevant articles after reviewing abstracts.

Table 1: Search strings used to identify literature on technology roadmaps for excavation in construction

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Search Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(automation OR technology OR intelligent) AND &quot;roadmap&quot; AND safety AND resilience</td>
</tr>
<tr>
<td>2</td>
<td>(automation OR technology) AND &quot;roadmap&quot; AND (trend* OR pathway* OR feature*)</td>
</tr>
<tr>
<td>3</td>
<td>automation AND &quot;roadmap&quot; AND excavator</td>
</tr>
<tr>
<td>4</td>
<td>Connected Autonomous Vehicles</td>
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</tbody>
</table>

The second objective was addressed by a different search strategy in order to identify existing and emerging technologies for automated and connected excavators. Scopus, PQ/ABI, Web of science, EBSCOhost were searched based on their relevance to engineering and business data. The search strategy shown in Table 2 were linked with the Boolean operator AND. After the title and abstract 49 full text articles were included in the literature review. The data extracted in this search includes all technologies and methods for monitoring construction processes and detecting objects/obstacles on the ground and underground during the excavation process. Other types of technological innovation are beyond of the scope of this research and therefore have not been considered in this paper.

Table 2: Search strings used to identify innovations and technologies for excavation in construction

<table>
<thead>
<tr>
<th>String</th>
<th>Search String</th>
<th>Boolean operator</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>(automat* OR technology* OR automat* OR intelligent*) AND</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(resilient* OR safety OR &quot;resilience engineering&quot;) AND</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(excavate* OR &quot;earthmove* equipment&quot;) AND</td>
<td></td>
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3. Results and discussion

3.1 Technological context

The process of technological innovation takes place through highly complex socio-techno-economic systems, in which regulation and marketing play an important role [6]. “Technology Delivery System” (TDS), is a useful techno-centric approach for finding innovative content that translates ideas into reality. So, technological development analysis is needed, and the typical need in this area is to identify key players and stakeholders and understand how these elements work together and act as a system.

Huang et al [6] categorised the TDS literature into three parts – a technical perspective, a delivery perspective, and a system perspective. The technology perspective points out that R&D processes is crucial to the development of a new technology, and the key step in this regard is technology road-mapping (TRM). According to Phaal et al. [7], a technology roadmap enables organisations to integrate the commercial and technological aspects into the emergence of new technologies. Not only that, a technology roadmap is both a planning and forecasting tool, which promotes the integration of the two [2]. In fact, a technology roadmap can also be used to make a plan, to consider uncertainties or to make at least some assumptions for future plans.

Scenario planning is a tool currently used to deal with uncertainty in the literature. Scenario planning attempts to anticipate hypothetical futures [8] and has been utilized as an efficient attempt to consider the dynamics of business environments [9]. Consequently, scenario planning is prominent strategic planning tool that dominates technology roadmapping [9].

3.2 Technology roadmap

Various methods can be used to capture the information needed for the technology roadmap, including: qualitative, quantitative and hybrid methods. Qualitative methods include: expert interview, Delphi,
discussions, seminars/workshops, often connecting academic researchers, industrial stakeholders, and government officials. Quantitative methods include: text mining, bibliometrics, computer-based graphical techniques, artificial intelligence, intelligent information techniques, pattern recognition, and machine learning. Hybrid methods include i) computer-based techniques for processing large amounts of raw data, as well as to lessen extensible data dimensions for more manual operations; and ii) expert-based qualitative methods that play an important role in selection and evaluation [5].

Patent analysis is an alternative method that raises awareness of technological development trends [1], [10]. Kim et al [10] conducted patent analysis in the construction industry that relied on keywords established by expert opinion and literatures, and a patent map was produced based on these keywords. Technology roadmaps rely heavily on qualitative methods, in particular, expertise [3], as it creates credible responsibility for the results.

A technology roadmap has three main layers: Market, Product, and Technology. The interaction and relationships of these layers require precise analysis [3], [9], [10]. Due to the different characteristics of the technology roadmap layers, it is not sufficient to develop a technology roadmap using a single method [9]. Market planning analysis and evaluation requires external scenarios that are uncontrollable, while internal scenarios are primarily strategic, controllable product and technology planning decisions.

Therefore, techniques are needed to analyse the elements of each technology roadmap layer and their relationships. These include: (1) Analytic Hierarchy Process (AHP), applies to technology and product layers due to the characteristics of its decision-making process, [1], [9], [10]; (2) Cross Impact Analysis (CIA) applies to the market layer due to its ability to measure the impact of external environment [9]; (3) Quality Function Deployment (QFD) [1], Association Rule Mining (ARM) [3], and decision matrix (GRID) identify the relationships between markets, products and technologies.

QFD is a reliable and innovative management tool for cross functional coordination in a matrix to outline customer needs and engineering characteristics of products, and to identify trade-offs and relationships in clear and simple quantitative models [1]. ARM is able to correlate large amounts of data, which helps to make further decisions because it can expose unknown relationships and calculate dependency information through confidence measurement adaptation [3]. In addition, there is another technique called Hierarchical Decision Model (HDM) which is an evolutionary model built in a hierarchical structure with the same concept as AHP, but with various numerical comparison ranges [11].

Recently, researchers have concentrated on the application of roadmap on the paradigm of service, which means adding a new layer to the existing technology roadmap in terms of “Services”, which has the same standing as the product layer [1]. In fact, service science constructs a conceptual base for service-oriented business models to build a robust and flexible IT-based business models that respond efficiently to the needs of distinct customers. Accordingly, servitisation refers to the ability to improve the organization’s capability to acquire more valuable products by integrating planning processes, providing services and production value [1].

3.3 Technology and Automation

In addition to using advanced robots for automated task execution, sensor technologies as well as reliable data fusion models and advanced uncertainty algorithms are required.

Automation systems should be described and activated in such a way that become a best-fit for the proficiency of both human and machine. Different Levels of Automation (LOA) express human-machine interaction and cooperation. Each level determines a specific point in which a class of tasks is automated. This signifies that automation can alter across a sequence of intermediate levels at the two extremes, bounded by fully manual work, and a fully autonomous setting [12]. Between these extremes, automation levels can be invented and the new taxonomy link to previously proposed levels or by adding new ones. [12]. Furthermore, adaptive automation is needed and is analogous to dynamic function allocation, in which there is not a predetermined or fixed division of labour among human and machine agents, but it is context dependent, dynamic and flexible [12].

There are some general purpose technologies that act as automation enablers including IT infrastructure, Communication, Internet of things, plus cloud computing, cyber-physical systems, Building Information Modelling, sensors and new wearable technology devices. See Figure 1. Cloud computing can be used in different industries to notably enhance the quality, efficiency, reliability, and productivity of the automation process which results in improved perception, faster planning, accurate modelling, lifelong learning, large-scale systems, and sophisticated robots [13]. Combination of “Human-in-the-Loop Cyber-Physical Systems (HiLCPSS),” with Building Information Modeling (BIM), makes it possible to gain proactive improvements of construction and operational safety by setting up activity-level construction site planning [14]. Wearable sensing devices application helps toward occupational health and safety management, in physically critical and hazardous construction [15].
Information technologies enable automation

However, recent focus in intelligent transportation systems, notably in government-associated research and development activities, has been concentrated on automated vehicle (AV) and connected vehicle (CV) technology and systems [16], [17] and the divergence in their formation time frames [16]. CV systems have the capability to accept a broad number of Information Technology System applications, and to closely connect vehicles and infrastructure components into a reasonably-integrated transportation system-cooperative systems. Automated vehicle (AV) systems have had an older unstable history, which has a robust factor of technology push. However, AV systems enhance transportation system operations much better when joined with CV systems [16].

3.3.1 Monitoring and detecting technologies for over the ground objects:

Novel construction site automated data capturing technologies include: Global Positioning System (GPS), Radio Frequency Identification (RFID), Laser Detection and Ranging (LiDAR), Ultra Wideband (UWB), and video/audio capturing systems which call Real-Time Location Systems (RTLSs) to overcome deficiencies of traditional monitoring methods [18]–[23].

Real time positioning devices such as GPS and UWB are used as automated vehicle tracking technologies to provide 3D locations of equipment and stationary plant is a valuable data for planning and management of resources [18], [24]. Many technologies are available that can capture equipment pose data such as laser-based methods, Inertial Measurement Unit (IMU), and active and passive marker-based motion tracking systems [25]. Location data captured by RTLSs can facilitate the identification of machine-induced safety hazards and the analysis of operation productivity [18]. Location-based Guidance Systems (LGSs) were produced by integration of RTLS geo-positioning data, 3D design models, and Digital Terrain Model (DTM) to support construction equipment operators. This support can be a cabin-mounted display as a visual guidance to operators, or control of the equipment movement and position [19]. Automated Machine Control and Guidance (AMC/G) are accessible LGSs in the market which are adopting expensive high-accuracy GPS. Other cost-effective systems which utilise RTLSs such as UWB are also proposed [19].

The recognition of construction operational resources has an important burden in achieving fully automated construction [26]. Hence, Computer Vision based methods has been significantly used to automatically monitor and detect people, buildings, plant, materials and equipment on construction site from images or videos to improve safety and productivity [27], [28]. Conventional surveillance cameras have not been efficiently used as a result of labour-intensive process of manually extracting data from the images and videos before they are eliminated to save memory [24]. Therefore, high-resolution digital wireless cameras and high capacity storage devices have been adopted to a great extent at construction sites as a result of their good enough return on investment, as well as producing helpful management information for construction engineers/managers to monitor and control sites remotely and dynamically [26].

3.3.2 Monitoring and detecting technologies for under the ground objects:

Excavator collision with buried utility networks and assets results in damage to pipes and cables, worker injuries and deaths. Various geophysical sensors have been utilised to locate buried utilities, such as passive magnetic fields for electrical cable detection, vibro-acoustic methods for pipe detection, incorporated small sensors for water pipe detection, low-frequency electromagnetic sensors, and Ground Penetrating Radar [29]. Kolera & Bernold [30] reviewed current underground utility detection technologies and geophysical non-invasive methods.

3.3.4 Multisensory/ Data fusion approach

Data fusion is a process in which acquired signals from multiple sensors are integrated based on some algorithms to facilitate decision making by improving system reliability, and reducing fuzziness of information [31]. Quantitative and qualitative methods have been used for data fusion such as rough set, maximum entropy approach, fuzzy integral, Dempster–Shafer (D–S) evidence theory.

Single geophysical techniques are not able to identify all types utility in varying soil conditions [32]. The multisensory approach is based on the combined application of geophysical technologies and if multi-sensor data is integrated appropriately, a more accurate and complete buried utility network representation can be built [29], [32].
Information technology approaches are required to achieve the full potential benefits of multisensory approach. Computer science has considered the collision detection concept in different applications such as computer-aided design and manufacturing, robotics, simulations, and computer games. The information technology approach combines computer graphics visualization, geospatial databases, and tracking technology to depict the position of the subsurface utility lines relative to the equipment operator and the excavation crew [32]. Information technologies such as web-based services are using geospatial databases to store buried utility data and display them to the user in two-dimensional (2D) or three-dimensional (3D) visualization on desktop workstations, smart phones, tablets, and personal digital assistants. Augmented Reality (AR) has been used to visualize underground utilities to assist utility inspection and maintenance, as well as improving visual perception for buried utility and excavation safety [33]. By utilizing AR, the user receives a mixed view of the real world and virtual underground utility lines [32].

4. Conclusions

The components required for a technology roadmap were identified, enabling an excavator to make autonomous decisions. The components of the technology roadmap deliver construction site safety, productivity, and resilience, through avoiding strikes, and using knowledge. The components are markets, products/services, and technologies. Market and product/service components have not been fully dealt with this paper. Technologies for detection fall into three groups: real time location based systems; technologies to detect above ground assets, those to detect below ground assets, and multi-sensory data fusion technologies. Furthermore, enabling technologies, such as communications and cloud storage were identified.

This paper used text mining method which limits the research to quantitative methods. To enhance the reliability of this work, the components need to be considered and validated both in isolation. This will enable a technology roadmap for automated construction to be developed.

Furthermore, modeling the components of a technology roadmap was recommended in the literature, in order to understand interdependencies and to create a living technology roadmap for continuous iteration [2].

5. References


