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The Future of Automated Plant in Construction – A UK Perspective

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Abstract

Within the construction industry, heavy mobile machinery is typically known as plant. Plant has seen a transformation from its earliest, animal powered form, through steam and combustion engine driven machines through to the modern multifunctional devices applied in construction across the globe. However, construction is facing a number of significant social, environmental, and technical challenges. In response there has been a rising interest in the use of digital and automated technologies which can be applied to the construction sector. One particular aspect of this is the use of Connected and Autonomous Plant (CAP) to replace traditional, human operated machinery. Incorporating CAP as part of the wider digitalisation of the construction industry promises to deliver gains in productivity, safety, welfare, sustainability, quality, and cost. However, the achievement of these benefits will require a step change in the approach to the design and construction of plant, and in the way that plant operates on construction sites.

This paper presents a potential future for the deployment of plant on construction sites. It discusses how sites could evolve to accommodate the new role of CAP and how people and CAP will need to work together. It discusses how National Highways have been seeking to drive transformation in construction through the development of a vision and roadmap for CAP, which encourages all stakeholders to collaborate and aims to catalyse the development and adoption of these technologies.

Keywords

Connected Autonomous Plant, Construction, Automation, Autonomy, Digitalisation.

1. Introduction

The UK construction industry is facing a number of significant challenges, including the climate crisis, an aging workforce, and rising material and production costs. In response to these challenges there has been a rising interest in the use of digital and automated technologies which can be applied to the construction sector, (Leeds, 2017) and (Jones, 2018). One particular aspect of this is the use of Connected and Autonomous Plant (CAP) to replace traditional, human operated machinery, (McKinsey & Company, 2020) and (HM Government, 2022). The removal of human involvement in plant operation could enable significant improvements to be made in the safety and welfare of construction workers, through the transition to a skilled workforce managing the deployment and operation of automated machines in construction activities, delivering significant improvements to productivity, efficiency, and quality, (Korec, 2006), (Caterpillar, 2016), and (McKinsey & Company, 2021).

However, although industry is clear in expressing its desire for change, there are concerns about the ability to implement these new methods of construction, particularly in the context of the current approach to commissioning and delivering construction projects. The development and implementation of new technologies is expensive and currently these costs are borne by contractors and operators using the equipment, even though the benefits are passed to clients. Furthermore, the plant hire model under which UK construction operate poses challenges to the adoption of new technologies due to the impact on the operation, readiness, and profitability of those ventures. While innovators and early adopters can see the benefits of the new methods, it is likely technology may not have the greatest influence on the rate of adoption – for example if commercial incentives are not clear, decision makers will not select or develop new methods, resulting in inevitable delay.

This paper discusses the background of plant within the construction sector and explores what constitutes the developing CAP technologies. It then sets out a vision for how plant might be deployed as part of the ongoing digitalisation of the construction industry and the activities that National Highways and partners have been undertaking to implement this vision on their current and future construction sites.

2. Background

2.1 History of Plant

Plant includes pieces of mobile heavy machinery which are used to carry out construction activities. The original forms of heavy machinery were human or animal powered assemblies of simple machines, such as the block and tackle or wheel and axle, which were used to provide mechanical advantage when carrying out heavy labour. With the advent of the industrial revolution of the 18th and 19th centuries the human or animal powered nature of these devices changed, initially via steam, through to the internal combustion engine. This provided greater productivity due to the increased capacity of these machines and was instrumental in the delivery of the large-scale infrastructure projects of the 19th and 20th centuries. In modern usage, plant typically refers to Earth-Moving Machines such as dumptrucks, excavators, compactors, etc., which remain a core focus on today's jobsites. When we consider automation inconstruction, it is clear that this will remain the case and such machines will continue as a hugely important strand ofwhat constitutes CAP.

However, there is merit in considering if we should extend the definition of plant beyond its current definition. If we consider plant to be any machine which assists in construction, which would be in-keeping with the Latin origin of the word ('plantere' - to fix in place or to form and make) and the case law definition of "apparatus used for carrying on the business" (HM Revenue & Customs, 2016), this would extend plant to include physically smaller technologies that could be deployed on construction sites. For example, this could include the use of UAVs for surveying, small robotic technologies for pre-marking or laying out sites, or assistive technologies such as collaborative robots for the movement and placement of material.

Plant in UK Road Construction As the landscape of construction in the UK has changed, so has the plant needed to fulfil projects. For example - the greenfield motorway building projects of the sixties and seventies required extensive earth-moving as the high-speed nature of these roads required limited gradient and curve. The roads were unable to follow natural contours of the land and had to be cut into, and elevated above, the natural landscape, (Yeadon, 1990). These projects favoured motorscrapers that were very efficient at moving large volumes of earth. Indeed, these volumes peaked at 48 million m^3 in 1978 and dropped to 30 million m^3 by 1984, (Barker, 1988), as most major routes were in-place. Today much of the work is spread across minor road improvements, bypasses and widening schemes. Although the total volumes of earth moved are still high, the projects tend to require specialised earth-moving, which suits the more versatile dumper / excavator combination, (Alkass & Harris, 1988). This is important to note, as versatile machines that are capable of carrying out many different tasks are more difficult to fully automate, (Dadhich,Bodin, & Andersson, 2016). Hence the emerging examples of CAP currently deploy semi-autonomous functionality and task focused autonomy (e.g., automated grading control on excavators), (Singh, 1997), (Caterpillar, 2016), (Winter, 2020).

2.2 Connectivity

The "Connected" part of CAP refers to plant's ability to communicate with other plant, and other external networks and systems. Sharing information from onboard telematics supports a wide range of uses that can optimise plant operation – for example reducing idle times or improving haul routes. It is likely to become a key constituent of automation, as an enabling technology. Connectivity also allows machines and their environment to be represented in high-fidelity real-time digital twins (Walker, Smith, & Bosché, 2021) to facilitate further automation, as well as simulation-based optimisation of construction sites. This is explored further in Section 3.2.

2.3 Automation vs Autonomy

It is important to distinguish between Automation and Autonomy of construction plant. Automation refers to the conversion of a (well defined) task which is typically carried out by a human to one which is carried out by a machine or computer. Autonomy considers the capacity of a system to operate as an independent unit to complete a task, without being controlled or manipulated by another system or human. For many aspects of construction, the goal will be to establish an automated system to complete the task with no requirement that it operates independently or outside defined and well understood operational constraints. This is explored further below.

However, despite having made this distinction, the term Autonomous is often used to cover both aspects when discussing both on- and off-road vehicles and is intended to imply the lack of a human role in any of the operations of the vehicle. For example, if one piece of plant is carrying out a repetitive well-defined task such as excavating a trench and placing it into a dump truck which transports it to a spoil site, this situation would be described as autonomous activity although each machine is not acting as an independent, self-sufficient unit.

2.4 Operational Design Domain

Whilst the autonomous operation of individual items of plant continues to evolve, it is important to consider that the capability that will be achievable by an item of plant on site will be strongly influenced by the environment in which the plant is operating. This is defined within the Operational Design Domain (ODD) of the plant, which determines the environment and conditions in which the plant can be expected to operate. There are two aspects of the ODD to consider – the basic ODD of that piece of plant (that is, the environment in which this plant could successfully operate even if it had a human controller – e.g., could this equipment work on this grade?) and the ODD of the automating system (the operational environment in which the autonomous system can safely complete tasks without needing human intervention). It is important to note that construction brings unique challenges in both defining an ODD and ensuring that the plant remains within it:

- Construction sites are of variable size and form.
- Construction sites are dynamic, always changing environments.
- Construction sites are exposed to external uncontrollable factors.
- Operations are regularly concerned with modifying the environment in some way.

This greatly contrasts with the situation for on-road vehicles, where one can safely assume that the vehicle will be operating within a defined environment that was created for it to be operating there. However, the routes through which CAP evolves will affect how ODDs may need to be defined and modified - which may themselves be limited or controlled through the use of a well-defined and controlled site, as discussed in the following sections of this paper.

3. Future of Plant Operation

3.1 Approaches to Automating Plant

There are two broad approaches to automating plant:

1. The plant has relatively little perceptive and decision-making ability but is used in an environment which has high quality centralised control infrastructure
2. The plant is equipped with a control system of sufficient perceptive and decision making quality that it can effectively be treated in the same way as a human driven machine with minimal support from the infrastructure

Many current off-highway automated vehicle systems centralise the control of multiple vehicles into a central computer. The decision-making process for each vehicle resides in the worksite's central computer. The tasks undertaken are entirely deterministic with little or no tactical decision making required. Each vehicle has a relatively simplistic perception and control system to allow it to carry out instructions from the centralised control infrastructure. Any deviation from the normal operating procedure, e.g., if an obstacle is encountered, has to be dealt with by the central control system, or its human supervisor, and usually results in the vehicle pausing while the problem is resolved. The ODD for these types of vehicles is limited to sites where a control system and its associated infrastructure (mapping, communications, etc.) is available. Vehicles designed to operate in such a system cannot operate independently and would be defined as *Automated* but not *Autonomous*.

Therefore, on a construction site, the first of the above approaches could be achieved using a central control model. Each item of construction plant (CAP) would operate as a 'dumb' robot, carrying out instructions from the central system. The central system would hold a digital model of the site in its current state and a model of the intended product. Computer aided manufacturing software would guide the process of changing the site from its current state to the intended product. The site could operate in the same way as an automated production line in a factory – the ‘robots’ would carry out instructions passed to them from the central system, without the need for each item of plant to have any ‘understanding’ of its task. The plant would pass information back to the central system to continuously update the current model.

The second of the above approaches is likely to present the greater challenge to the development of CAP. However, it is unlikely that fully autonomous heavy construction plant will ever be desirable within the construction industry – by its nature, construction requires some central oversight to ensure that each process is contributing to the ultimate goal of the project. It may be technically possible to develop highly autonomous plant that is able to take on much of the tactical level decision making for the process being undertaken, in much the same way that a human machine operator might. Such machines might be able to:

- Select their own path to a work location and position themselves appropriately for the task at hand
- Set themselves up for work, ensuring stability, access, and clearance for themselves and collaborating plant, e.g., dumpers working with excavators
- Plan the task, e.g., choosing where to place spoil so that a trench can be easily backfilled
- Choose the appropriate attachments for a particular task, e.g., excavator bucket
- Continuously monitor the progress and quality of the task

However, the automation of these tactical level tasks is by no means trivial, especially when applied to complex tasks like excavation. Autonomy of this nature will, in many instances, require construction plant to have a holistic ‘understanding’ of the site and plant that it is collaborating with. Therefore, the provision of a future, connected site that facilitates the implementation of central control and lower levels of in-plant complexity becomes attractive.

3.2 Providing Future Site Infrastructure for CAP

On-highway automated vehicles are designed to function on roads that have little or no dedicated infrastructure to automated driving – this is because of the significant challenge providing the required infrastructure on a sufficient proportion of the road network that would make on-highway automated vehicles that rely on this type of infrastructure feasible. The assumption that on-highway automated vehicles will operate without supporting infrastructure increases the challenge of automating these vehicles because of the complexity of the perception task, e.g., accurately identifying the presence and status of traffic lights. On a worksite there is the opportunity to provide physical and digital infrastructure elements to the site itself to assist the process of automating operations. For example, it may be possible to reach a high level of automation, with a relatively unsophisticated automated vehicle, if that vehicle can be centrally controlled by a computer that has an accurate and up to date High Definition map, a low latency communication system and a robust access control system to ensure the worksite is kept clear of intruders. Such an approach to automation has been successfully adopted within the mining industry, particularly in the Australian and South American mining sectors, (Ralston, Reid, Hargrave, & Hainsworth, 2014), (Rogers, et al., 2019), (Ali & Frimpong, 2020). However, there are associated challenges and negative impacts when introducing automation to a sector – once again, the mining industry provides some relevant examples to the construction industry. Particular challenges range from impacts on job security, income, and other human factors (Paredes & Fleming-Muñoz, 2021) and (Lynas & Horberry, 2011), issues with development amongst disadvantaged sectors of the population (Holcombe & Kemp, 2018), to cybersecurity challenges with implementation (Tubis, 2020).

Key infrastructure elements for highly automated construction therefore include:

- High definition ‘digital twin’ of the site, updated in real time
- High bandwidth, low latency, two-way communication
- High precision, low latency location services

The availability of each of these infrastructure elements enables more centralised control and co-operation and reduces the necessity for high levels of processing power and autonomy within individual machines. These infrastructure elements are strongly interdependent: there is no point having a central system that doesn’t have a clear picture of what is currently happening on site and what needs to happen next; there is no point having that information if you can’t share instructions with machines on the site or receive updates from them on their progress; and there is no point doing any of it if the machines are not able to position themselves accurately on the site and in the plan. However, this infrastructure is technology agnostic. Whether the site uses RTK-GPS or a projected laser grid, 5G, or Wi-Fi is immaterial, provided the capability of the method chosen is sufficient for the purpose at hand.

Taken to its ultimate conclusion, it is foreseeable that it would be necessary for site infrastructure to provide location services with millimetre accuracy, the facility to bidirectionally transfer gigabits of data per second and have a digital twin with a four-dimensional plan of the site, updated many times per second. As sites transition from their current manual systems towards automated alternatives there is likely to be a steady ratcheting in the capability of all three areas of infrastructure, with the key stumbling block being the availability of data management systems capable of processing the information provided to them in real time. However, this is not a fundamental technical barrier but simply the result of market inertia, which has slowed the development of BIM, CAD, and digital twin software relative to the development of location and communication systems. This element of the transition to fully automated sites will require a fundamental shift in the way designers of construction projects work - moving away from the simple creation of final snapshots fixed in time, to four dimensional products that take full account of the tasks involved in each stage of the construction process. While the potential technical barriers to delivering the required site infrastructure are likely to be easy to overcome, the organisational shift in the relationship between designers, surveyors and site operators may prove to be more of a challenge.

In the interim period the steady ratcheting of capability is likely to be driven via distributed technologies built into individual machines supported by existing cellular communication networks. Thus, surveying equipment will capture data that can be shared with 3D machine control systems, those 3D machine control systems will be able to record and upload their work to central data hubs and so on, (Barazzetti, Previtali, & Sciaoni, 2020) and (Walker, Smith, & Bosché, 2021). The key capability difference between this model, which currently operates on some sites, and the model for our future fully automated site, is the future-site's need for high-bandwidth low latency communication that is constantly available and protected against any interruption. Thus, rather than sharing data on the (current) 'as-and-when' basis, the central system will communicate constantly with machines to ensure that the latest information on the state of the site is always shared. Whilst it is conceivable that this capability may be furnished by external sources, such as 5G, these communication systems are likely to require a high safety rating to meet the needs for a secure, reliable, and safe fully automated site.

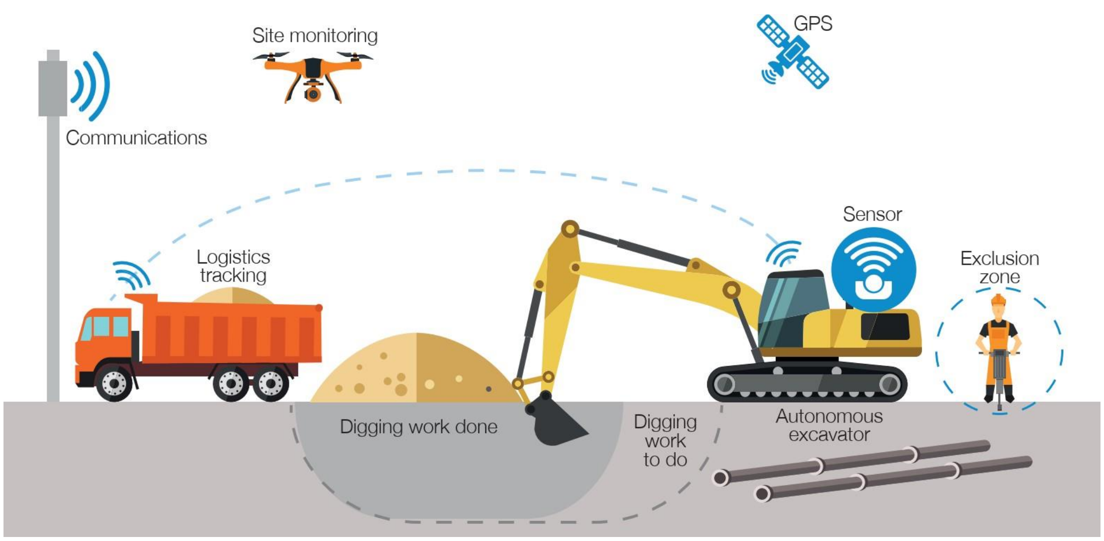

Figure 32 The Connected Site

3.3 The interaction between humans and Plant on the future site

As automation of construction evolves the human-plant boundary and interactions will need to change to accommodate the new capabilities of CAP. There are multiple aspects to this problem – firstly, it is important to consider the safety elements of automated plant operating alongside humans. Currently, a large number of construction activities take place with humans and plant in close proximity. For example, excavation of trenches with a human determining the depth, or the use of banksmen to monitor the movements of plant onsite. If automated plant is to be used in these circumstances it is crucial that the behaviour of the plant is consistent with the expectations of the workers operating alongside it. Although a non-standard approach may be determined to give greater operational benefits, there is a significant safety risk associated with the plant executing this manoeuvre if the workers do not expect it.

Potential solutions to this problem include restricting the behaviour of the plant to being "human-like" or removing any workers from operating alongside the plant. The latter of these strategies has been successfully deployed in mines and ports that are operating automated machines for productivity improvements. In addition, there is the potential for creating dynamic exclusion zones that wrap around the human workers as they move throughout the site, which interact with the plant onsite to create a digital zone that the plant cannot enter, *Figure 32*.

An additional complexity is how the deployment of automated systems will impact the livelihoods of existing plant operators. Although fully automated systems for complex tasks are not yet viable, a number of assistive tools have been developed which reduce the skill requirements for operating plant whilst achieving high quality outcomes. This is beneficial to the overall construction site, by alleviating the labour shortage the industry faces, but has adverse outcomes on the highly skilled existing operators. There is a need to manage a transition from plant operators to plant supervisors, who have the necessary experience to judge the performance of (semi-)automated plant operating on a construction site and maintain their operations. This has the potential to exist as one skilled professional managing multiple pieces of automated plant, intervening when necessary.

4. A Roadmap to the Future of CAP

In the above we have discussed a subset of the range of challenges and barriers to delivering automation in construction. To understand the wider challenges and actions needed to address them, in 2020 National Highways published a first-of-a-kind Roadmap for Connected and Autonomous Plant, (Highways England et al., 2020). This Roadmap drew on the expertise of over 75 stakeholder organisations. Through consultation, questionnaires and workshops the development of the Roadmap identified the wide range of barriers to the adoption of CAP, including: the lack of a legislative framework that permits and facilitates the use of automation; the need for greater financial investment and recognition of the benefits that would be achieved; contractual programmes which do not incentivise the use of CAP; and the difficulties in developing technology and connectivity across the wide range of plant used in the construction sector. The Roadmap developed a programme of activities across nine workstreams to stimulate the widespread deployment of CAP as a series of roadmap milestones are achieved.

The Roadmap was jointly launched by National Highways and the Infrastructure Industry Innovation Partnership[1] (i3P) in June 2020. The Roadmap predicts that, if the deployment of CAP within the UK construction sector can replicate the productivity and efficiency benefits that automation achieved in the manufacturing sector, benefits of £200Bn could be achieved by 2040. However, this requires that the steps outlined in the Roadmap are rapidly acted upon – a delay of 5 years would see the 2040 savings reduced by over 50% due to delays in the deployment of the beneficial technologies and innovations.

A particular milestone identified within the Roadmap was the need to develop a taxonomy for classifying the automated capabilities of construction plant. The Roadmap suggested that the creation of such a taxonomy would provide a unified language for the industry to understand how plant developed by different Original Equipment Manufacturers (OEMs) and third party, retrofitted solutions could be used to achieve tasks with reduced or no human intervention. This would facilitate the specification of development strategies, contracts, standards, and procurement strategies that could be readily understood across the industry, promoting a unified direction. To this end, National Highways commissioned the development of a taxonomy for the automated capability of plant, which has been published by National Highways and TRL, (National Highways, TRL, 2022).

5. Conclusions

The construction industry currently faces significant challenges but also great opportunity to transform the nature of the sector by adopting the digital revolution that other industries have already embraced. We have presented a potential future for the deployment of plant on construction sites and discussed how sites could evolve to accommodate the new role of Connected and Autonomous Plant (CAP). Whilst there is wide scope for the development of technologies deployed on individual plant to automate its operation, we have seen that plant must operate in a wide range of challenging conditions, or Operating Design Domains, which themselves place greater challenges on the development of these technologies. These barriers could be lowered through the deployment of connectivity and intelligence within the site itself, managed via central control systems and implemented through pervasive high-speed communications. The monitoring, communication and processing technologies that will achieve this future site infrastructure are already emerging. Finally, we have discussed how National Highways have developed a roadmap for CAP to understand the

[1] https://www.i3p.org.uk/en/

challenges that must be overcome. This roadmap highlights the technical, social, environmental, and commercial b enefits that will be achieved through the delivery of the vision for autonomy across construction sites and seeks to drive transformation in construction and encourage all stakeholders to develop and embrace this new future.

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