A Taxonomy for Connected Autonomous Plant

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Abstract -

National Highways commissioned the development of a Roadmap for Connected and Autonomous Plant (CAP), which proposed a programme of activities which would aim to deliver the widespread deployment of CAP. A particular milestone activity identified as an early target within the Roadmap was the development of a taxonomy for understanding the capability of construction plant for operating without human involvement. This would provide a unified language to understand how plant can be used to achieve tasks with reduced or no human intervention. This paper presents an overview of the process used in developing a taxonomy to achieve this purpose, including the principles underlying the taxonomy, and the taxonomy itself. This builds on previous automation taxonomy work and applies it to the construction context and is further applied to two examples of autonomous compaction plant. It is concluded that the levels establish a unified language for the capability evaluation of automation of plant. This will support and catalyse the development of technology roadmaps amongst plant and technology manufacturers, enable procurement processes that incentivise the deployment of CAP within construction management, and support innovation practices by providing an understanding of the safety and operational implications of deploying automation on construction sites. It is also identified that the application of this taxonomy is not limited to the Construction environment.

Keywords -

Connected Autonomous Plant (CAP); Taxonomy; Automation; Autonomy; Plant

1 Introduction

The UK construction industry is undergoing transformational change, as it adopts digitised and automated processes to overcome the challenges facing the sector. Due to the importance of heavy machinery (colloquially known as "plant" within the UK) for construction, the use of Connected and Autonomous Plant (CAP) is of particular interest to the industry, with new technologies being applied to a wide range of activities, such as geofencing of plant operation, the use of 3D machine control to meet the design requirements, remote collection of data for both design and as-built, semi-autonomous extraction and movement of materials, and the introduction of offsite and robotic construction methodologies.

However, the UK construction industry has not adopted a unified approach to this transformation, resulting in varying levels of deployment of CAP across sites, and poor information transfer between organisations. For example, the use of continuous compaction control has been a standard industry practice within mainland Europe for over 15 years but has not seen significant adoption in the UK until recent years. However, while some major projects (e.g., HS2) are implementing it, widespread adoption remains some years away [1]. To alleviate this, National Highways commissioned the development of a Roadmap for Connected and Autonomous Plant, [2]. Development of the Roadmap drew on the expertise of over 75 stakeholder organisations, through a series of questionnaires and workshops. This stakeholder engagement identified a number of barriers to the adoption of CAP including: a lack of a legislative framework that permits and facilitates the use of automation; the need for sufficient financial investment with appropriate recognition of the benefits 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. To address these barriers the Roadmap proposes a programme of activities across 9 workstreams, which would aim to deliver the widespread deployment of CAP as milestones are achieved.

The Roadmap was jointly launched by National Highways and the Infrastructure Industry Innovation Partnership (i3P) in June 2020. The Roadmap estimates 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, then benefits of £200Bn could be achieved by 2040. However, this requires that the steps outlined in the Roadmap are rapidly actioned – a delay of 5 years would see the 2040 savings reduced by over 50% as a result of delays in the deployment of technologies and innovations.

A key early milestone identified within the Roadmap is the development of capability levels and taxonomy for classifying the automated capabilities of construction plant. Standards and taxonomies are useful tools for driving innovation and development by specifying a vision of the future and a potential pathway to achieving it [3]. For example, the creation of a taxonomy provides a unified language for the industry to understand how plant developed by Original Equipment Manufacturers (OEMs) and technology retrofitted by third party developers can be used to achieve tasks with reduced or no human intervention. This facilitates the specification of development strategies, contracts, standards, and procurement strategies that can 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.

2 Methodology

As automation has been developed and implemented in other industries, there has been the parallel development of supporting taxonomies so that each industry can understand their progress towards full automation. Hence, the first stage of the development process of a taxonomy for the automation of construction plant was an extensive literature review of other industries' taxonomies. This review considered the agriculture, aviation, manufacturing, maritime, military, mining, rail transport, road transport, and space sectors. The underlying principles and assumptions of each taxonomy were examined, and their applicability to other industries considered, so that best practice for the construction industry could be identified.

Following the review, an initial version of the taxonomy was drafted. This draft was subject to project team peer review throughout its development. Following the production of the final draft version, it was then reviewed through a series of workshops held with industry stakeholders from 32 organisations between the 30th of November and 2nd of December 2021. These stakeholders were drawn from all sectors that interact with plant throughout the construction process, from OEMs that design and develop plant, designers who create the designs that plant implement, procurement and contract writers who determine the types of plant used on site, site managers who control the deployment of plant within a construction site, and plant operators who physically use the plant. These stakeholders were drawn from the community which National Highways established during the development of the Roadmap. Stakeholders were invited to participate through an online questionnaire which was distributed to the community and publicised through social media and word of mouth. Following this, the positive responses were analysed to understand what type of organisations they belonged to (OEM, client, end user, etc.). During the workshops the stakeholders were asked to rate (on a scale 1-5, where a higher score is more useful / easier to understand) the taxonomy on its utility (achieving a mean score of 3.9/5 and a standard deviation of 0.85) and how easy it is to understand (achieving a mean score of 4/5 and a standard deviation of 0.80). The feedback from these workshops was collated and used to refine the taxonomy. The taxonomy was launched in the UK at FutureWorx in March 2022, and is presented in the following sections.

2.1 Literature Review

The full content of the literature review is given in [4], which presents the contents of this paper in greater detail. Here we present a summary of the review, focusing on the taxonomies which are of greatest interest and relevance to the development of a taxonomy for construction plant.

A key early development of a taxonomy for automation was the 10-point scale classifying the automation of undersea teleoperators, developed by [5]. In subsequent work [6] Parasuraman recognised that this taxonomy focused on decision selection and action implementation, and did not fully describe the capabilities of the human information processing system. It was therefore proposed that the human information processing system could be abstracted to four classes of functions which could each be automated to different degrees: 1. Information Acquisition, 2. Information Analysis, 3. Decision and Action Selection, and 4. Action Implementation. However, no detailed taxonomy was developed to implement this proposal until [7], who used the 4-stage human information processing system as the basis of a taxonomy to describe automation of Air Traffic Control centres. This taxonomy acted as the basis for a simplified version which was presented in [8].

In [9] Clough presented a taxonomy for the operation of Unmanned Aerial Vehicles (UAVs), drawing on a very similar classification of human behaviour to that proposed above. However, this drew on the Observe-Orient-Decide-Act principles that were developed by John R. Boyd for combat principles and are summarised in [10]. Notably, the central tenant of Clough's taxonomy is that "if building machines to replace human capability, they should be understood in the same way we understand human actions".

Perhaps the most widely known taxonomy has been developed by the Society of Automotive Engineers (SAE) for use in describing Connected Autonomous Vehicles (CAVs) operating on the road network[11]. The basis of this taxonomy is conceptually different to other taxonomies, defining a dedicated driving task (DDT) comprised of two aspects of object and event detection and response (OEDR), and the lateral and longitudinal control of vehicle motion. The different levels of automation are achieved by incrementally handing control over each aspect of the DDT to an automated system from the human. The SAE taxonomy has two extensions to the DDT for higher levels of automation – the responsibility for safe operation of the CAV and the Operational Design Domain (ODD), which define the constraints in which the CAV can safely drive without human intervention.

2.2 Basis for the Development of the Taxonomy

Construction presents unique challenges that make it particularly challenging for introducing automation. A large proportion of these challenges feature in the complex ODDs in which plant typically operate:

- Construction sites are of variable size and form which are typically not designed for plant to be there (in contrast to the road environment for CAVs).
- Construction sites are exposed to external uncontrollable factors.
- Operations are regularly concerned with modifying the environment in some way.

This is explored more fully in [4]. In addition to these challenges, the range of tasks which construction plant are expected to perform is significantly more complex than other industries and it is more typical for plant to be augmented with after-market systems which modify its performance in some way. As such, we have developed a more granular taxonomy to accommodate these differences.

In developing the taxonomy for the automated capability of plant, three aspects of the above taxonomies were identified and utilised. Firstly, we adopted the same central tenant as Clough and developed the taxonomy on the basis of the 4-stage human information processing loop (hereafter referred to as the Observe-Understand-Decide-Act (OUDA) loop), with some slight modifications to terminology for clarity. We refer to this as a loop because it happens continuously as we (or a machine) interact with our environment to achieve a particular task, see Figure 1. This task can be considered from a strategic level, which may feature a small number of these loops, or from a very detailed, immediate activity level where hundreds of these OUDA loops are occurring in quick succession (or indeed quasi-simultaneously). It is important to note that the 4 stages are an abstraction to aid in understanding the concept and may not be how an automated machine is implemented – some aspects may be combined or hard coded and some aspects may not be explicitly defined. However, the abstraction is conceptually useful for discussing how different kinds of automation might be implemented, and the automated capabilities different systems might achieve. It is also the case that the validity of subsequent stages is dependant on information available in the previous stages and that subsequent stages cannot rely on more information than is available in the previous stage. The levels are also asymmetrical, meaning capability comparisons cannot be made between equally levelled stages, that is to say, a level 2 understand stage does not equate in automation to a level 2 act stage.

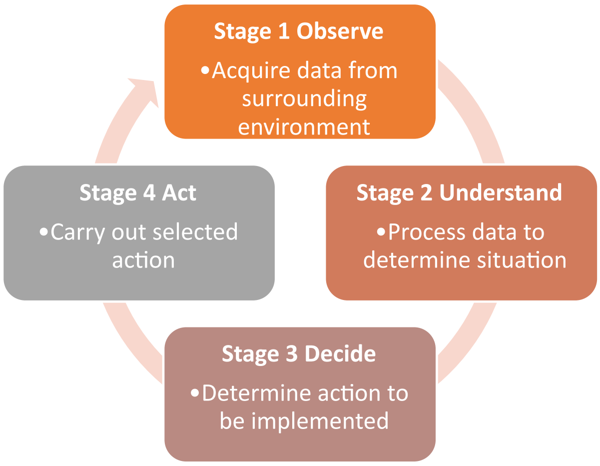

Figure 1. Stages of the human information processing loop [6, 10]

The second area included in the development of the taxonomy is the need for an explicit classification of Fallback and Responsibility. This is of critical importance to the construction industry, where plant is being operated in complex environments with a mix of other vehicles and pedestrian workers. A clear taxonomy for Fallback and Responsibility defines who or what is responsible for the safe operation of the plant and who or what is expected to respond to any unexpected incidents or changes to the operating conditions of the plant. This provides a clear understanding to plant operators and site managers about the safety conditions that need to be established so that plant of particular capability can be deployed on a given site.

A final area, which is important to consider when defining a taxonomy, is the influence of the Operational Design Domain (ODD) on how the taxonomy can be applied. In simple terms, the ODD defines the conditions, both physical and digital, in which the plant can perform at its expected level of automation. It is worth noting that the ODD is a property of both the automating system and the system being automated. That is, the computer controlling the machine has some conditions in which it can safely control said machine, as well as the machine itself having some conditions in which it can operate, even if it was a human controlling it.

In the SAE taxonomy for CAVs operating on the road network there is no explicit discussion of ODD – it is either limited (i.e., there are some constraints on the system's ability to replicate human driving ability) or it is unlimited (i.e., there are no constraints on the system, and it can replicate or exceed a human's driving ability in all conditions in which the vehicle itself can operate). However, this simplification was felt to be inappropriate for the construction industry due to the highly complex nature of construction sites in comparison to the road network . Hence whilst CAVs are designed to operate in an environment which has been created for their operation, CAP will operate in environment which are not tailored for it. In [4] a more explicit discussion of ODD is included, alongside a detailed consideration of what physical and digital parameters should be included when defining the ODD of a particular piece of plant. The following sections describe the resulting taxonomy for automated plant developed in this work.

3 Taxonomy for the Automated Capability of Plant

3.1 Stage 1: Observe

Observing is the act of acquiring information (Observations) on the current situation from the surrounding environment through various sensing organs / sensors and through any existing communications channels. The taxonomy is presented in Table 1.

Table 1. Participation of human and system for each level of Automation for Stage 1: Observe

Level	Name	Sensor
0	No Automation	Human
1	Partial Automation	Human & System
2	Full Automation	System

3.2 Stage 2: Understand

After the observations on the surrounding environment and current situation are acquired through the Observe stage, this data must be processed to develop an understanding of the situation. To accommodate the different aspects of the Understand stage we consider three components, *Compare, Predict, and Learn*, defined as:

- *Compare:* Understanding the current state by comparing the Observations to existing values and thresholds.
- *Predict:* Understanding the future state through a pre-defined model against which the Observations are applied.
- *Learn:* Understanding the future state by learning from the outcomes of past Decisions and Actions and applying this.

We include both prediction and learning to provide the potential for operatives and systems to develop their skills. The taxonomy is presented in Table 2.

Table 2. Participation of human and system for each level of Automation for Stage 2: Understand

Level	Name	Compare	Predict	Learn
0	No Automation	Human	Human	Human
1	Automatic Comparison	Human & System	Human	Human
2	Automatic Prediction	Human & System	Human & System	Human
3	Full Automation	System	System	System

3.3 Stage 3: Decide

In the Decide Stage the outcomes of Understanding are used to develop a set of possible actions that could be carried out, and a Decision made on which action to select. Hence Decide contains three components – *Generate, Select, and Inform* - defined as:

- *Generate:* The creation of a set or list of possible actions based on the understanding of the situation (from the Understand stage).
- *Select:* The choice of one of the actions. This can be an unrestricted selection (pick any option, or even an option not presented as part of the Generation step, i.e., can go off-list - an Open List) or a restricted selection (choose an option that was presented as part of the Generation step, i.e., cannot go off-list - a Closed List).
- *Inform:* Provide awareness to the party responsible for approving and/or implementing the selected action.

It is important to note the generation of a list of actions is unlikely to be explicit in most implementations of an automated system, but it is a useful concept to differentiate the different levels of automation. The taxonomy is presented in Table 3.

Table 3. Participation of human and system for each level of Automation for Stage 3: Decide

Level	Name	Generate	Select	Inform
0	No Automation	Human	Human	Human
1	Open List	System	Human	Human
2	Closed List	System	Human	Human
3	Informed Selection	System	System	Human
4	Full Automation	System	System	System

3.4 Stage 4: Act

The selected Decision must be implemented through Action. To assist in understanding the roles of the human and the system at each level of automation within the Act stage, we consider two components:

- *Implementation:* The party which initiates and carries out the action selected at the Decide stage.
- *Monitoring:* The party which ensures that the action selected at the Decide stage is being carried out as intended.

The taxonomy is presented in Table 4.

Table 4. Participation of human and system for each level of Automation for Stage 4: Act

Level	Name	Implement	Monitor
0	No Automation	Human	None
1	Automated Guidance	Human	System Guides Human
2	Automated Intervention	Human	System Restricts Human
3	Supervised Automation	System	Human Monitors System
4	Full Automation	System	System

3.5 Fallback and Responsibility

The concept of Fallback and Responsibility underpins the information processing chain. We define these as:

- *Fallback:* Who or what ensures that, when the plant suffers from a component failure, encounters an unexpected situation, or leaves its Operational Design Domain, it either continues to operate or fails in a safe manner.
- *Responsibility:* Who or what ensures that the task is being carried out (either manually or automatically) in a safe and proficient manner to the desired quality.

It is possible for each component of the information processing chain to feature different levels of automated fallback and responsibility, which would create a complex classification system. To simplify this, the lowest level of automation of fallback and responsibility can be used to indicate the level of human responsibility expected. To describe the taxonomy for fallback and responsibility, we have considered there to be two aspects of fallback and responsibility which can be automated - *Judgement and Intervention*, defined as:

- *Judgement:* Who or what decides when the plant has entered a situation which is not within the ODD of the plant.
- *Intervention:* Who or what takes over the operation of the plant when it has a entered a situation which is not within the ODD of the plant.

The taxonomy is presented in Table 5.

Table 5. Participation of human and system for each level of Automation for Fallback and Responsibility

Level	Name	Judgement	Intervention
0	Human Monitoring	Human	Human
1	Human on Request	System	Human
2	System	System	System

3.6 Combining the Individual Taxonomies

In the above, we have established a taxonomy for each stage of the OUDA loop and for Fallback and Responsibility, (together referred to as OUDA-R for simplicity) for CAP. These have been discussed as separate, standalone classifications such that each could be independently automated. However, when applying these to a particular piece of plant they would interact, with each stage having implications for future stages.

A simple example is that of undertaking the Observe stage with a level 0 system. Here no observations are made by autonomous components, and hence it is not possible for any meaningful level of autonomy to be applied to the Understand, Decide, and Act stages. This can be generalised to a useful principle for determining if a particular combination of levels is allowed – information collected and used at each stage must be passed to the relevant party for that party to remain involved in the processing loop in subsequent stages. In simpler terms, this means that if a human or automated system is not involved at an earlier stage then this party should not be involved in subsequent stages.

4 Application to Example Plant

We have selected two types of existing technology to demonstrate the potential application of each of the taxonomy components described above. We have chosen to focus on two example compactors, as this is a relatively simple construction activity which primarily involves controlling a plant to operate within a defined area to achieve a target amount of compaction. In contrast to an excavator, the way in which a compactor interacts with its environment is much simpler, as the compactor does not add or remove material. As such, automation within the compaction space is more easily achieved than other construction tasks.

4.1 Robomag

Figure 2. BOMAG Robomag Autonomous Roller

The Bomag Robomag, Figure 2, is an autonomous roller which can be deployed without a manual operator to carry out a pre-defined compaction task which is specified in the design documents uploaded to it. The Robomag operates within a geofenced area, determining how to achieve the target level of compaction in a safe manner and provides a continuous record of how this task was completed.

Observe ***Level 2*** - Robomag is equipped with GNSS, LIDAR and stereo cameras to allow it to observe it's environment in high-fidelity automatically. It also has drum sensors and other proximity sensors for collision avoidance.

Understand ***Level 2*** - Robomag uses observations to understand its environment automatically. For example, the GNSS receiver enables the machine to understand its position within a geofenced site area, the drum sensors provide automated understanding of stiffness.

Decide ***Level 3*** - The machine calculates the most efficient way of completing pre-set tasks within the geofence and begins operating, a manual route override is available prior to tasks beginning.

Act ***Level 4*** - The machine implements the predefined compaction task, without the ability to override these operational inputs. Utilising interpreted data from drum sensors, Robomag automatically adjusts compaction force for consistent stiffness, increasing for soft spots and decreasing for hard spots.

Responsibility ***Level 2*** - The machine is responsible and capable of maintaining its safety without intervention from a human.

4.2 CAT Command for Compaction

Figure 3. CAT CS56B Compacter

The Cat CS56B, Figure 3, is an example of a standard compactor which has been augmented with an automatic system to achieve compaction, the CAT Command for Compaction package. This enables a human operator to define a target area by driving the compactor to each corner of the space, set a target compaction value or number of passes, and record a driving line which the automated system will replicate until the target is achieved.

Observe ***Level 2*** - The CAT CS56B contains all required sensors including dual RTK positioning and radar object detection to allow the vehicle to run in AUTO mode, but requires a human to observe the environment for safety reasons.

Understand ***Level 2*** - The system uses observed parameters to understand all environmental parameters required to complete the compaction task.

Decide ***Level 3*** - The operator inputs an overall task and the system assesses if it is able to run in AUTO mode to achieve this task by deciding what actions are necessary. If the systems are operating as normal, the machine will carry out its task until completion.

Act ***Level 3*** - The machine implements the input compaction task. The difference to Robomag, and hence its lower level, is that this machine is being more closely supervised. The operator must react to system messages to continue in AUTO mode.

Responsibility ***Level 1*** - The system is responsible for maintaining the safety of the machine in AUTO mode; however, it will ask for human intervention where required.

5 Discussion

The experience gained in applying the taxonomy to example plant has shown that there is a need to be clear on whether the levels describe a subsystem, or the system (plant) as a whole. It is possible for a specific subsystem of plant to be very highly automated and hence score highly, but this may not apply to the entire machine. When classifying item of plant it is important to clearly convey what is being assessed for its automated capabilities. When considering the classification of plant holistically, we recommend labelling it as the lowest scoring combination of the considered subsystems as this will overestimate the role of the human operator. This is beneficial in the construction environment where safety is the paramount factor.

A concept related to this is that the taxonomy has been developed for application to specific pieces of plant, but it would be equally possible to consider automation as being a property of the task to be completed. That is, there may be benefit in assessing the degree of human involvement required to successfully implement a particular construction task, no matter the number of machines involved in achieving this.

We also note that in the above examples both of the compactors score relatively highly within the taxonomies. This is partly due to the specific and narrow scope of the operations the compactors are expected to perform. Focusing on specific types of task could enable OEMs to develop highly automated systems, as the expected ODD and task requirements are well understood. In contrast an excavator, for example, undertakes a wide range of activities, which presents a greater challenge for OEMs to overcome when developing automated systems. Thus, as the use of automated technologies expands on construction sites we might expect the initial applications to be in the more achievable areas.

It is also worth noting that although a system may score highly against the OUDA-R taxonomy this does not imply that it would be a ‘good’ system for use within a given site. There are two elements to this. Firstly, although a system may be highly automated it may have significant mechanical or operational deficiencies when used in a particular environment that renders the machine unsuitable for deployment. Secondly, a high level of automation may not be the best way of achieving some tasks – automation is best suited for highly repetitive, precise tasks which suit computerised control, whereas human control allows for highly adaptive and responsive operations to be implemented.

Finally, we have discussed above the Roadmap for CAP, and its milestones. The Roadmap suggests that the implementation of CAP could be encouraged through both technical and commercial development. Hence, in addition to supporting a common language across automated technology in CAP, the levels could help to provide a common language for use in contracts that aim to encourage deployment of automated construction techniques. Our examples suggest that this will require care to ensure that contractual requirements are staged to match the technological capabilities to the defined construction activity - the levels provide the tools to support this.

6 Conclusion

This paper has presented the development of a new taxonomy for classifying the automated capability of plant, and the resultant definitions of each level within the taxonomy. The levels have drawn on previous experience in other industries, refined and adapted to meet the needs of autonomy in construction. This has lead to a four stage process plus a fallback stage (OUDA-R). An initial peer review of the levels carried out in the stakeholder workshops and feedback received during the launch has suggested that the proposed approach should be both practical and understandable to the industry. To demonstrate application we have applied the taxonomy to two different compaction systems to show how an assessment of automated capability could be carried out, and discussed the challenges associated with such an assessment. These levels can be utilised by industry to greatly improve information transfer when discussing and considering automation of plant. This will support and catalyse the development of technology roadmaps amongst plant and technology manufacturers, enable procurement processes that incentivise the deployment of CAP within construction management, and support innovation practices by providing an understanding of the safety and operational implications of deploying automation on construction sites.

The proposed taxonomy must be applied by industry to provide an understanding of the functional suitability of the taxonomy, so that it can be refined. Industry would also benefit from considering what approaches to automation will be adopted, and if there is a need to develop further taxonomy for the automation of tasks. As identified in the Roadmap [2], there should be no delay to adoption of CAP technologies and supporting work such as presented here, as this may reduce 2040 savings by over 50%.

7 Future Work

Future work for the authors, National Highways, and wider industry is to deploy the taxonomy across a wide-range of construction sites to begin tracking autonomous capability of multiple machines at scale. From this key performance indicators (KPIs) can be created and then CAP expectations and mandates made into contracts to affect these KPIs. Additional work has already begun with standardisation bodies (BSI/ISO) to ensure the taxonomy can be ratified at a larger scale as well as influence other standards. A method of certifying plant against these levels may also be explored to reduce duplication of effort as well as ensure uniformity and fairness in scoring.

Although the taxonomy was developed for use within the construction industry, there is no fundamental aspect which restricts its use to the construction sector. As part of the refinement process, understanding how it applies to other sectors and its utility beyond the construction sector will be explored. This is of particular relevance to industries which also make use of heavy machinery such as mining or agriculture.

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