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A NOVEL INTEGRATED APPROACH TO PROJECT-LEVEL AUTOMATED MACHINE CONTROL/GUIDANCE SYSTEMS IN CONSTRUCTION PROJECTS

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SUMMARY: *The current research aims to further investigate the application of Automated Machine Control/Guidance (AMC/G) in construction projects and proposes an integrated approach for: (1) Improving the administrative infrastructure required for the optimal application of AMC/G; and (2) Orchestrating the machine-level AMC/G technologies into a coherent project-level system committed to the coordination of operations towards the overall project objectives. Based on the importance of 3D design models and Digital Terrain Models (DTM) as the basis for contracting AMC/G projects, a new work and information flow is proposed and its contribution towards streamlining the utilization of AMC/G is scrutinized. Furthermore, by integrating AMC/G technology with a multi-agent architecture encompassing several project stakeholders and real-time simulation, a novel approach is introduced to increase the safety and productivity of the entire project.*

KEYWORDS: *Automated machine control, Administrative process re-engineering, Multi-agent system, real-time simulation*

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1. INTRODUCTION

Improving productivity and safety of construction projects is among the main priorities of the construction industry (Beavers et al. 2006). New tracking technologies are providing tools for improving productivity and safety by enabling on-site data capture and decision making using the Global Positioning System (GPS), Real-Time Location Systems (RTLSs), and other geo-positioning technologies (Perkinson et al. 2010). These tracking technologies are integrated with 3D design models and Digital Terrain Models (DTMs) in two modes: (1) Automated Machine Guidance (AMG): which supports the machine operator through the provision of continuous guidance on a digital screen mounted in the cabin of the machine, or (2) Automated Machine Control (AMC): where the position, elevation, and orientation of an earthwork machine, such as a grader, are measured using GPS and/or other types of sensors, and used by an on-board computer to control the position of the blade of the machine, eliminating the need for staking or other manual measurements. AMC/G are used mainly in earthwork projects but can be also used in lifting and paving operations, and building curbs and gutters (Peyret et al. 2000). In the rest of the paper, we will refer to these two modes by AMC/G for brevity.

Previous research has indicated that AMC/G has the potential to improve the overall quality and efficiency of construction projects and to enhance the ability of transportation agencies and contractors to deliver projects safer, faster, and cheaper (Dunston and Monty 2009; Frantzen at al. 2010; JCMMRI 2012; Peyret et al. 2000; Rausch et al. 2010;Vonderohe 2009). Results from these researchers claim that AMC/G can lead to productivity increases of 15-30% and a total cost saving of 4-6%. In spite of the benefits of AMC/G, their usage is still limited to large projects. There are several challenges that have to be overcome in order to maximize the benefits of using this technology in the 3D surveying-design-contract-construction-inspection workflow (Dunston and Monty 2009; Torres and Ruiz 2011; Vonderohe 2009). These challenges can be classified as: (1) Technical, such as the accuracy and interoperability of the DTMs, 3D design models, and equipment tracking; (2) Administrative, such as formalizing the provision of 3D models and the responsibilities and quality standards related to their usage; and (3) Financial, such as the initial cost of the hardware and software, and the cost needed for developing 3D models.

Therefore two main problems have been identified with regard to the application of AMC/G. Firstly, there are administrative shortcomings that barricade the smooth application of AMC/G in the construction projects; and secondly, the current application of the AMC/G is limited to machine-level productivity optimization which is not sufficient to address the project-level monitoring and decision-making needs.

In our previous research, we have investigated the concept of the Smart Construction Site (Zhang et al. 2009) where workers, equipment, and materials are continuously tracked. The collected information is processed in near real time to update the as-built model and the simulation of upcoming tasks, and to provide navigation guidance and safety warnings in case of potential collisions of cranes. The present research proposes adding intelligent decision-making at different operational and managerial levels of heavy construction projects. This will help overcome some of the above challenges, resulting in an overall improvement in productivity and safety.

The objectives of this paper are: (1) To review the state-of-the-practice and state-of-the-art of the usage of AMC/G and related technologies proposed in this research; (2) To propose a high-level system design of a Multi-Agent System (MAS), integrated with Real-Time Simulation (RTS) to coordinate AMC/G site operations and resolve operational and managerial conflicts; and (3) To demonstrate the potential benefits of the proposed approach using a case study.

2. LITERATURE REVIEW

2.1 Automated Machine Control/Guidance (AMC/G)

The advances in GPS technology have induced significant research on the application of the GPS for automation of construction equipment in pursuit of increased productivity, improved safety and reduced costs. AMC/G is a broad technology which encompasses several issues at the technical, data and organizational levels. On the technical side, AMC/G addresses issues concerning planning, implementing and monitoring of the movement of machines between two spatial points, which in robotics and machine control are referred to as path and motion planning (LaValle 2006). The second aspect of AMC/G is data provision and processing which comprises data inputs about the topography of the site and the geometry of the objects on the site. Finally, at the organizational level, for AMC/G to be effectively utilized, a streamlined workflow needs to be performed among the main stakeholders including the contractors, clients and designers.

Peyret et al. (2000) developed two separate systems for the real-time control and monitoring of compactors and pavers. These systems are designed to fulfill the dual objective of: (1) Assisting the operators in performing their tasks through the provision of real-time data; and (2) Helping the site managers in conducting quality control and analysis via collecting the spatio-temporal data of the operations.

Perkinson et al. (2010) proposed a framework to make use of GPS-collected data for enhanced management and decision-making purposes. The central objective of their methodology is to ensure that all the productivity-related data can be efficiently collected in the course of the project development and further used for planning, scheduling and control.

Several systems are under development to provide telematics information of the AMC/G equipment to and from a central office, job trailer and other equipment, such as the Connected Site and SiteLINK 3D (Noland 2010). Similar systems are already available in the surface mining industry (Jamasmie 2010). Machine-to-Machine (M2M), Machine-to-Office (M2O) and Office-to-Machine (O2M) communications allow for sharing different types of data, such as machine condition, location, productivity, work quality, and 3D design model updates.

Some governmental bodies and construction companies have started to appreciate the value of employing AMC/G in heavy earthmoving and road construction projects. For example, Wisconsin Department of Transportation (WISDOT) has conducted research on adopting regulations for the application of AMC/G in highway construction projects (Vonderohe 2007; Vonderohe and Hintz 2010). Their efforts are mainly focused on the implementation strategies for regularizing 3D design models and DTMs in their projects.

Duston and Montey (2009), in collaboration with Indiana Department of Transportation (INDOT), have also investigated the issues for streamlining the application of AMC/G systems focusing on: (1) Analysing the data needs and provision, (2) Investigating standards, codes and permission concerns, (3) Analysing the liability distribution and project information security, and (4) Reviewing implementation costs.

The benefits of employing AMC/G are manifold, although some obstacles caused mainly by the current state of the practice can be also identified. Table 1 summarizes the AMC/G perceived benefits and obstacles.

TABLE 1: Perceived benefits and obstacles of AMC/G implementation (adopted from Vonderohe and Hintz 2010; Jahren 2011)

Advantages
More accurate grading and smoother ride
Avoidance of re-work
Faster operations
Significant cost reductions
Improved safety of operations
Environmental-Fuel savings
Ease of constructability review
Less dependency on the operator's expertise
Reduced surveying and staking time/effort
Reduction in re-engineering from design to construction process owing to using 3D models
Reduced traffic interruptions
Safety of the traveling public

Obstacles
Lack of agency specifications
Lack of equipment
Lack of knowledge concerning benefits
Budgetary limitations
Conversion of paper plans to 3D models
File preparation to achievement of the appropriate model
Lack of competent personnel for implementation
Dependency on third-party consultants for DTM creation

Most noticeably, significant cost savings, faster operations and improved precision are identified as chief advantages of the AMC/G implementation. Similarly, the project could benefit from AMC/G through reduced dependency upon the expertise of operators, less time and effort required for staking and surveying, and less need for the design-to-construction process re-engineering. It is also reported that by virtue of faster operation, less interruption is made to the traffic. Despite these potentials, implementation of AMC/G is hindered by the lack of administrative regulations and lack of equipment as well as budgetary limitations. In addition, given that the technology is still under development, there is little awareness of the benefits of AMC/G amid stakeholders. Difficulty of converting the plans and preparing the model for AMC/G, lack of competent personnel and dependency on a consultant for DTM creation are also reported to forestall the implementation of AMC/G.

2.2 Administrative Infrastructure

In order to take full advantage of AMC/G technology, it is important for project owners to develop specifications for the use of this technology, and to require the contractors to follow those specifications. The specifications must cover: accuracy limits, quality control and quality assurance (QC/QA) procedures, risks allocation for errors, and payment mechanisms. Furthermore, there is a need to develop an implementation strategy for adopting this technology in construction projects. Vonderode (2007;2009) and Duston and Montey (2009) have reviewed the implemented measures and adopted practices of various DOTs in the US for accommodating AMC/G friendly administrative infrastructure. These reports cover the types of AMC/G equipment allowed by DOTs and address the subsequent liability and financial issues. It could be construed from these reports that the terms AMC/G and AMG are used interchangeably. However, the reports provide evidences suggesting that the DOTs are moving towards AMC, particularly with their numerous references to grading operations. Table 2 delineates the criteria which determine the variance in the practice of different DOTs. Table 3 summarizes the state of the practice and the administrative adjustments made towards streamlining the application of AMC/G in construction projects based on the above reports (Duston and Montey 2009; Vonderode 2007). It categorizes the DOTs' state of the practice into used technologies, obligations of the contractor, documents and data format provided by DOTs, liability issues regarding error correction and data adjustment, incurred costs and QA/QC. In Canada, according to our telephone interviews with most of the provincial ministries of transportation, including New Brunswick, Ontario, Saskatchewan, Quebec and British Columbia, although AMC/G is starting to be appreciated as a promising technology with palpable gains, there is a need for major actions towards the regularization of AMC/G in transportation projects.

As shown in Table 3, some DOTs are more advanced in terms of transition to 3D design models, and thus they provide a more AMC/G friendly workflow environment. For instance, DOTs of Indiana, Iowa, Minnesota and New York have managed to secure a level of flexibility which allows contractors to go beyond the recognized technologies and venture new methods. Iowa DOT has already mandated the use of GPS-based AMC/G for designated areas for which a AMC/G DTM exists. As for the development of the 3D models, some DOTs, e.g. Iowa and New York, have taken the responsibility to develop DTMs while in some other states, e.g. Montana, the contractor is required to develop the DTMs. Nevertheless, almost no state has gone far enough to be confident of the accuracy of their developed models, and therefore they all transfer the responsibility for the accuracy of the provided data and corrections to the contractors. Similarly, all states have established QC/QA regulations based on 2D data used for the contract and refrain from leveraging the 3D models as the basis for QC/QA.

TABLE 2: Administrative criteria for AMC/G implementation

Technology	Can AMC/G be implemented? Can other new technologies be utilized?
Documentations and Responsibilities	What documents does the transportation agency provide to the contractor? Who is responsible for the development of 3D design models? What documents does the contractor need to provide to the transportation agency? Does the contractor need to provide training on AMC/G equipment?
Liabilities	Who is liable for the errors in the 3D models? Who is bearing the costs for the errors and subsequent corrections?
Control	How the quality of the project is controlled? Who is providing the control points?

2.3 Multi-agent Systems (MAS)

The concept of agents comes from developing thinking machines with the capability of solving problems (Shoham and Leyton-Brown 2009). Agents are relatively independent and autonomous entities that operate within communities in accordance with complex modes of cooperation, conflict resolution, and competition in order to survive and perpetuate themselves (Russel and Noryig 2003). Agents are capable of perceiving their environment, but only to a limited extent. By exchanging information and coordinating with other agents, they can acquire more information about the environment and make better decisions that maximize their own utilities. There are several ways of planning for MASs either in a centralized or distributed manner (Durfee 1999). The centralized method treats the entire team as a single complex agent and then generates plans for this agent, whereas the distributed method generates plans for individual agents and uses coordination techniques to combine these plans. Each agent can generate a partial plan independently and the coordination of these partial plans can be centralized or distributed to form a single coherent overall plan (Shoham and Leyton-Brown 2009). The use of MASs to address the challenging problems in construction sites has not been deeply addressed yet.

2.4 Real-time Simulation (RTS)

Simulation models provide the ability to capture the complexity of construction operations beyond simple mathematical formulation and have been used to analyse construction operations on a limited scale. Usually, those models are used at the planning phase to evaluate alternative construction scenarios (Lu et al. 2007). An astonishing productivity improvement of 30% to 200% by virtue of applying simulation in various types of projects is reported in (Halpin and Martinez 1999). Zayed and Halpin (2001) implemented Discrete-Event Simulation (DES) for the study of concrete batch-plant operations. Hassan and Guber (2008) approached investigation and optimization of Continuously Reinforced Concrete Pavement (CRCP) operations through computer simulation. Halpin and Martinez (1999) developed a Cyclone-based model to simulate the construction of breakwaters and wharves using floating caissons as a real-world application of simulation techniques.

However, traditional simulation models use statistical data to estimate task durations. In order to make the simulation results more realistic and reflective of the changes during the task execution, RTS has been suggested by several researchers. Song et al. (2008) have described a framework of RTS for heavy construction operations. Real-time data and process knowledge are coupled to enable a self-adaptive modelling process that validates-

TABLE 3: State of the practice in implementing AMC/G in construction at DOTs in the U.S.A.

State	Used Technologies	Contractor's Obligations	Data Provision by DOT	Liability w.r.t. Data Accuracy and Adjustment	Costs	QC/QA
Florida	Designers can submit files using available formats	Not Available	Not Available	Not Available	Not Available	Not Available
Georgia	GPS AMC Supplementary laser guidance when required	Not Available	DOT provides electronic digital files in their standard format	Not Available	Not Available	Not Available
Indiana	GPS and Robotic Total Station AMC/G All new technologies upon review and approval	Development of required 3D models 8 hours of training on GPS/RTS and AMC/G system Provision of GPS rover, professional surveying services and grading plan	DOT provides 3D model for AMC/G if available	DOT is not responsible for the accuracy of provided 3D models	Not Available	Contractor provides adequate control point,
Iowa	Mandatory use of AMC/G for designated areas Unspecified types of AMC	AMC/G equipment acquisition Transformation of provided data to compatible formats Provision of GPS rover Daily inspection of AMC/G equipment Uncompromised accuracy Submission of a AMC/G work plan	Engineer provides localized coordinate system DOT provides CAD files, AMC/G DTM and alignment data	Contractor is responsible for the accuracy of provided data Contractor modifies provided electronic data Contractor assumes the risk of error when information is used out of intended context	Contractor bears all the costs The bid for AMC/G grading is measured and paid for at the lump sum contact price	Engineer sets initial control points Contractor provides control points and stakes at critical points, sets hubs at the required points and preserves all the reference points and monuments
Kentucky	Not Available	Requires certain EDFs with the Final plans	Not Available	Not Available	Not Available	Not Available
Maryland	GPS and RTS AMC/G	Provision of GPS rover 8 hours of training on GPS/RTS and the AMC/G system Provision of a surveyor to perform verification Submission of DTM to DOT Demonstrate the accuracy of the AMC/G system to DOT	DOT provides contract documents and DTM data	Contractor corrects all errors and adjusts the data to the satisfaction of DOT	Not Available	Contractor provides adequate control point, stationing and stakes and sets initial control points Contractor provides control points and stakes at critical points
Michigan	GPS AMC	Not Available	DOT provides design files for AMC	Not Available	Not Available	Not Available
Minnesota	GPS and RTS AMC/G All new technologies upon review and approval	Provision of RTS to DOT for control Notification about utilized AMC/G equipment within 15 days after award of the contract	DOT will provide 2D and 3D or DTM files upon contract approval	No guarantee for the accuracy of the provided data by DOT Change of the model is performed by DOT	DOT does not pay for the correction of errors No direct payment is made for AMC	Not Available
Missouri	GPS AMC	Development of required 3D models	Electronic digital files of plans and profiles needed for 3D models is provided by DOT	Not Available	Not Available	DOT has contractor staking procedure Check elevations are based on project plans
Montana	GPS AMC Supplementary laser guidance when required	Development of required 3D models Quality control on AMC/G use	DOT provides paper plans	No checking of the models by DOT	Not Available	Filed checks by radial survey DOT has quality specification on final product
New York	GPS AMC All new technologies upon review and approval	Mandatory use of the DOT's CAAD software Provision of Detailed contract control plan Provision of GPS rover	DOT provides 3D model for AMC	DOT has specifications on use of the model DOT has to approve any modification of the model	Not Available	Checks on originally-measured points Contractor and DOT use same documents for control
North Carolina	GPS AMC	Contractor develops 3D models from paper plans	DOT provides paper plans	Not Available	Not Available	DOT requires full staking
Pennsylvania	DOT has formulated some addendum to their publications	Not Available	Not Available	Not Available	Not Available	Not Available
Washington	GPS AMC	Not Available	Not Available	Not Available	Not Available	DOT provides surveying control Construction staking is done by contractor

-and refines a process simulation model. Compared with traditional simulation, RTS has the potential to improve the accuracy of performance forecasting while reducing modelling burdens on end users. Recent developments of RTS support decision making and control during project execution by overcoming some of these challenges (Zhang and Hammad 2012; Zhang et al. 2012; Zhang et al. 2011; Hammad and Zhang 2011; Lu et al. 2007). Using RTS allows for examining different courses of action (what-if scenarios) that a decision maker can take to correct the performance of a construction process and keep it on target in response to changes that happen on site.

3. PRPOSED APPROACH

To enhance the application of AMC/G in construction, we propose a two-dimensional approach. First dimension is concerned with the administrative process re-engineering which, in turn, aims to suggest modifications required to attune the underlying organizational and administrative processes to the AMC/G-assisted project execution. This dimension includes improvement of the work and information flow across the project lifecycle as well as legitimization of any new provisions that could be necessitated by the new technology.

Second dimension is devoted to further improving the safety and productivity of the construction operation by proposing an automated project-level organization for the application of AMC/G. This approach aims to orchestrate the machine-level AMC/G technologies into a coherent project-level system committed to the optimization of single operations towards the overall project objectives, with consideration of enhanced safety. Therefore, AMC/G is employed beyond the guidance and control of single on-site units, and transcends to an enabler for complex data handling and real-time analysis of operations. This approach is based on integrative application of a MAS architecture and RTS. The assumption of this approach is that all construction machines are equipped with GPS, or other positioning technologies, so that their spatial position and relative orientation can be continuously tracked.

3.1 Administration process Re-engineering

As explained in Section 2.2, although transportation agencies have started to appreciate the need for re-engineering their workflow for regularization of AMC/G in projects, the adopted measures are far from sufficient. The current workflow, for design-bid-build project delivery method, is schematically drawn using IDEF0, Integration Definition, process modeling platform as shown in Figure 1(a). The process is viewed from the perspective of a strategy planner who intends to examine the efficiency of the current process and look into how to improve the process in terms of reducing redundancies and re-work as well as streamlining the data exchange and re-formatting. The majority of U.S. transportation agencies we studied follow this workflow. A transportation agency approaches a designer for the design (A1 and A2 in Figure 1(a)), and, regardless of the availability of 3D models, will later use 2D design models as the basis for bidding (A3). Once a contractor is appointed to the project, most frequently, the contractor is required to develop and adjust the DTMs and 3D design models usable by the AMC/G technology of their choice (A4, A5 and A6). Subsequently, the contractor will create an AMC/G work plan, directly executable by machines, (A7). Using the work and control plans, the engineers and contractor will control the operation. To conclude the project, the final work needs to be checked and approved by the engineers of the transportation agencies (A9).

The current workflow involves a great deal of redundancy and re-work that could be removed. For instance while in some cases the designers develop a 3D model, only a 2D model is given to the contractor who has to re-develop the same 3D model. This problem could be resolved through re-engineering of the administrative process and transiting from 2D design models to 3D design models as the primary source of the design. In this fashion, the design company will be obliged to deliver to the client the required 3D models.

Other issues surrounding the use of AMC/G in construction projects in the current workflow are: (1) Transformation of 2D models to AMC/G operable 3D models is reported to be cumbersome, error-prone and time-consuming (Yabuki 2011;Vonderohe 2007); (2) Clear QC/QA for AMC/G enhanced project execution is missing, and the adopted transplantation of conventional QC/QA regulations involves deficiencies in terms of inadequate QC/QA plans for AMC/G assisted project executions; (3) By not clarifying the liability issues for design errors and subsequent data adjustments, or in some cases by transferring all the risks to the contractors, transportation agencies fail to provide incentive for contractors to implement AMC;

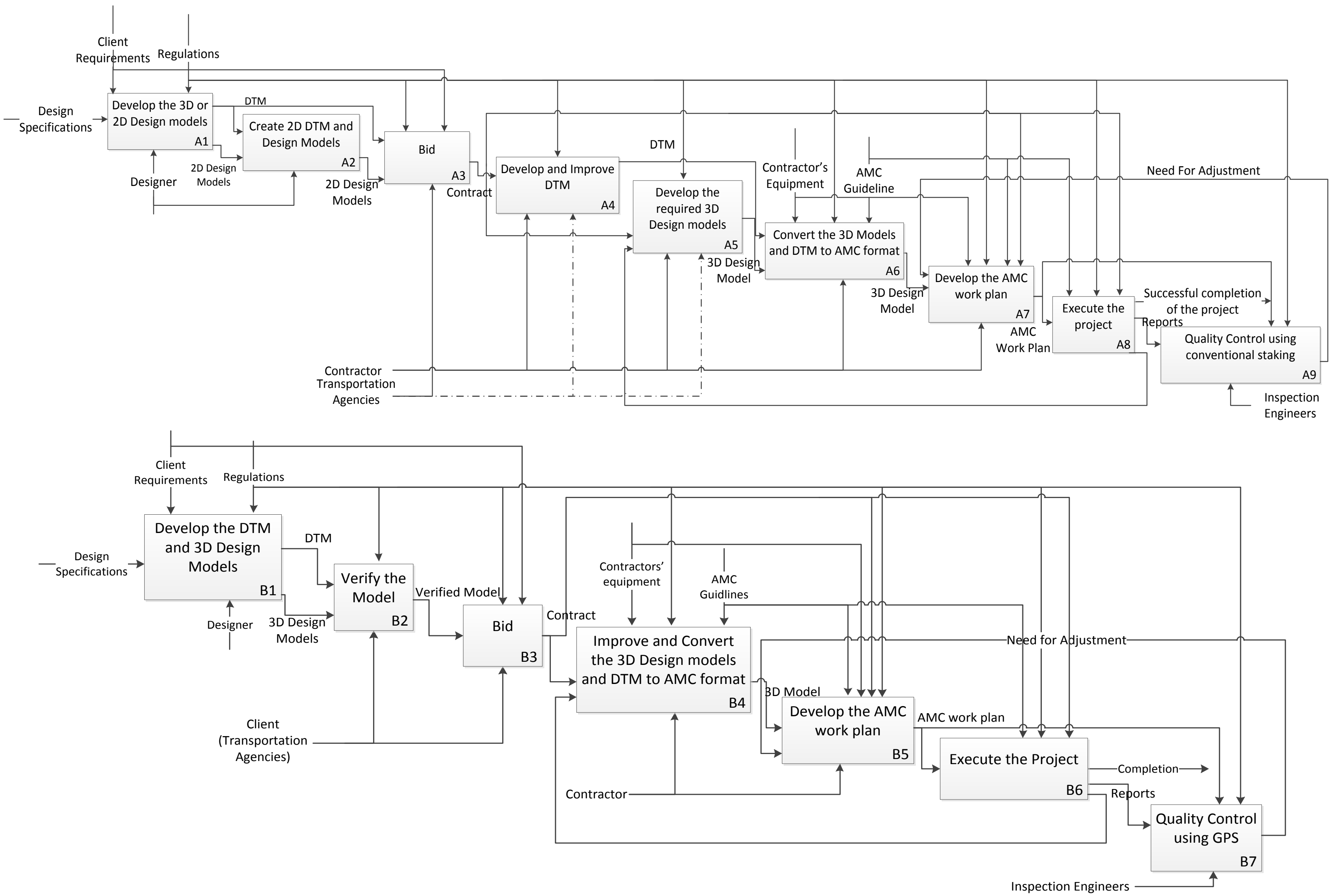


FIG 1: Current (a) and improved (b) workflows for application of AMC/G in transportation agencies using design-bid-build delivery method

(4) The lack of interoperability between different digital formats; (5) Security and ownership rights pertaining to the use of digital files are not properly addressed; (6) AMC/G tasks are susceptible to large errors due to the power vested in the technology; and (7) The data used for the execution of the project and further QC/QA are not unified.

Transition from 2D models to 3D models as the basis for contracting will contribute greatly towards the unification of documents used for execution and control. It is also recommendable that transportation agencies and engineers, investigating more meticulously the advantages of AMC/G, re-define the staking requirements and control plans for QC/QA purpose and harness the inherent power of new positioning technologies, e.g. GPS, towards QC/QA. Additionally, transportation agencies need to experience the use of AMC/G in projects more committedly so that they can reach to an articulation of responsibilities and liabilities that are more assuring to contractors. To resolve the ownership rights issues, it is proposed to utilize digital signature and data encryption scheme. This could be further enhanced through the implementation of version and change management using a unified data communication platform. It is noteworthy that the legitimization of the electronic exchange of data would allow better tracing and recording of the data exchange, and thus increase the security and ownership rights of digital files.

Incorporating the above consideration for improving the process, Figure 1(b) illustrates our proposed workflow for the application of AMC/G. It suggests that 3D models and DTMs, unlike the conventional method, could be used as the base documents for bidding (B1-B3). In this fashion, the contractor needs only to improve, i.e. increase the level of detail, and convert the data format commensurate with their AMC/G technology of choice (B4).

Further amelioration to the process is the deployment of GPS and other state-of-the-art positioning technologies for the purpose of staking and quality control (B7). This will help reduce the amount of effort and time required for QC/QA in the course and at the end of the project. Another measure that is incorporated in the improved workflow process is the inclusion of a verification phase prior to handing over the documents to the contractor (B2). This practice would allow the engagement of transportation agencies more actively and committedly in the process, and thus offsetting the liability distribution amid major stakeholders. As shown in Figure 1(b), the proposed improvement will shorten the process by two blocks, which represents a considerable level of smoothening.

While Figure 1 schematizes the process for design-bid-build delivery method, we can further explore the improved process for the design-build delivery method. In this mode, the design and construction of the project will be assigned to the same entity. This will greatly help reducing the problem of interoperability as companies could confidently use their own standard for the entire process. The process model for this mode of project delivery is shown in Figure 2.

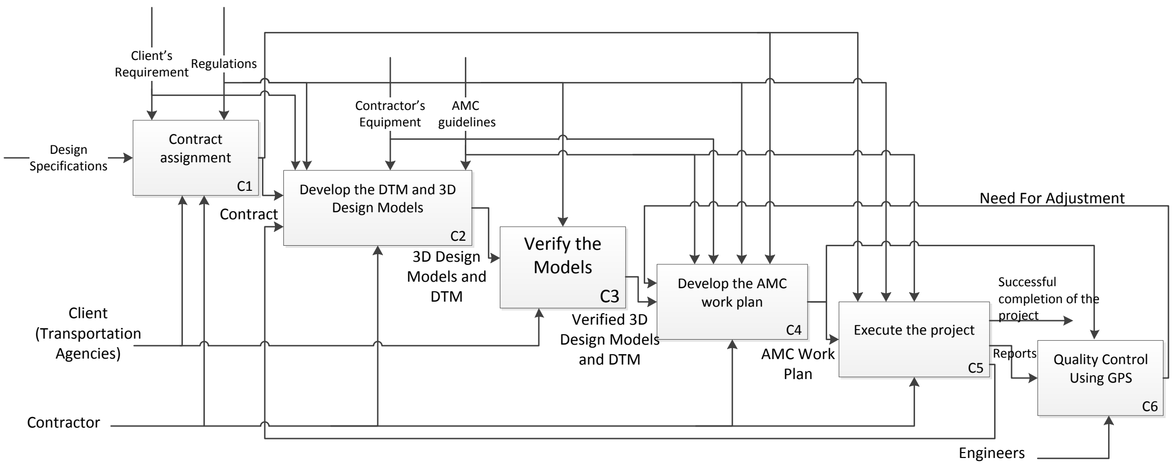


FIG 2: Improved workflow for application of AMC/G in transportation agencies using design-build delivery method

A more futuristic vision of administrative process is to exploit a MAS structure. In this setting, every involved stakeholder is represented by an agent in the MAS. The agent system, using the power of MAS in coordinating communication, collaboration and negotiation of diverse players, would help smooth the data and information flow. Agents would monitor the data exchange in terms of compliance with the receivers' required data conditions, capacity, format, and delivery timeframe. In cases of conflicts, the agents could embark on negotiations and identify the most economic concession strategy to resolve the problem.

It is worth noting that 3D models will offer increased accuracy of any cost estimations to be performed throughout the process, be it by the contractor or transportation agencies. Conventionally, average-end-area method is used to calculate the earthwork volume and cost, which is based on the averaged area between two successive cross-sections multiplied by the distance between the cross sections in the interval ascertained by the required level of accuracy. However, the development of 3D models would allow transit to the surface-to-surface (S2S) method which offers greater accuracy (Vonderohe and Hintz 2010) at no extra cost and in shorter time (Yabuki 2011). S2S method is based on the matched triangulation of the two surfaces, as-is and as-designed, and the calculation of the volume of the triangular prisms formed by connecting the equivalent corners of the triangles from the two surfaces.

The proposed administrative process re-engineering, where 3D models are used as the basis for contracting, adds the following benefits for using AMC/G technology: (1) Eliminating redundancies and rework of 3D models, (2) Faster and easier quality control, (3) Reduced interoperability problems, especially when design-build project delivery method is used, (4) More accurate cost estimations, (5) Better tracking of changes, (6) More balanced liability distribution in light of more engagement of transportation agencies, and (7) A better life-cycle usage of 3D models in the operation and maintenance phases.

3.2 Architecture of the Proposed MAS

A multi-layer agent architecture is proposed in which agents supporting the operators of single machines constitute the lowermost layer of the agent hierarchy. These agents process and manage the huge amount of collected sensory data into useful information that can be used in decision making at different operational and managerial levels. Figure 3 shows a simplified version of the proposed MAS architecture where several teams are working in proximity to each other. Four functional components could be distinguished according to the distribution of the responsibilities:

(1) Coordinator Agents: Coordination encompasses agents representing site coordinators. Within this component, two types of agents are distinguishable, namely the General Coordinator Agent (GCA) and Team Coordinator Agents (TCAs).

The coordination agents make critical decisions, e.g. new work plans or command for suspension of the operation, using data from all other components, and further communicate their decisions with the appropriate Operator Agents (OAs) for the execution. Essentially, this component consists of GCA and TCAs. However, depending on the characteristics of the project, the phase of the project and simultaneous operations, several teams and sub-teams can be formed. Each team is coordinated and supported by a TCA. The role of a TCA is to assign tasks to the subordinate OAs or sub-TCAs and to collect information from them. The TCAs also communicate the necessary re-planning decisions from and to the OAs and the GCA. Other example tasks of a TCA are: (a) Checking the equipment utilization and planning maintenance schedules at the team level; (b) Managing load counts, cycle times and utilization in order to optimize performance (e.g., estimated arrival times, travel times, and on-road times for permitting requirements); and (c) Giving safety warning to nearby agents when a potential collision is detected.

The GCA is responsible for monitoring and controlling the tasks at the project level to insure the smooth performance of the operations of all teams. For this purpose, the GCA interacts with the RTS component and communicates its results to the TCAs. Example tasks of the GCA are: (a) Analyzing the equipment utilization and productivity at the project level; and (b) Checking and controlling subcontractors' activities. Upon the detection of any organizational conflicts (e.g. transfer of wrong data format) or operational (e.g. time-space overlap of activities) by a TCA or an OA, the GCA generates several alternative scenarios by modifying the resource allocations and/or activity sequences, and in collaboration with RTS, identifies the most economical alternative.

(2) Operators' Agents: the lowermost agent layer in the hierarchy of agents is OAs. These agents support the operators of each machine to accomplish their tasks. As described in Section 2.3, agents are self-contained entities that have knowledge about the state, interests and objectives of the real-word objects they represent. Essential to the real-time decision making performed by the MAS is the updated understanding of agents about their own states and the environment, or in other words context-awareness. Given that all pieces of equipment are equipped with GPS and various other types of sensors, e.g. accelerometers and angular sensors, OAs can use accurate location and sensory data to determine not only their precise location but also the pose of the equipment. The pose of the equipment refers to its orientation and position resulting from the change of the geometric relationships of its various rigid components along the different degrees of freedom (DOFs). As will be explained in Section 3.3, the information about the pose of the equipment can be used to identify its state. Example tasks of an OA are: (a) Providing a path to control a machine based on the DTM, the 3D design model, location of subsurface utilities, and the kinematics and engineering constraints of the machine; (b) Collecting data about the work done by the machine and reporting to the respective TCA; (c) Checking the equipment utilization; and (d) Managing the compliance of operators and drivers with regulations (e.g., on road speeds, uninterrupted hours of operation).

(3) Information Agents: This component is in charge of handling the information required for machine control and encompasses Site State Agent (SSA) and Design Document Agent (DDA). The SSA provides information about the site (e.g. the DTM obtained by Light Detection and Ranging (LIDAR) scans), as the ingredient for the decision-making done by the coordinator agents and the forecasting performed by the RTS. The DDA furnishes the 3D design models and updates them should any changes be made in the course of the project. Given the responsibility of DDA and the diffused nature of information sources in construction projects, DDA domain could be further expanded to incorporate administrative applications of the MAS. In this sense, agents representing stakeholder (i.e., contractor, client, designer, etc.) interact with the DDA and contribute to providing the right design documents to the coordinator and operator agents and the RTS.

(4) Real Time Simulation (RTS): The RTS is responsible for the calculation of the productivity rates and durations of forthcoming construction activities using simulation methods based on real-time information gathered from agents. This responsibility includes forecasting the productivity of different operations, given the planned resource allocation scheme and work settings. In addition, the schedules resulting from the RTS can be integrated with the 3D model to create 4D models that can be used to detect spatio-temporal conflicts among concurrent tasks (Hammad et al. 2012; Mawlana et al. 2012). The outcomes of the RTS are communicated with the coordinator agents for analysis and decision-making.

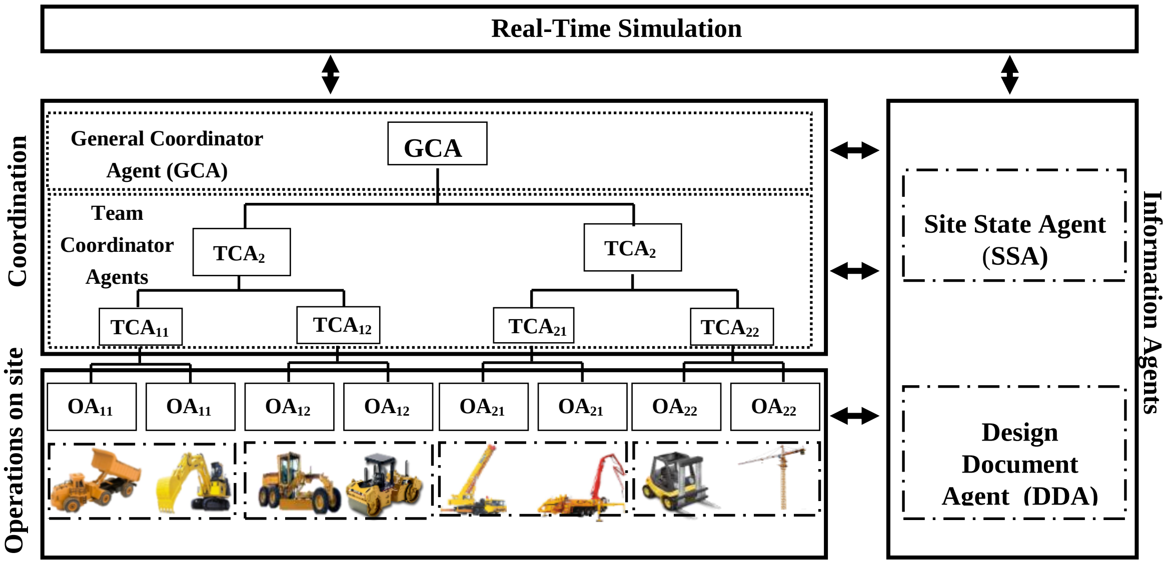


FIG 3: Simplified MAS Architecture

It should be emphasized that the role of agents is to support the decision-making process and not to replace human operators and coordinators. In this sense, agents present the required information to the users based on their roles and the context of the information using different levels of detail. For instance, the display unit mounted in the cabin of the construction equipment is used to display the path of the blade of the machine and the sequence of movements the machine has to follow. However, the display unit at the management office is used to display the productivity curves of the machines, the maintenance and fuel requirement of machines, the delayed activities, etc.

3.3 State Identification by Agents

In the proposed framework, updated information about the site is available by SSA and DDA, who monitor the progress of the project and keep track of environmental and geometric changes in the site. However, it is essential for agents to have the precise knowledge of their own state in real-time so as to enable unilateral and multilateral decision making.

For this to materialize, each OA needs to have a knowledgebase exclusively tailored for each type of equipment that encapsulates the rules to transfer the location and time data into meaningful information about the state of the equipment, i.e. the phase in the operation in which the equipment is engaged. A knowledge-based system uses rules based on the concurrent consideration of the pose data of the different equipment to infer the state of each piece of equipment. For some equipment, it is required to identify the zone within which the equipment is operating. Zones are defined as areas outlined by virtual geo-fences within which certain tasks are expected to be executed. For instance, knowing the site layout, it is possible to outline the areas for loading, hauling, dumping and returning of the truck. The rules in the knowledgebase combine the result of the zone-detection with other parameters, such as speed, to perform the state identification. For instance, in a simple loading-hauling-dumping operation, for the truck to be identified in the loading phase, its corresponding tags need to be identified in the loading zone, they have to be the closest to the excavator and the truck's velocity needs to be zero. Table 4 tabulates the state identification rules used for the truck and excavator OAs in a simple earth-moving operation.

TABLE 4: Rules in the knowledgebases of the truck and excavator OAs

Equipment	State	Identified Zone	Dynamic Variables	Identification Rule
Truck	In Loading queue	Loading	Velocity, Distance to the excavator	The truck is in the loading zone but it is not the closest truck to the loader and its velocity is zero
	Waiting for loading	Loading	Velocity, Distance to the excavator, State of excavator	The truck is in the loading zone, it is the closest to the loader and its velocity is zero but the excavator is not in dumping
	Start of Loading	Loading	Velocity & Distance to the excavator	First reading of the Loading state
	Loading	Loading	Velocity, Distance to the excavator, State of excavator	The truck is in the loading zone, it is the closest to the loader, its velocity is zero and the excavator is dumping
	End of loading	Loading	Velocity, Distance to the excavator, State of excavator	The truck is in the loading zone, it is the closest to the loader, its velocity changes from zero and the excavator states changes to swinging
	Hauling	Hauling	Velocity	The truck is in the hauling zone and its velocity is not zero
	Out of service	Hauling	Velocity	The truck is in the hauling zone and its velocity is zero
	Dumping	Dumping	Velocity& Distance to the Conveyer	The truck is in the dumping zone., it is the closest to the conveyor belt, and its velocity is zero
	In dumping queue	Dumping	Velocity& Distance to the Conveyer	The truck is in the dumping zone, it is not the closest unit to the conveyor belt and its velocity is zero
	End of dumping	Dumping	Velocity& Distance to the Conveyer	The truck is in the dumping zone, it is the closest to the conveyor belt, velocity changes from zero and it is getting far from the conveyor belt
	Returning	Returning	Velocity	The truck is in return zone and its velocity is not zero
	Out of service	Returning	Velocity	The truck is in the return zone and its velocity is zero
Excavator	Under loading	N/A	Velocity & Motion direction	The bucket is predominantly moving in a vertical plane with a low velocity
	Swinging (loaded)	N/A	Motion direction & Distance to the truck	The bucket is predominantly moving in a horizontal plane and it is moving toward the truck
	Dumping	N/A	Motion direction & Distance to the truck	The bucket is relatively stationary and its location intersects with the truck's bed
	Swinging (empty)	N/A	Distance to the truck & Motion direction	The bucket is predominantly moving in a horizontal plane and it is moving away from the truck
	Idle	N/A	Velocity	The bucket is not moving

In the light of the result of state-identification, each OA is able to identify its current state and communicate it with other OAs and TCAs so as to identify anomalies and discrepancies with the planned schedule. For instance, safety threats can be detected once the excavator departs from its assumed workspace. Also, the state information can be used to calculate the durations of different activities, further compared with the expected assumptions and used to fine-tune the simulation for updated scheduling, planning and resource optimization.

3.4 Real-time Simulation

A simulation model represents a real-world operation through the interrelations of the time and resources associated with the independent time-consuming elements of that operation (e.g. Halpin and Martinez 1999). The information about the durations of activities is based on historical data. However, RTS frequently updates the initially assumed time and resource values of operation elements to better represent the actual dynamism and volatility of the surrounding environment (Song et al. 2008). In the proposed approach, data about the current as-built status of the operation and site conditions will be provided via DDA and SSA respectively. Additionally, the present status of the equipment could be reflected via corresponding OAs, TCAs and/or GCA. Using this information, the RTS could more realistically perform operation forecasts in desired intervals or at critical times. It should be emphasized that the notion of real-time should not be construed as an uninterrupted chain of simulations as the operations proceed, but instead it should be understood as periodically performed simulation in intervals that are determined by the critically of the operations or when a simulation is requested by the GCA in response to an urgent unforeseen occurrence.

In this sense three roles could be defined for RTS in the proposed approach: (1) To periodically report to the GCA; (2) To provide updated forecast about the operations triggered in response to the design change update reported by DDA; or (3) To simulate the various scenarios requested by GCA when an unforeseen circumstance befalls. The GCA will generate a set of possible scenarios through varying the time and resource values associated with the elements of an operation and request from RTS the feedback on performance, e.g. productivity and cost, of different scenarios. Subsequently, the RTS will present the results to GCA for selecting the optimum scenario.

3.5 MAS Communication and Conflict Resolution

The TCAs provide intelligent behaviour for coordinating the work of OAs working together on the same task where their motion planning should be coordinated. The TCAs can also resolve conflicts among different teams of machines working on different tasks in proximity to each other. The teams may belong to different contractors and may not be willing to compromise their own interests. In this case, the GCA is responsible for coordinating the work based on the project priorities.

Once a potential conflict is detected, the involved TCAs communicate with the GCA by exchanging messages and they make decisions based on negotiation. For example, if re-planning is needed, the GCA decides which team has a higher priority. The priorities of the teams are decided according to several criteria such as the criticality of the task undertaken by the team. If more than one priority rule are applicable, a conflict may occur between these priorities. The overall priority can be calculated based on functions that quantify the priorities with relative weights, and summing up these priorities as a single priority value.

3.6 Perceived Advantages of the Proposed Approach

The benefits of the proposed approach will transcend those of the operation-level AMC/G implementation elaborated in Section 2.1. The proposed approach offers improvement in productivity beyond optimization of a single operation by adopting a holistic view of the project and considering the interdependencies of operations. In this context, safety issues and conflict-prone activities will be considered beyond single operations and the impact of modifications could be evaluated over the entire project.

The proposed approach will integrate the operational advantages of AMC/G with additional benefits at the managerial level, allowing managers to make informed decisions about the project using real-time data and simulation data. The MAS structure would offer faster conflict resolution, owing to the faster identification of the problem area and communication and negotiation between the agents. The negotiation capability of the agents will allow resolving claim problems before they evolve into litigations. The GCA will keep track of the project evolution, meaning that it would be even easier to pinpoint changes in the design or schedule and the motivating reason behind it. Moreover, MAS structure will provide benefits that span over the entire life-cycle of the project, from design to demolition. In this regard, information stored in DDA and SSA can be always referred to by the GCA and the GCA will be able to form any required TCA/OA structure in the context of construction or repair and rehabilitation projects.

On the operational side, on top of project-level optimization, it will be possible to have smoothened team collaboration with clearly defined rules and jurisdictions. This is further supplemented by the capability of the approach to forewarn about potential time-space conflicts between different operations and generate alternative solutions to circumvent accidents. Finally, the proposed approach, giving the highest priority to safety, allows the prevention of any safety hazard by stalling the operation(s) at any required level. Table 5 summarizes the benefits of our proposed MAS structure.

TABLE 5: Benefits of the proposed approach in managerial and operational areas

Area	Benefits
Managerial	Faster conflict resolution Transparency of the project evolution and improved document management Life-cycle solution to managerial problems
Operational	Project-level optimization Smoother team collaboration Enhanced time-space conflict and accident avoidance Rapid project-level response to safety risks

4. CASE STUDY

The following case study aims to validate how the knowledge about the state of the equipment, encapsulated within the corresponding OAs, can be derived from location and sensory data and further used for the decision making and real-time simulation. Although the implementation of a fully integrated system is beyond the scope of the present research, a prototype system is developed to test the proposed approach. The starting assumption of this case study is that all pieces of equipment are equipped with an RTLS, which will ideally be replaced by AMC/G, so that their poses are tracked in real-time. The objective of the case study can be decomposed into the following tasks: (1) Filtering and correcting the location data so that data errors are minimized; and (2) Inferring the state and pose information from the location using the rules from Table 4.

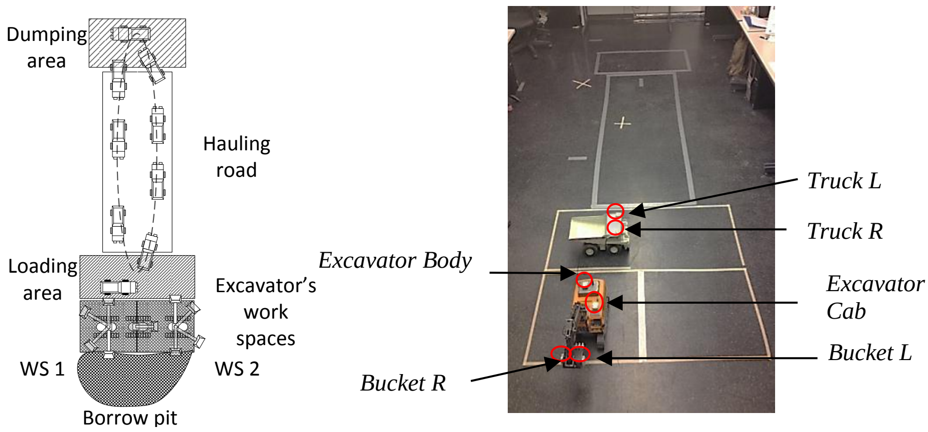
4.1 Setting of the Test

A test was carried out in the laboratory environment, where two radio-controlled (RC) machines, one 1/24 scaled model truck, and one 1/12 model excavator (Hobby Engine, 2013), were utilized to simulate a simple loading-hauling-dumping operation. A Real-time Location System (RTLS), i.e. Ultra-Wideband technology (Ubisense, 2013) was used in this test to monitor and log the equipment's movements.

The case study covered four full cycles of loading and hauling, which consisted of loading, hauling, dumping and returning operation for the truck and the loading, swinging, dumping, swinging back and repositioning operations for the excavator. Zones within which each of the afore-mentioned operation takes place were marked and their corresponding coordinates were determined. These zones later establish the base for the state-identification of the equipment. Figure 4 shows the setting of the case study which contains four main parts, namely, the excavation area, loading area, hauling area and the dumping area. The truck is loaded in the loading area by the excavator; it moves to the dumping area and dumps its load. On the other hand, the excavator obtains a load from borrow pit, swings to the loading area, dumps the material into the truck and swings back. The excavation area is divided into two workspaces which define the sub-sections within the excavation area in which the excavator is expected to work according to the safety and plan requirements. After two cycles of the truck, the excavator repositions to a new workspace within the same excavation zone, which is marked by WS2 in Figure 4(a), and continues to load the truck for two more cycles. A five-minute test was performed in which 4 cycles of loading-and-dumping were simulated.

Figure 4(b) depicts the test environment, the site layout and the zoning and different UWB tags attached to different parts of the equipment. Four UWB tags were assigned to the excavator and two were assigned to the truck in order monitor their movement. Sensors are installed at the locations providing the best coverage for the area. The slot interval was set to 16 which is equivalent to 9.61 readings per second. However, after the analysis of the test results, the actual average update rate was determined to be about 8 readings per second.

On the specifications of the equipment used in the case study, the truck has two motors that allow the movement of the body (drive forward/backward, turn right/left) and the bed of the truck (up/down). The excavator has five motors that allow the movement of the body (drive forward/backward, turn right/left) and the boom (moving forward/backward and up/down). Both models can be manually controlled using a remote control with different buttons and joysticks that allow the movement of one DoF at a time.



(a) 2D model of the case study

(b) A picture of the actual case study, UWB tags are marked on the picture

FIG 4: The zoning and layout of the case study

4.2 Data Processing

The raw location data gathered from the site require multi-step processing before they can be used for data analysis. The processing is required to compensate for the missing or erroneous data. As shown in Figure 5, the data processing includes the following steps: (1) The tags IDs are identified and grouped according to their geometric relationships with respect to the objects to which they are attached to (e.g., tags attached to the body of excavator); (2) The locations of the same tag are averaged over a short period of time, i.e. 1 second; (3) The location data are filtered based on the geometric constraints, i.e. the fixed distance between the tags on an equipment. To determine the acceptable range of error, the distance between the tags are calculated, and using the standard deviation (σ) of distances, any readings that fall outside the range of actual distance between two tags ± 2σ are considered as outliers and deleted; (4) If the error associated with each reading is determined as acceptable from the previous step, then the location data are corrected so that the geometric constrains are satisfied. For instance, as shown in Figure 6(a), if the calculated distance based on the readings of A1 and B1 is more than what it is measured to be (L), the amount of error is calculated, and the correction is equally distributed between the two tags, resulting in points A'1 and B'1; (5) The same filtering and corrections are performed for the operational constraints, e.g. maximum speed. For instance, as shown in Figure 6(b), if the distance between two consecutive readings A'1 and A2 of the same tag attached to a piece of equipment is L', while based on the maximum speed of the equipment this distance cannot be more than L, a correction is applied to the latter point and the new location is calculated (A'2); and finally (6) If there are any missing data it will be calculated using interpolation. Once the data is processed and the erroneous data are filtered and corrected, the rules from the knowledge-based system, shown in Table 4, are used to identify the state of the equipment.

The data were logged and processed using the data processing shown in Figure 5. The effect of the data processing on the traces of movement for different tags is shown in Figure 7.

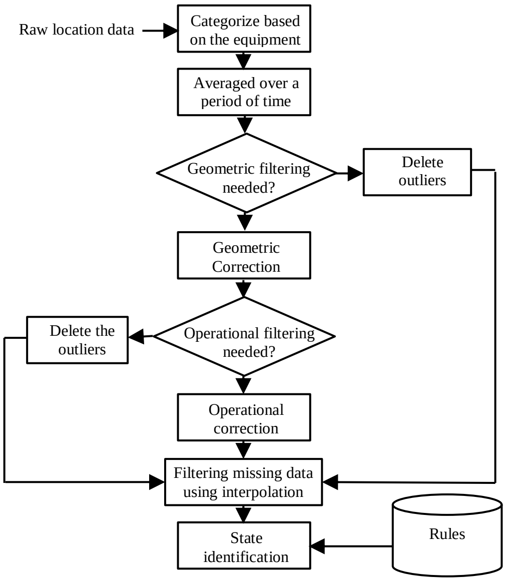
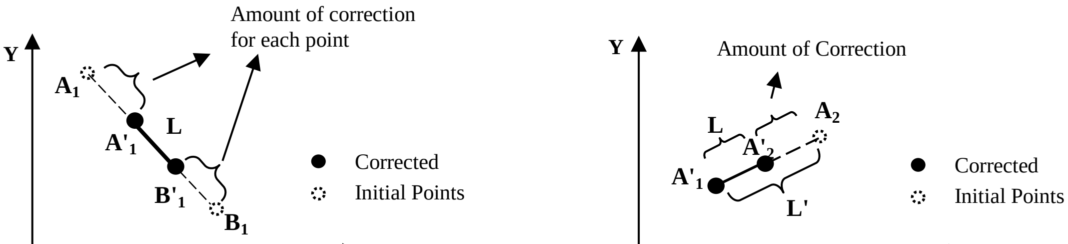
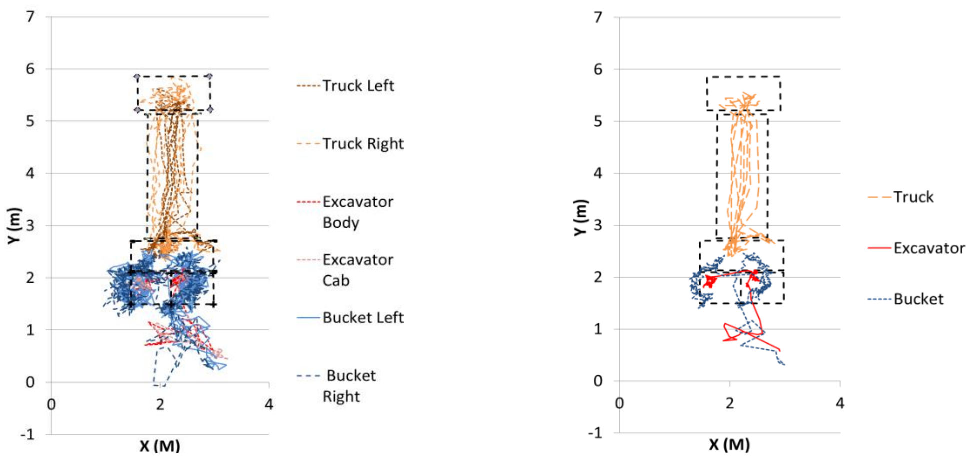


FIG 5: Flowchart of data processing for state identification



(a) Geometric Constraint Correction *(b) Operational Constraint Correction*

FIG 6: Corrections based on the geometric and Operational Constrains



(a) Before data processing (b) After data processing

FIG 7: Operation's processed data

Table 6 shows an excerpt of the result of applying the state-identification rules from the knowledgebase.

TABLE 6: Excerpt of the state-identification for the truck

Equipment	Time (s)	Zone	Distance to the Excavator (m)	Speed of truck (m/s)	State
Truck	58	Loading	0.45	0.02	Waiting for loading
Truck	59	Loading	0.36	0.02	Waiting for loading
Truck	60	Loading	0.34	0.00	Start of Loading
Truck	61	Loading	0.25	0.00	Under Loading
Truck	62	Loading	0.18	0.01	Under Loading
Truck	63	Loading	0.37	0.09	End of Loading
Truck	64	Hauling	0.90	0.55	Hauling
Truck	65	Hauling	1.59	0.60	Hauling
Truck	66	Hauling	2.10	0.49	Hauling
Truck	67	Hauling	2.83	0.73	Hauling
Truck	67	Dumping	3.35	0.47	Dumping

Figure 8 shows the results of the state identification for the entire test. Dotted lines in Figure 8 represent the transition between two adjacent states and the continuous lines indicate the continuity of the equipment in the corresponding states. The unrealistic ratio of different states in relation to one another, e.g. the hauling time to waiting time for the loading, can be ascribed to the combined effects of the scale of the equipment and site together with the equipment's operational speed. Also, given that only one truck was utilized in this test, states that involve waiting in queues are not pertinent to this case study.

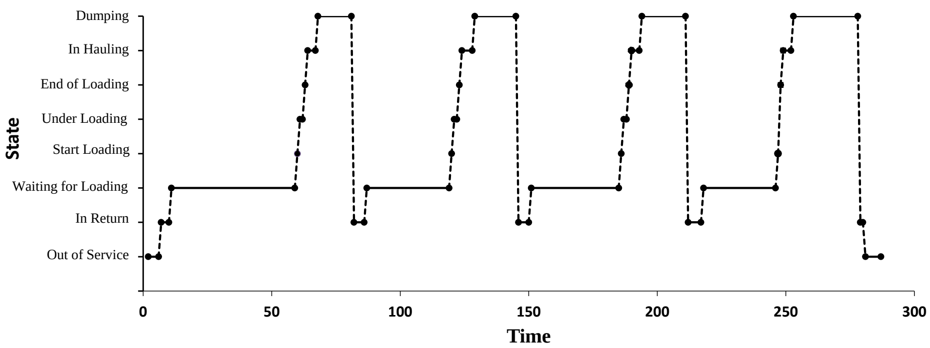


FIG. 8: *The transition of the state of the truck through the test*

As explained in Section 3.3, these results could be used for various purposes. For instance, if the operation had been simulated using the assumptions shown in Table 7(a), the productivity, and thus the total duration of the operation, would have been expected to be as shown in the same table. However, using the average values for the duration of different activities from the test, the simulation, and the subsequent productivity, can be adjusted according to Table 7(b), assuming that the service time of the excavator remains the same. The results suggest that the actual productivity of the operation is 4.6% less than assumed which is also manifested in a longer total duration of 13 seconds for the 4-cycle operation. In the proposed concept, the GCA identifies the mismatch between the planned schedule and the actual state of the operation and triggers the RTS.

TABLE 7: *Simulation parameters values as assumed (a) and measured in real-time (b)*

(a)

Simulation Parameters	Duration (s)	Productivity (Truck/min)	Total Duration (s)
Excavator service time	60		
Loading time	2	0.9	267
Hauling time	6		
Dumping	10		
Returning	3		

(b)

Simulation Parameters	Duration (s)	Productivity (Truck/min)	Total Duration (s)
Excavator service time	60		
Loading time	3.50	0.86	280
Hauling time	4.25		
Dumping	16.33		
Returning	5		

Similarly, as explained in Section 3.3, the above results can be used for safety purposes. For instance, if the truck leaves the designated zones within which it is expected to work, this deviation can be identified by the responsible TCA who will trigger safety warnings. Also, if two pieces of equipment that have a certain proximity threshold, i.e. they are not supposed to work closer than a certain distance, trespass the threshold, a safety warning can be triggered, and subsequently, the OAs can take immediate actions, such as stopping the equipment.

5. CONCLUSIONS AND FUTURE WORK

The presented study has investigated a novel approach for improving the productivity and safety of construction projects integrating AMC/G with a multi-agent system and the RTS.

In the administrative dimension, it was found that the current practices of project stakeholders would hardly provide incentives for the contractors to exploit the inherent power of AMC/G in their projects. It is, therefore, required to modify the current administrative work/information-flow to address issues such as re-designing, liabilities, ownership rights, QC/QA and interoperability. Most saliently, it is identified that to streamline the application of AMC/G in construction industry, it is of crucial importance to recognize and legitimize 3D design models and DTMs as the basis for the contracting. On this ground, a new workflow for AMC/G assisted project execution is proposed and delineated in terms of its benefits over the conventional state of the practice. Additionally, in the technology dimension, a novel approach is proposed for a project-wide coherent system for automated operations integrating AMC/G with the MAS and the RTS. In this approach a multi-layer MAS architecture is designed to monitor, coordinate and control the operations of construction machines and to resolve managerial conflicts. The proposed MAS structure is underpinned by four distinct components, namely coordinator agents, operator agents, information agents and real-time simulation. This structure would allow organizing construction machines into teams and establishing two-way communication and commanding channels between operation-level agents and coordination-level agents. The system is continuously endorsed by the information agents which furnish the information needed for decision-making and analysis. Knowledgebases are proposed to be used by the OAs to enable the agents' context-awareness, using a set of state identification rules that are based on the location and time data. RTS is used to empower the decision-making with the continuous analysis of productivity and safety. The case study demonstrated the feasibility of OAs' context-awareness and state identification using the knowledge-based system.

In the light of the findings of this paper it can be concluded that: (1) Implementation of such a broad approach requires more than the study of the technical aspects and it is required to identify the administrative infrastructure required to formalize the applications of AMC/G in construction more thoroughly. However, a wide variety of operational and managerial conflicts could be effectively addressed using the proposed approach; (2) The combination of the proposed MAS structure and RTS transcends the application of AMC/G from a machine-level coordination tool to a project-level monitoring and decision-making platform that contributes greatly to enhancing the site safety and project management ; and finally (3) As shown in the case study, a knowledge-based system can help endow context-awareness to the OAs, allowing them to make real-time unilateral and multilateral decision makings in view of the real-time state identification of different pieces of equipment.

In order to have a full-fledged implementation of this approach, our future work will include the following: (1) The proposed MAS needs to be fully developed. Furthermore, the algorithms to resolve issues arising from conflicts between agents need to be further developed using collaboration and negotiation methods; (2) It is necessary to identify the most appropriate simulation technique and further bridge the simulation engine to a 3D model for the purpose of 4D visualization and clash detection; and (3) The integration of the above studies needs to be implemented in actual case studies to validate the expected outcomes.

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