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Framework for an intelligent earthwork system Part I. System architecture

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Abstract

Recently, there has been an increase in the demand to enhance the intelligence of construction equipment and systems. Especially for semiautonomous and autonomous systems that have great potential for impact on the construction industry, artificial intelligence approaches are required to generate instructions and plans necessary to perform tasks in dynamically changing environments on their own. The framework for an intelligent earthwork system (IES) is suggested by the authors. It generates a plan automatically for construction equipment, provides a means of cooperation between construction equipment seamlessly, and improves worker safety. This paper describes some factors that can affect earthwork operation performance, five emerging technologies that can be adapted to implement an IES, the system architecture, and the system control strategy for IES.

Keywords: Construction automation; Earthwork; Intelligent system; Agent-based system

1. Introduction

There have been increasing demands to enhance intelligence of construction equipment and systems. The large portion of previous researches on construction automation has been focused on the addition of sensors and control systems to existing construction equipment. A limited amount of research, however, has been conducted in developing intelligent construction equipment and systems. Construction equipment types can be categorized into four groups based on the control method: (1) mechanized equipment, (2) numerically controlled equipment, (3) remotely controlled equipment, and (4) semiautonomous and autonomous equipment [1]. In the case of semiautonomous and autonomous equipment that have great potential for impact on the construction industry, artificial intelligence (AI) should be equipped to generate instructions and plans necessary to perform tasks in dynamically changing environments on their own.

When developing intelligent construction systems, the major problems can be classified into seven principal categories: (1) how to enable construction equipment to sense its environment, (2) how to enable construction equipment to analyze information sensed, (3) how to enable construction equipment to

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generate execution tasks and plans, (4) how to enable construction equipment to execute the given tasks, (5) how to enable construction equipment to recognize conflicts, (6) how to enable construction equipment to reconcile the conflicts, and (7) how to enable construction equipment to communicate and interact. Based on the understanding of the environment, it should emulate human behaviors. To solve these problems, a new approach is required for designing and implementing a semiautonomous or autonomous construction system.

Some researches on developing an automated system for civil works have been conducted, e.g., a semiautonomous truck system by Saito et al. [2]; an autonomous excavator by Carnegie Mellon University [3]; automated nonintrusive production measurement systems by the National Institute of Standards and Technology (NIST) [4]; an open communication system (CANopen) for mobile construction equipment by the University of Magdeburg [5]; an automated landfill system (ALS) by Tserng et al. [6,7]; and an agent-based cooperative system for landfill operations by Kim et al. [8].

The major goal of the research conducted by the authors is to develop a conceptual framework for intelligent earthwork system (IES) that will enable a group of construction equipment to automatically generate tasks and to efficiently perform earthwork operations in a cooperative manner. The proposed framework is to be applied to semiautonomous earthwork system with minimum human intervention. In the earthwork system, the role of humans is making cognitive decisions, which may be beyond the capability of the system. For the full-implementation of an IES, advanced technologies are needed. Until now, there is a limited number of available technologies for implementing an IES. Thus, more advanced technologies should be developed and applied in near future. The implementation of the proposed system will result in improved worker safety and work quality, as well as reducing project duration and skilled worker requirements.

Even though the proposed system is not tested yet in the real world, our main contribution is to provide theoretical background for developing an IES. This paper describes some factors that can affect earthwork operation performance, four emerging technologies that can be adapted to implement an IES and its system architecture. The system control strategy, then, is suggested. Finally, information flow between functions is explained.

2. Earthworks

Earthwork operations are connected with all cutting, filling, spreading, compacting, and grading in preparation for road construction, embankment construction, and building construction. These operations are relatively repetitive and machine-oriented, being performed under the pressure to improve productivity, efficiency, and safety.

2.1. Earthwork phases

Earthworks are viewed as a continuous process of three sequential phases: (1) site preparation, (2) rough grade development, and (3) finish work [9], as shown in Fig. 1. The earthwork starts with the preparation of the material to be moved. This step is finished when clearing, grubbing, and stripping topsoil have been completed. Following preparation of the material, it is moved from its source to the target location. The haul distance varies from only a few feet to several miles. If required, the spreading and compacting operations are followed by hauling of the material. Finally, the finishing work is processed to satisfy specifications.

There are several variables that influence earthwork practices, among them, earthwork characteristics, job-site conditions, equipment characteristics, and construction methods, which are explained in Section 2.2. Because of the variability, the duration of earthwork varies from one project to another.

2.2. Factors affecting earthwork operation performance

The operation performance can be measured by several performance criteria, which can be classified into time (duration), cost, and safety. It is evident that effective operations are a multicriteria problem. However, in this section, the focus is on the duration of operations.

The production rate can be calculated by dividing the number of units produced by the duration of earthwork operations, and the minimization of project

Phase 1: Site preparation
- Clear and grub -Vegetation and debris
  (e.g., tree, brush, buried vegetation, trash, stumps, roots, etc.)
- Strip - Topsoil

Phase 2: Rough grade development
- Push for cut and fill
- Haul for more distance cut and fill
- Compact
  Fill where required to bring site to rough grade
  (to be compacted at least 90~95% of the maximum density at the optimum moisture content of the fill material)

Phase 3: Finish work
- Grade – Bearing surface
- Ditch – Drainage ditches and utility connections
- Backfill
- Compact (where required)

Fig. 1. Earthwork phases (modified from Ref. [9]).

duration is highly dependent on the production rate. There are a wide variety of factors that affect the duration of earthwork operations. Considering the significance of their influence, the affecting factors can be categorized into four groups, which are closely correlated with each other, as shown in Fig. 2.

In the first group, work types and volumes are directly related to the duration of earthwork operations. Obviously, the different types of work will result in a different duration. Even the same type of work will have different work durations due to the differences in work volume, site conditions, construction methods, and so forth. The availability of space affects the productivity of equipment in the given workspace. Concurrent activities of multiequipment interfere with each other because of their requirement for workspace within a confined area.

Affecting factors associated with the job site conditions include weather, soil conditions, and road conditions. Weather affects the duration of earthwork operations. In general, bad weather decreases the efficiency of construction equipment. Various types of soil create different levels of difficulty in stripping and excavating soil, and are related to the rolling resistance that affects both production rate and the financial investment of an earthwork contractor. The slope of on-site roadways is related with the effectiveness of haul and return trip of construction equipment. Off-site road conditions such as traffic conditions affect the delivery or hauling process of soil from a borrow pit to a filling area.

Equipment is an important resource for heavy construction projects that require a large concentration of construction equipment. Under a unique set of construction conditions, the selection of equipment is directly affected by the characteristics of equipment. In an equipment-intensive project, it is clear that the proper equipment selection will result in the minimi-

Work characteristics
- Work type and volume
- Space constraint

Job-site conditions
- Weather
- Soil types and conditions
- Road conditions – on-site/off-site

Equipment characteristics
- Capacity (Production rate)
- Efficiency
- Cycle time
- Failure rate
- Economic haul distance
- Motion and path planning strategy

Management
- Planning the sequence of work
- Select a proper number of equipment

Fig. 2. Four groups of affecting factors.

zation of project duration and the maximization of output of work tasks.

The last group, management of operations, includes planning the sequence of work tasks, and allocating the proper amount of required equipment. For example, if two or more equipment fleets are involved in earthwork operations at the same place at the same time to transport the stripped soil to the fill area, there will be space interference that will result in the decrease of productivity. To avoid this problem, the interference-free sequence of work tasks should be planned in advance. Depending on the work environment and hauling distance, a variable amount of construction equipment should be assigned to each equipment fleet rather than a fixed amount throughout the earthwork operation process.

Among various affecting factors, planning the sequence of work tasks, equipment selection, and equipment motion and path planning are controllable factors to minimize the duration of earthwork operations. Therefore, IES aims at controlling these factors.

3. Available technologies

There are several emerging technologies that can be adapted to implement an IES. The IES cannot be successful without efficient and proper real-time monitoring and controlling of inputs and outputs about environment and construction equipment itself. Other industries such as the mechanical and manufacturing industries are the valuable sources of these technologies. Although some technologies from other industries are not directly suitable for the construction industry, proper modification will satisfy the needs. This section will briefly review five technologies, namely, (1) distributed artificial intelligence (DAI), (2) global positioning system (GPS), (3) sensor and sensing technology, (4) wireless communication technology, and (5) path-planning technology.

3.1. Distributed artificial intelligence (DAI)

DAI is a subfield of Artificial intelligence (AI). It is concerned with solving problems by applying both artificial intelligence techniques and multiple problem solvers [10]. The world of DAI can be divided into two primary arenas: (1) distributed problem solving (DPS) and (2) multiagent system (MAS). Research in DPS considers how the work of solving a particular problem can be divided among a number of modules, or nodes, that cooperate at the level of dividing and sharing knowledge about the problem and about the developing solution [11]. In MAS, research is concerned with coordinating intelligent behavior among a collection of autonomous intelligent agents and with how they can coordinate their knowledge, goals, skills, and plans jointly to take action or to solve problems.

There are some reasons why the DAI concept is appropriate for IES. First, due to possible changes in the initial conditions, the replanning of almost all task execution is often necessary. Equipment breakdowns, accidents, and other unexpected conditions are some causes of changing the initial plan. DAI can provide an effective way to deal with these kinds of changes. Second, several agents that have distributed and heterogeneous functions are involved in earthwork operation at the same time. They should perform tasks in a cooperative manner. DAI can provide insights and understanding about interaction among agents in the construction site in order to solve problems. In addition, data from these agents should be interpreted and integrated. Third, every agent has different capacity and capability. This implies that there are a great number of possible agent combinations that are time and cost effective to perform given tasks. Fourth, it is easy to decompose tasks for earthwork operations. An example of tasks involved in earthwork operations are stripping, hauling, spreading, and compacting.

3.2. GPS technology

The global positioning system (GPS) is a worldwide satellite-based navigation system operated and maintained by the US Department of Defense. GPS provides several important features including its high position accuracy and velocity determination in three dimensions, global coverage, all-weather capability, continuous availability to an unlimited number of users, accurate timing capability, ability to meet the needs of a broad spectrum of users, and jam resistance [12].

Currently, GPS is used in various fields ranging from avionics, military, mapping, mining, and land surveying, to construction. One example of construction application is SiteVision™ GPS system, which is an earthmoving control system developed by Trimble

Navigation. With horizontal and vertical accuracies better than 30 mm, it allows the machine operator to work to design specifications without the use of pegs, boards, or strings. This system can give the operators all the necessary direction for precise grade, slope, and path control. Planned grade is achieved in fewer passes with less rework. With the SiteVision™ GPS system, accurate earthmoving operations take less time with lower fuel and maintenance costs on large-scale earthmoving projects [13,14]. There is another possible application for construction equipment. An equipment motion strategy for the efficient and exact path for earthwork operations can be determined by GPS position data with preplanned motion models.

3.3. Sensor and sensing technology

A sensor is a device or transducer, which receives information about various physical effects such as mechanical, optical, electrical, acoustic, and magnetic effects and converts them into electrical signals. These electrical signals can be acted upon by the control unit [15]. Construction equipment's ability to sense its environment and change its behavior on that basis is very important for an automated system. Without sensing ability, construction equipment would be nothing more than a construction tool, going through the same task again and again in a human-controlled environment. Such a construction tool is commonly used for construction operation currently, and certainly has its place and is often the right economic solution. With smart sensors, however, construction equipment has the potential to do much more. It can perform given tasks in unstructured environments and adapt as the environment changes around it. It can work in dirty and dangerous environments where humans cannot work safely.

In IES, these GPS and sensor technologies are used for (1) real-time positioning, (2) real-time data collection during operation, (3) equipment health monitoring, (4) work quality verification and remediation, (5) collision-free path planning, and (6) equipment performance measurement.

3.4. Wireless communication technology

Wireless communication can be defined as a form of communication without using wires or fiber optic cables over distance by the use of arbitrary codes. Information is transmitted in the form of radio spectrum, not in the form of speech. So, information can be available to users at all time, in all places. The data transmitted can represent various types of information such as multivoice channels, full-motion video, and computer data [16].

Wireless communication technology is very important for the earthwork operation system, because equipment moves form place to place on a construction site, and data and information needed should be exchanged between construction equipment agents in real-time. With wireless communication technology, communication is not restricted by harsh construction environments due to remote data connection, and construction equipment agents and human operators can expect and receive the delivery information and services no matter where they are on the construction site, even around the construction site.

For agents in IES to interact and cooperate effectively, the IES requires three functional components: (1) a common communication language, (2) a common understanding of the knowledge exchanged, and (3) an ability to exchange whatever is included in (1) and (2). An agent exchanges messages within structured plans with other agents, which are supposed to perform construction tasks. These plans are defined by a communication protocol, which should be developed for the IES. The communication protocol should be clear enough to reason with the contents of a task assignment, and define vocabularies that set the primitive concepts in the communication model.

3.5. Path-planning technology

Without an automated navigation system for construction equipment, an IES cannot be achieved. Thus, for the full implementation of the proposed system, the development of efficient and effective path planning is required. The purpose of a path planning for mobile equipment is to find a continuous collision-free path from the initial position of the equipment to its target position. The path planning for a mobile robot can be categorized into two models that are based on different assumptions about the information available for planning: (1) path planning with complete information and (2) path planning with incomplete information.

The first model assumes that a robot has perfect information about itself and its environment. Information, which fully describes the sizes, shapes, positions, and orientations of all obstacles in two-dimensional (2D) or three-dimensional (3D) space, is known. Because full information is assumed, the path planning is a one-time and off-line operation [17,18]. Latombe [19] categorizes path planning with complete information into three general approaches: (1) road map, (2) cell decomposition, and (3) potential field method.

In the second model, an element of uncertainty is present and the missing data is typically provided in real-time by some source of local information through sensory feedback using an ultrasound range or a vision module [18]. A robot has no information on its environment except a start position and a target position. The sensory information is used to build a global model for path planning in real-time. The path planning is a continuous on-line process. The construction and maintenance of the global model based on sensory information requires heavy computation, which is a burden on the robot [20].

In reality, a mobile construction robot cannot have perfect information on its environment. The information about the location of obstacles should be collected by sensors on the construction robot and a path can be generated based on the sensory information. This information can be obtained with visual, laser, ultrasonic, or photoelectric sensors.

4. System architecture

The main goals of IES are: (1) to generate a plan automatically for construction equipment that performs earthwork operations such as stripping, pushing, hauling, spreading, and compacting of soil in continuously changing environments, (2) to secure planning and execution information on earthwork operations, and put them together integrally, (3) to rationalize quality control corresponding to the execution by construction equipment, (4) to provide a seamless means of cooperation between construction equipment, and (5) to reduce worker requirements and improve worker safety. IES generally consists of three sorts of principal subsystems as shown in Fig. 3: (1) task-planning subsystem (TPS), (2) task-execution subsystem (TES), and (3) human control subsystem (HCS). Following is a brief description of each subsystem.

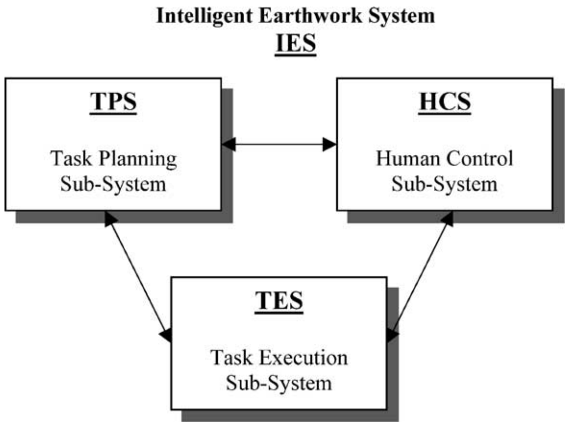

Fig. 3. Principal subsystems of the IES.

4.1. Task-planning subsystem (TPS)

TPS is responsible for identifying and planning of filed operation tasks that have been confided to it. This subsystem acquires and analyzes all pertinent data to identify earthwork operation tasks and then produces an initial task list. The initial task list has first-level tasks, which can be decomposed into several subtasks called second-level tasks. The data analyzed include expected work volume and quality, work location, work environment, and time constraints. It is also responsible for updating the project master database. TPS announces a first-level task list to the equipment mediator agent of the task-execution subsystem (TES), while trying to satisfy the constraints, as well as global optimality criteria, and keeps track of the result of task executions. TPS can be considered as a software expert for IES.

4.2. Task-execution subsystem (TES)

TES is responsible for performing earthwork operation tasks in the first-level task list of TPS, providing a means of performing cooperative works between equipment agents, and monitoring the execution of given tasks. This subsystem examines the capability of each equipment agent (EA) for the performance of given earthwork operation tasks and allocates second-level tasks such as such as stripping, pushing, hauling, spreading, and compacting to EAs. The data analyzed are task requirements, equipment agent types, characteristics of equipment agents, control and sensory systems of equipment agents, and so on. After finishing the given tasks, TES notifies TPS to put them into a list of tasks which have been done, called a finished task list. In the unexpected event (e.g., equipment agent breakdown), unfinished tasks that are not completed are added into a rework list.

4.3. Human control subsystem (HCS)

HCS provides human operator(s) with a means for the input of control commands in order to recover system errors and for data visualization. It is supposed that IES can autonomously perform the given tasks, but still has a communication tool with humans who can intervene during trouble and can make cognitive decisions, which may be beyond the capability of IES. During trouble, the human operator can check task execution status and equipment agent's status through the interface agent (IA). With data visualization, it is easy to determine work volume, work progress, and equipment status.

All subsystems in IES are mutually connected with radio local area network (LAN). Using the latest information telecommunication technology, each kind of required information on earthwork operations such as control of work volume, control of operation process, quality control, etc., is shared seamlessly. IES is on the evolutionary link between the preprogrammed operation system and the fully autonomous operation system.

4.4. Agents of task-planning subsystem (TPS)

The principal subsystems and their corresponding agents for IES are presented in Fig. 4. TPS consists of a master database (MDB) and a task-planning agent (TPA). Each element of TPS is described next.

4.4.1. Master database (MDB)

The efficiency of task planning depends on the quality and integrity of a well-designed information database. MDB has four kinds of information: (1) environmental information such as 2D/3D topographical data, earth volume distribution data for earthwork,

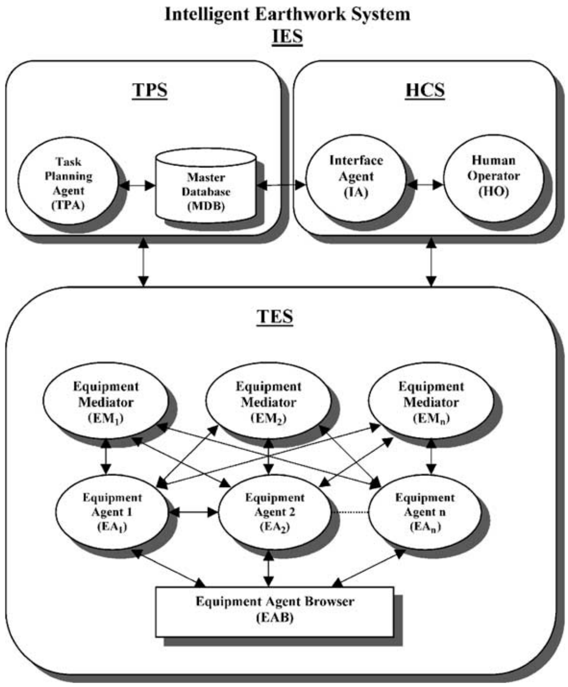

Fig. 4. Agents of subsystems.

the partitions, called the cells, of a construction site, the position data of all cells, the target volume (capacity) of all cells, the current volume of all cells under earthwork operation, the types and characteristics of soil or solid waste materials of each cell, the rolling resistances for different surface conditions, and weather conditions; (2) task lists such as an initial list, an activated list, a finished list, and a rework list; (3) work quality information; and (4) construction process information. MDB stores both permanent and temporary information, which is used and processed in task planning and executions. Whenever the earthwork operation tasks are done by equipment agents, this database is updated.

4.4.2. Task-planning agent (TPA)

TPA extracts information on topological and terrain data, site-specific parameters, work quality, and constraints from MDB to determine earthwork operation tasks. It performs automated volumetric calculations to find the amount of materials removed, placed, and compacted for each cell, and then identify tasks for earthwork operations. Every task with task requirements becomes a task object, and a set of correlated task objects comprises a task package that is placed in a set of task packages called the initial list. Any task package for which all prerequirements are finished is moved from the initial list to another set of tasks called the activated list. When the activated list has multiple task packages, these are prioritized using a prioritization rule, satisfying global goals. Once prioritized, task packages are announced according to the priority. After task packages are executed by equipment agents, they are moved from the activated list to the final set of task packages called the finished list. After that time, TPA updates the MDB contents.

4.5. Agents of task-execution subsystem (TES)

TES consists of equipment mediators (EM), multiple equipment agents (EA), and an equipment agent browser (EAB) as follows.

4.5.1. Equipment mediator (EM)

The mediator is one type of what is known as federation approach. EM allows many heterogeneous EAs to be associated, and is used to coordinate the activities of the relevant EAs to improve the earthwork operation task execution efficiently. Each EM is created for a task package as necessary and is destroyed after the given task is completed. EM is responsible for decomposing a first-level task of the task package into several second-level tasks, distributing second-level tasks, selecting proper EAs for task execution, monitoring the status of task execution, and providing tools of communication and cooperation among EAs. Task allocation is performed according to negotiation rules. EM provides IES with lower-level decisions for the task execution unless critical situations occur.

4.5.2. Equipment agent (EA)

EAs represent the means of stripping, pushing, hauling, spreading, and compacting soil or solid wastes, such as front-end loaders, scrapers, motor graders, tractors, compactors, draglines, dozers, and so on. Every EA is capable of accepting and rejecting given second-level tasks, which means it can make a decision on its own based on the status of the EA. EA can be envisaged as an independent system that can work either in cooperation with other agents or in isolation. Usually, when EA is involved in earthwork operations, it is yoked together with other EAs for the duration of the work in order to achieve the global goal in a satisfactory way. Cooperation among several pieces of EA is fundamental to achieve more than the sum of what each can achieve individually. The internal structure of EA is described in Section 4.7.

Multiple EAs with an EM in TES can form an agent cluster, which consists of an equipment mediator (EM), and one or more equipment agents (EAs) to execute a task package, based on the given task package. To achieve cooperative works, a number of EAs are dynamically created and grouped into agent clusters, which can be created only for the period necessary and destroyed as needed. For example, one set of EAs could be needed for a certain operation of a given task, but for the next operation, some agents could be added or dropped.

4.5.3. Equipment agent browser (EAB)

EAB is responsible for finding all EAs queried by the human operator (HO) and extracting relevant information about them. Information includes equipment type, equipment characteristics, equipment status, and work volume that is done by each piece of equipment. Equipment characteristics include engine power, net weight, rated capacity, turn radius, maximum speed, bucket volume, loaded and empty weight percentage on driving wheels, mean time between breakdowns, repair time distribution, move-in and hourly cost, etc.

4.6. Agents of human control subsystem (HCS)

HCS has an interface agent (IA), which is designed for human operator(s). Following is a brief description of agents of HCS.

4.6.1. Interface agent (IA)

IA provides human operators with interactive tools that are used to visualize data, to monitor status of IES' agents, and to input changing human operator's needs (i.e., quantity or quality requirements for task executions) and commands for recovering system errors. IA extracts all required data based on a human operator's requests, and resolves conflicts and inconsistencies in information, current tasks, and environmental models, thus improving decision-support capability of IES. Humans are able to control the amount of agent autonomy through IA.

4.6.2. Human operator (HO)

IES is neither completely under the control of humans or agents in IES, nor completely autonomous. Even though every agent has intelligence with knowledge-based control ability to perform independent or cooperative tasks, human supervision is required for cognitive decision-making beyond the agent's capability. Thus, HO acts as a supervisor of IES.

4.7. Internal architecture of equipment agent

The internal architecture of EA is displayed in Fig. 5. The structure of EA can be divided into four layers as follows.

4.7.1. Communication layer

This layer includes the communication tools, which are responsible for sending and receiving real-time data and messages, and for transporting commands and bids between agents for effective earthwork operations. It describes the communication protocols between agents and characterizes the way that agents take into account real-time data and messages they receive. This layer also allows EA to act by sending control commands to the actuators where the actions are actually executed.

4.7.2. Coordination layer

The coordination layer is responsible for calculating a bid value, submitting a bid for a task assignment, and making a contract. If the task announced is so simple that one EA can finish it without the consideration of cooperative work, this layer makes a bid for a task assignment. After making a contract, it decomposes the second-level task into simple actions, which are executed by the individual EA without interacting with other EAs.

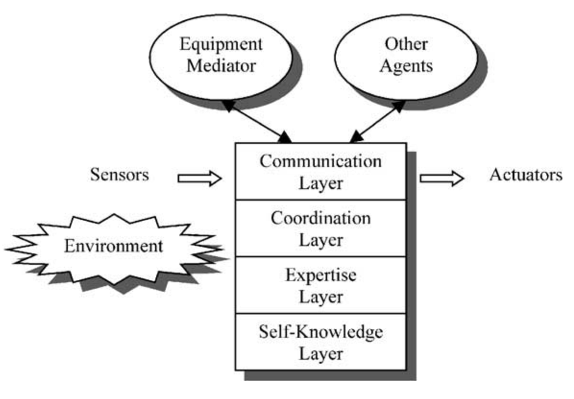

Fig. 5. Internal architecture of an EA.

By contrast, if the task consists of various subtasks and/or has a lot of work volume that cannot be performed by one EA, the coordination layer finds a group of EAs, which all together are able to perform the given task, and then a makes a bid for a task assignment. To perform this type of task, several EAs have to cooperate, because each EA can only play a part to execute a specific task. The main problem to be solved here is to create a consistent group of EAs, called a well-matched team. This means that the consistent group of EAs is guaranteed to succeed in executing the given task as long as there are not exceptional events.

If the assigned task does not comply with the agent's goal or other internal constraints, then the given task may be rejected. When there are exceptional events such as break down of the EA, errors in task execution, etc., this layer may notify EM to add unfinished tasks into a rework list.

4.7.3. Expertise layer

The expertise layer contains knowledge about actions and treatments, which are used by the EA to carry out the given task. This knowledge consists of negotiation algorithms, bid value calculation methods, operation rules, collision-free path-planning algorithms, error-recovering methods, etc.

4.7.4. Self-knowledge layer

The self-knowledge layer can be divided into two parts: (1) equipment specific information such as performance characteristics, physical dimension, weight, speed, power, capacity, production rate on given tasks, failure rate, operating life, location (i.e., GPS data), work cycle, etc.; and (2) management specific information such as ownership cost, operating cost, operating hours, down time, idle time, maintenance schedule, etc.

5. System control strategy

Recent research on multiagent system control has focused on moving away from a centralized control approach, which is a top-down approach to master the overall system. In a centralized control approach, all information is stored in one node, and is processed by a node on a high level. Most detailed commands are sent from this node to other nodes that execute the given commands. Thereby, this control approach has global knowledge concerning the overall tasks and the environment, is powerful enough to plan and schedule the subtasks, and can find the optimal solution for task execution. However, when large-scale systems such as construction systems and manufacturing systems are considered, this approach has some drawbacks: high design complexity, low flexibility, and NP complexity.

To overcome the inadequacy of the centralized control approach, a decentralized control approach is developed for multiagent systems. This approach decreases design complexity, and is very reactive and highly flexible. Agents in multiagent systems with decentralized control approach have a high degree of autonomy. However, it is hard to predict system behavior and performance, it takes relatively a long time to do decision making, and it is difficult to realize global optimization [21].

The system control strategy for IES should be capable of adapting to emerging tasks and changing environment, and managing uncertainty such as equipment breakdown in order to meet the needs of earthwork operations. To achieve this adaptability and reconfigurability, hybrid control approach is used for IES. This is a partially centralized and partially decentralized approach. This control approach aims at ease of extension and modification, more flexible decision-making, and more effective error recovery. The functional layers of IES control approach are presented in Fig. 6. Each layer can be composed of various agents, which collaborate and negotiate with each other to execute earthwork operation tasks effectively.

All agents in the system have autonomy and interact with each other in a partially centralized and a partially decentralized way. In order to achieve a coherent global behavior of the system and in order to coordinate the local activity, two kinds of relationship between IES agents are used in the system: a vertical relationship and a horizontal relationship.

A vertical relationship represents interaction among TPA, HO, EMs, and EAs. This relationship is relatively hierarchical: TPA, which is in the uppermost layer of the control architecture, identifies earthwork operation tasks and globally schedules them based on information gathered from MDB and HO. EMs are obliged to attempt to announce tasks identified by TPA and make a contract with EAs to assign earthwork operation tasks. Then, EAs are requested to perform the given task in a cooperative manner and they are obliged to report to EMs what they have done. When a critical situation occurs, HO can directly control other agents to recover errors and can also change the level of autonomy of agents.

A horizontal relationship means (1) interaction between EMs and (2) interaction between EAs. EMs can negotiate each other for the global optimization of the system. EAs can exchange information on earth-

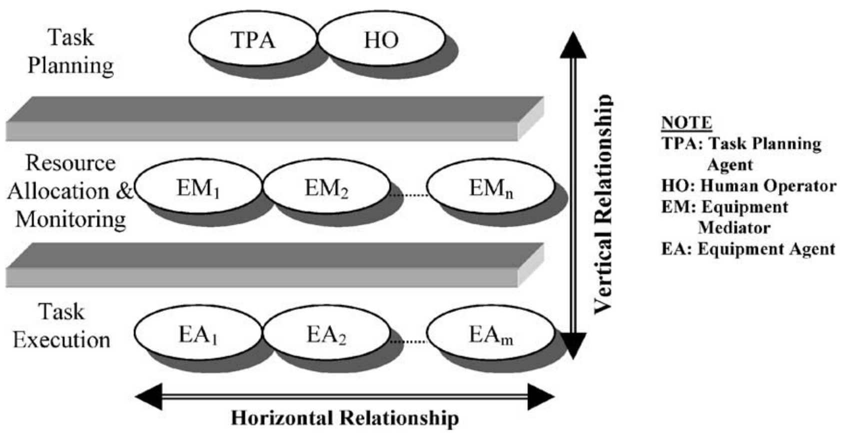

Fig. 6. Functional layers of the IES control approach.

work operations, their locations, and their availability for the flexible task execution. Each agent is responsible for its own movements or the actions it should take on the basis of interaction with other agents. This interaction is not hierarchical; rather it is associated with the aspects of conflict and cooperation.

6. Information flow between functions

IES consists of a multitude of functions, which are interconnected by a communication system. It supports (1) task identification and planning, (2) task allocation, and (3) task execution. The flow of information between functions has to be modeled in a precise manner to maintain the soundness of the proposed system. Fig. 7 briefly represents the conceptual information flow model and the interaction between system functions of IES. To implement a real system, the interactions between functions must be more complex to represent all microscopic information flow and controls of an intelligent construction system.

The graphical model in Fig. 7 contains three elements.

(1) Rectangles with rounded corners represent function activity boxes. Algorithms, rules, constraints, and construction methods, called function process policies, which are used for processing activities in the functions, are entered from the top, whereas all required data and information on task and IES' agents, called input data, are entered from the left. The output data of an activity box is sent to the next activity box. In a real system, information will also be fed back to the previous activities. An activity box may contain one or several activities, which are executed in parallel, in sequence, or in a hybrid fashion.

(2) Rectangles with square corners represent input and output data boxes.

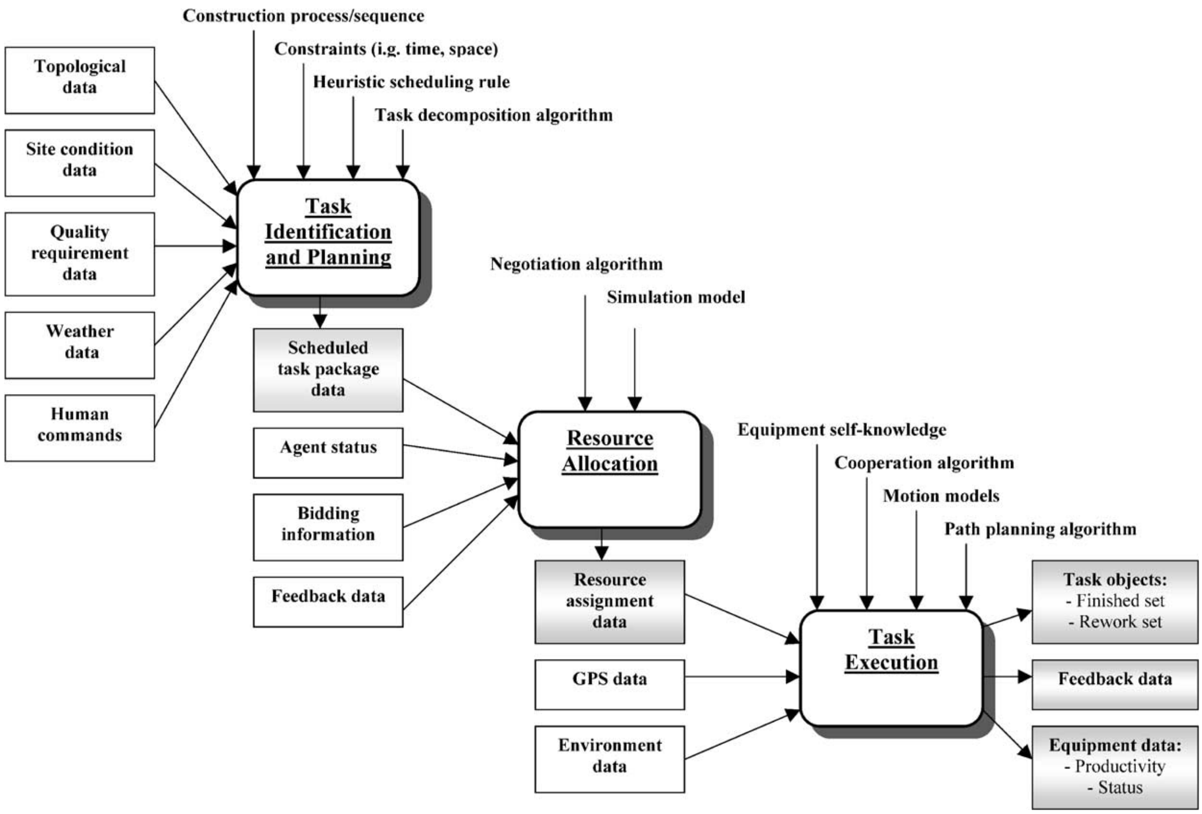

Fig. 7. Overview of information flow in IES.

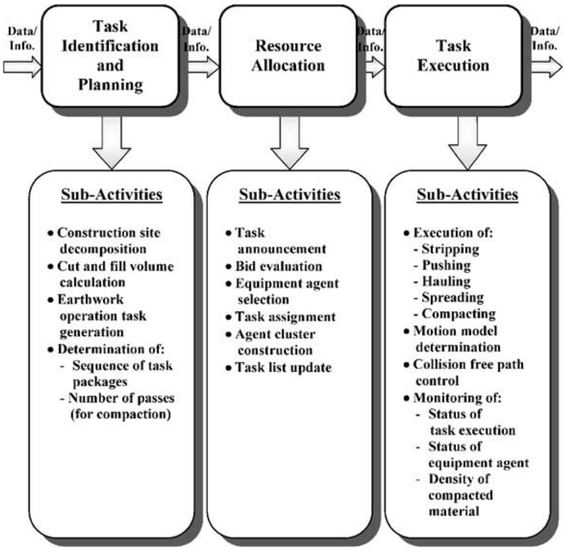

Fig. 8. Subactivities of each function.

(3) Arrows show information and logic flow, and relationships between the functions.

The initial input to task identification and planning includes topological data, site condition data, quality requirement data, weather data, and human commands. Based on a set of preestablished rules or criteria, the task identification and planning function performs several subactivities as shown in Fig. 8. This function processes information and data from input for task planning to decompose a construction site into several cells, which are designed for effective earthwork operations, and to estimate cut and fill volume. The result of these activities produces a set of task packages, which is provided to subsequent functions.

The next activity is the task allocation function where basic data (e.g., agent status, bidding information, and feedback data), which is needed to achieve an effective task allocation, is continuously collected from several agents in IES. This function announces and allocates tasks, which are in the activated task list, to available equipment agents with the help of the computer simulation tool using known methods and algorithms. The output of this function is specific task assignment data, which includes information on equipment agent selection and virtual cluster based on volume and characteristics of the given task.

The function, task execution and monitoring, is the last activity in IES. Input to this function is provided by task allocation function activity. To perform various subactivities as shown in Fig. 8, GPS data and environmental data are fed in real-time fashion from other agents. This activity is supported by equipment self-knowledge, and cooperation and motion-planning algorithms. Task execution and equipment status are constantly monitored for retask allocation support, equipment productivity calculation and feedback data collection.

7. Summary

This paper has briefly presented earthwork process and reviewed five available technologies to help implement an IES, such as DAI, GPS, sensor and sensing technology, wireless communication technology and path-planning technology. For the full-implementation of an IES, the five technologies mentioned above are not enough. Thus, more advanced technologies should be developed and applied. This paper has also described the system architecture of IES in detail. It consists of task-planning subsystem (TPS), task-execution subsystem (TES) and human control subsystem (HCS), which have two or more agents. All agents in the system have autonomy and interact with each other in a partially centralized and a partially decentralized way. Hybrid control approach is suggested for IES and the functional layers of the IES control approach are presented here. Finally, the flow of information between functions is modeled.

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