분산인공지능 기반의 토공 시스템 개발

Development of a DAI-Based Earthwork System

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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 in this paper. It generates a plan automatically for construction equipment and provides a means of cooperation between construction equipment seamlessly. This paper describes the system architecture, control strategy, task planning method, and resource allocation method for IES.

Keywords : Construction automation, Earthwork, DAI, 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 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 semi-autonomous or autonomous construction system.

The major goal of the research conducted by the author is to develop a conceptual framework for an 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 semi-autonomous 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.

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2. 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[2]. The world of DAI can be divided into two primary arenas: (1) Distributed Problem Solving (DPS) and (2) Multi-Agent 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[3]. 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. System Architecture

IES generally consists of three sorts of principal sub-systems as shown in Fig. 1: (1) task planning sub-system (TPS), (2) task execution sub-system (TES), and (3) human control sub-system (HCS).

3.1 Task Planning Subsystem (TPS)

TPS is responsible for identifying and planning of filed operation tasks that have been confided to it. This sub-system 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 sub-system (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.

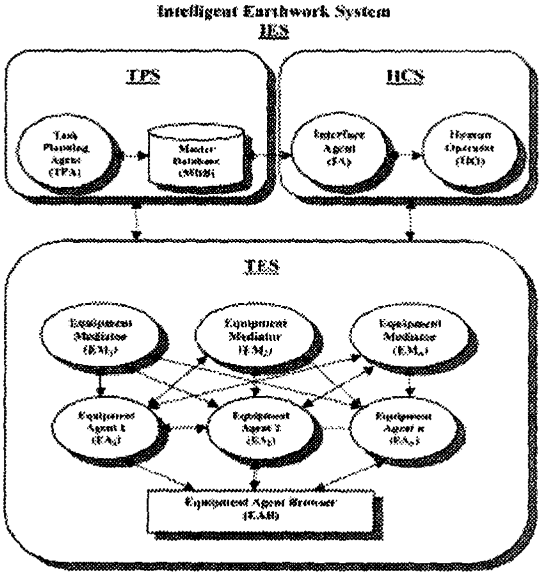

Fig 1. Principal Subsystem of IES

3.1.1 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, 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.

3.1.2 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 pre-requirements 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.

3.2 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 sub-system 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.

3.2.1 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.

3.2.2 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.

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.

3.2.3 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 break-downs, repair time distribution, move-in and hourly cost, etc.

3.3 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 agents status through the interface agent (IA). With data visualization, it is easy to determine work volume, work progress, and equipment status.

3.3.1 Interface Agent (IA)

IA provides human operators with interactive tools that are used to visualize data, to monitor status of IESs agents, and to input changing human operators 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 operators 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.

3.3.2 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 agents capability. Thus, HO acts as a supervisor of IES.

4. System Control Strategy

Recent research on multi-agent 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 multi-agent systems. This approach decreases design complexity, and is very reactive and highly flexible. Agents in multi-agent 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[4].

The system control strategy for IES should be capable of adapting to emerging tasks and changing environment, and managing uncertainty such as equipment break-down 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. 2. 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

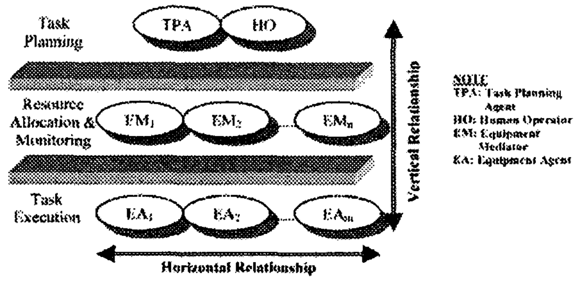

Fig 2. Functional Layers of IES Constrol Approach

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 earthwork 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.

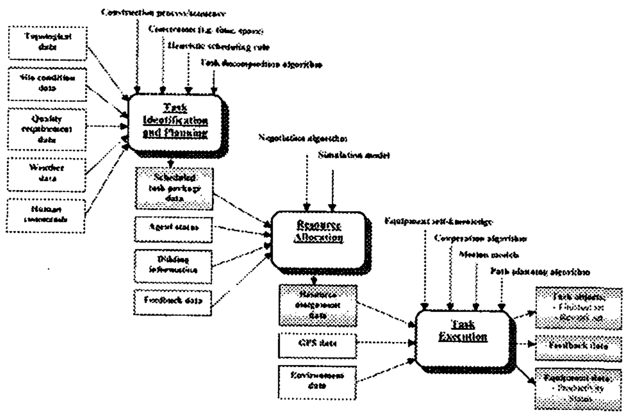

Fig 3. Information Flow in IES

5. Task Identification

To identify the task, the quantities of materials to be cut and filled should be determined from several input data (e.g., topological data, site condition data, quality requirement data, and weather data). Previous researches show that the earthwork volume can be evaluated by using a mass haul diagram that has long been used for the movement of materials or by applying heuristic and mathematical techniques. Previous methods, however, cannot be directly used for IES because they do not provide detailed information for field operation performed by IES agents.

5.1 Construction Site Partition

Using the quadtree algorithm, which is a data structure based on recursive decomposition, the construction site can be partitioned into several work areas, called *work cells,* as shown in Fig. 4. The size of a cell can be changed by the work volume that can be performed by one or a group of equipment within a certain period of time. In order to achieve more efficient task execution, the cell can be divided further into several small areas whose size is determined by the dimension of construction equipment. To represent work cell data, hierarchical data structure is used.

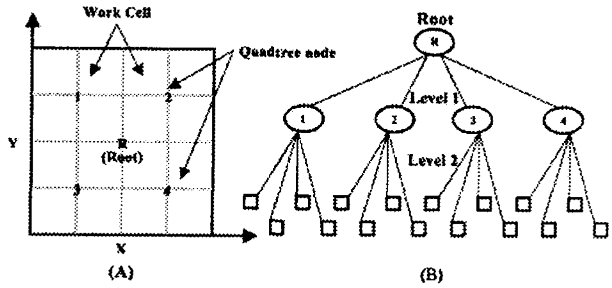

Fig 4. Construction Site Partition
(A) Construction Site and (B) Quadtree Data Structure

```
Work Cell
{
<Cell number>          { Integer number }
<Color>                { Black, White, Gray }
<Position>             { Center (X0,Y0,Z0), Upper right (X1,Y1,Z1),
                         Upper left (X2,Y2,Z2), Lower right (X3,Y3,Z3),
                         Lower left (X4,Y4,Z4) }
<Parent node>          { Node number }                // Pointer
<Sibling nodes>        { Sibling work cell numbers }  // Pointers
<Children node(*)>     { Children node numbers }      // Pointers
<Type of soil>         { Sand, Rock, Clay, Common soil, Clay-sand and rock mixture }
<Soil consolidation>   { Low, Medium, High }
<Swell factor>         { Number }
<Shrinkage factor>     { Number }
<Work volume>          { Planed cut (P_Cut), Planed fill (P_Fill),
                         Current cut (C_Cut), Current fill (C_Fill) }
}
                                                      Note: (*) Option
```

Fig 5. Data Fields of a Work Cell

After partitioning the construction site, the cut and fill volumes for each cell are calculated from input data. The volume calculation is easily achieved by surface-to-surface comparison with cut and fill contours or surface to a planed plane. Every work cell is an object and has information on node number, nodes color which represents the type of node, its coordination according to the entire construction site configuration, type of soil, cut and fill volumes, swell and shrinkage factors, and its parent, siblings, and children nodes (see Fig. 5). After partitioning the construction site, the cut and fill volumes for each cell are calculated from input data.

There are three available types of colors: *black, white,* and *gray.* A cell is said to be type *black* if its cut volume is larger than its fill volume, so it can provide other cells with soil. A *white cell* needs soil to be filled, spread and compacted. The difference between its cut and fill volume should be transported into this cell.

When the amount of cut volume is equal to that of fill volume, cut and fill volumes are zero, or earthwork has been done in a cell, this cell is a *gray cell*.

5.2 Task Object

The task object is an object that includes a specific task to be completed in a certain work cell, quality requirements, and the field operation level of detail (the second-level task) within a given task category. It has several data fields as shown in Fig. 6, which describe the characteristics of a task to be performed by individual or a group of equipment. It is created when one of the work cells for the field operation is selected, and the type of the field operation is identified. The object is temporarily stored in an initial task object list.

```
Task Object (TO)

{
<TO number>     { Integer number }
<What>          { Earthwork:
                  Stripping, Pushing, Hauling, Spreading, and Compacting }
<Where>         { Cell number }        // Pointer
<Quality>       { Density, Slope }
<Status>        { Enumeration type:
                  Initialized, Activated, Processing, and Done }
}
```

Fig 6. Data Fields of a Task Object

5.3 Task Package

A task package represents a set of correlated task objects. As shown in Fig. 7, it consists of a source, at which soil to be transported is stripped, and one or more targets, at which the stripped soil is transported. So, it will require one or more task objects to be completed and these task objects are accomplished by stripping, pushing, hauling, spreading, and compacting. The task package keeps information on how much soil volume is transported where.

```
Task Package (TP)

{
<TP number>     { Integer number }
<Source>        { Task object number: Volume }            // Pointer
<Targets>       { Task object number(s): Volume(s) }      // Pointer(s)
<Status>        { Enumeration type:
                  Initialized, Activated, Processing, and Done }
}
```

Fig 7. Data Fields of a Task Package

There are five types of task package as shown in Fig. 8. Basically, a task package consists of one or more task objects, a borrow pit, and/or a stockpile. The stripped soil is moved from a black cell to one or more white cell (Type 2). When there is no available white cell receiving soil any more, the soil is transported to the stockpile (Type 3 and Type 4). If there is no task object with a black cell in the activated list and there are one or more remaining task objects with a white cell, the soil is transported from a borrow pit to the white cell(s) (Type 5). Type 1 is a special case which means only one work cell is included in the task package. The stripped soil is moved from one portion of a cell to another portion of it. A series of operations such as stripping, transporting (pushing or hauling), spreading, and compacting can be modeled by a task package.

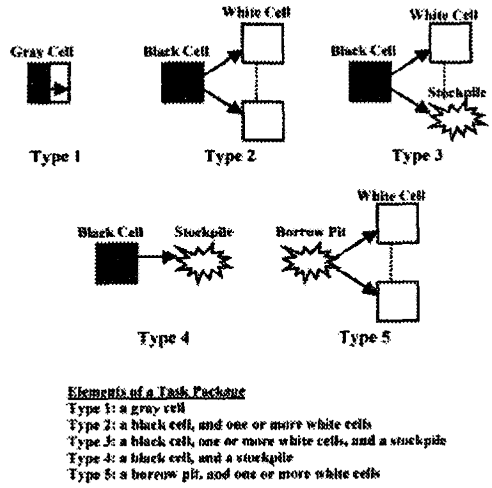

Fig 8. Five Types of Task Packages

6. Task Scheduling

The main goal of task planning/scheduling is to identify the optimal sequence of task packages in real-time to achieve the global goals of IES, such as the fastest field operation completion and the maximization of equipment utilization. Since the amount of equipment is limited, the amount of equipments idle time should be minimized, and the productivity of equipment should be maximized to achieve the maximum system efficiency and expedite project completion. When task packages are scheduled with multiple equipment agent fleets to achieve the goals of IES, space constraints should be reflected when deciding the priority of task packages. If several equipment agents share the same physical space at the same time, this situation will result in the reduction of work productivity. When considering space interference between two task packages to be scheduled or between task package-in-progress and a task package to be scheduled, it is possible to achieve effective task scheduling that can expedite field operation completion.

Since the performance of a scheduling policy mainly depends on characteristics of a problem domain, there is a need to develop a scheduling heuristic procedure that reflects the special context of IES.

Rule 1: No-Space Interference First (NSIF) - Every task package has a source and one or more target objects. If a target object is correlated with several sources, which means that stripped soil is transported from several white cells to fill the cell of the target object, and two or more equipment groups are involved at the same time to transport the stripped soil to the target cell, there will be space interference that will result in the decrease of productivity. When task packages are prioritized, the space interference of target objects should be considered in order to improve the productivity of field operation. The task package to be scheduled, which has no target object that has space interference with the target objects of task packages in progress, has higher priority. Even though a task package has no space interference, if the task package has a source that is the sibling work cell of a task object of task packages in progress, it should not be scheduled for the available equipment group to avoid possible space interference. If there are several task packages that have no space interference, then the next rule, Shortest Travel Distance First (STDF), is applied.

Rule 2: Shortest Travel Distance First (STDF) - If a task package should be scheduled for an available equipment group and there are several task packages that have the same priority on NSIF, the task package nearest to the source object of the previously completed task package should be scheduled first, in order to minimize the travel distance. If there are also several task packages that have the same priority on STDF, then the last rule, Random (RAND), is applied.

Rule 3: Random (RAND) - Remained ties can be broken by random order. Any task package is randomly scheduled for an available equipment group.

7. Resource Allocation

7.1 Agent Cluster

To achieve effective and efficient earthwork operations, IES should not be a static structure, because the continuously changing environment requires an adaptable and flexible system structure. When task packages are identified and scheduled, an equipment mediator (EM) for each task package is created. One of the EMs roles is to coordinate a cluster of a group of equipment agents (EAs). Basically, the agent cluster (AC) is a functional group of an EM and heterogeneous EAs, which will exist only for the period necessary. Clustering is triggered by the construction of an EM, is modified as needed, and is destroyed at the completion of the given earthwork operation tasks. The total number of agent clusters, which can be constructed at the same time, is equal to the default number of equipment groups.

The Task Execution Sub-system (TES) in IES is linked to MicroCYCLONE simulation system, and begins the simulation process to determine the optimal size of an agent cluster (AC) for the better utilization of resources and efficient task execution. As mentioned earlier, AC has a dynamic structure, which means the size of the AC can be changed during task execution. A task package consists of a source and one or more targets. Due to the change in the locations of the source and targets, the optimal amount of equipment is changed based on the different haul distances.

7.2 Negotiation Processes for Resource Allocation

The EAs negotiate with the EM by message passing to achieve goals for effective resource allocation. Mutual agreement is reached through communication.

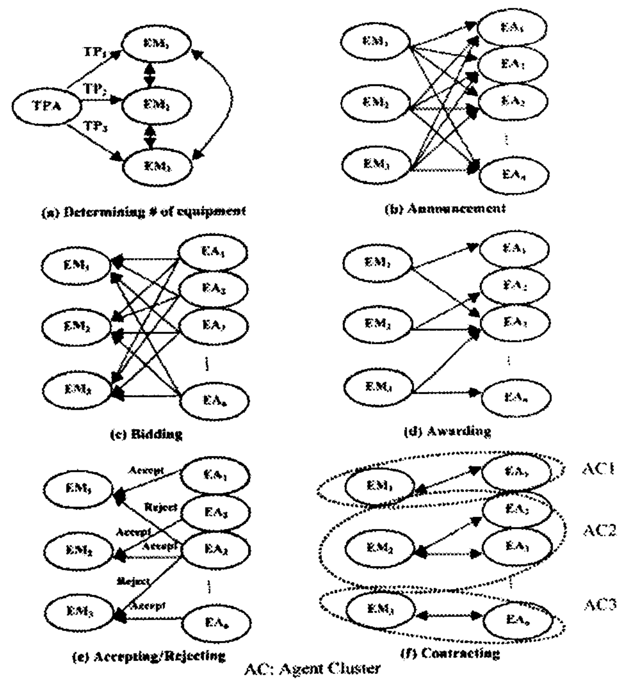

Fig 9. Negotiation Process for Multiple EMs

Suppose three agent clusters can be constructed at the same time as shown in Fig. 9. At step (a), the optimal amount of equipment for each cluster is determined, and if needed, the number of EAs for each cluster is further rearranged through negotiation between EMs. It is assumed that the EM has pertinent information it requires to determine resource requirements and its priority in selecting resources. At step (b) and (c), the EMs broadcast a call-for-bids message to all available EAs, wait for EAs replying messages, evaluate submitted bidding values, and then select one or more EAs for execution of the task. If an EA is selected by several EMs, the EA can accept only one award, as shown at step (d) and (e). In this case, after establishing mutual selection, a contracting process is completed and the EA that completes the contracting process is not considered as an available EA for another task execution until the given task is executed. Finally, at step (f), three agent clusters are constructed for task execution.

If an EM does not finish selecting the required number of EAs, steps (b) through (f) are repeated until the required number of EAs are selected or a given contracting time is out. Even if the required number of EAs has not been selected for an EM, when the contracting time is out the EM begins task execution. The Contract Net[5] concept is adapted for the negotiation process. However, it does not provide any means to assign a task to available EAs after completing a contracting process. To solve this problem, an additional process is suggested, in which an EM can select available EAs during task executions, if needed. This approach is very useful to deal with unexpected conditions (e.g., equipment break down). For the maximum efficiency of IES, all available resources should be assigned to earthwork operation tasks.

8. Summary

The framework for an intelligent earthwork system (IES) is suggested in this paper. It generates a plan automatically for construction equipment, and provide a means of cooperation between construction equipment seamlessly. Now some technologies are available for the full-implementation of an IES, such as DAI, GPS, sensor and sensing technology, wireless communication technology, robot path planning technology, and so forth, However, these tehcnologies are not enough. Thus, more advance technologies should be developed and applied.

This paper has described the system architecture and control strategy of the 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. This paper has also presented automated task identification method for construction equipment and effective resource allocation method for IES.

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요 약

최근 건설장비 및 시스템의 지능을 높이기 위한 요구가 증대되고 있다. 특히 건설산업에 영향력을 미칠 가능성 큰 반자동 및 자동화 시스템은 지속적으로 변화하는 환경내에서 임무를 스스로 수행하기 위하여 필요한 지시와 계획을 생성하기 위하여 인공지능 접근법이 필요하다. 본 논문에서 인텔리전트 토공시스템을 위한 프레임웍을 제시하고자 한다. 인텔리전트 토공시스템은 자동으로 건설장비를 위한 계획을 생성하고, 건설장비간에 협력을 할 수 있는 방법을 제시한다. 인텔리전트 토공시스템의 구조, 제어방식, 계획 및 자원배당 방법을 본 논문에서 제시하고자 한다.

키워드 : 건설자동화, 토공, 분산인공지능, 에이전트 기반 시스템