FRAMEWORK FOR AN INTELLIGENT FIELD OPERATION SYSTEM (IFOS) : PART 1 – SYSTEM ARCHITECTURE

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Abstract: In spite of the difficulties in designing and implementing automated technologies. the needs for improvement in safety. productivity. and quality have motivated several research efforts in the area of automation and robotics in construction. Recently. there has been an increase in demands to enhance 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 field operation system (IFOS) 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 emerging technologies that can be adapted to implement an IFOS. the system architecture. and the system control strategy for IFOS.
Keywords: Intelligent system. Automated planning. Agent-based system. Field operation

1. INTRODUCTION

There have been increasing demands to enhance intelligence of construction equipment and systems. A limited amount of research. however. has been conducted in developing intelligent construction equipment and systems. Many researchers have investigated the addition of sensors and control systems to existing construction equipment. 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) is required to generate instructions and plans necessary to perform tasks in dynamically changing environments on their own.

The major goal of the research conducted by the authors is to develop a conceptual framework for intelligent field operation system (IFOS) that will enable a group of construction equipment to automatically generate tasks and to efficiently perform field operations such as earthmoving and landfill operations in a cooperative manner. 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.

This paper describes some emerging technologies that can be adapted to implement an IFOS. and describes its system architecture. The system control strategy. then. is suggested. Finally. information flow between functions is explained. The methodology of automated task planning for IFOS is suggested in another paper submitted to ISARC 2001.

2. AVAILABLE TECHNOLOGIES

There are several emerging technologies that can be adapted to implement an IFOS. The IFOS cannot be successful without efficient and proper real-time monitoring. controlling. and decision-making abilities. Other industries such as the mechanical and manufacturing industries are valuable sources of these technologies. Although some technologies from other industries are not directly suitable for the construction industry. a little modification will satisfy the needs. The technologies used for IFOS are briefly reviewed in this section.

2.1 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 [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 IFOS. 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 field 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 field operations. An example of tasks involved in field operations are stripping, hauling, spreading, and compacting.

2.2 GPS and Sensor Technologies

The global positioning system (GPS) is a worldwide satellite-based navigation system operated and maintained by the U.S. 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 [4].

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 [5]. 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 IFOS, 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.

2.3 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 multi-voice channels, full-motion video, and computer data [6].

Wireless communication technology is very important for the field 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.

3. SYSTEM ARCHITECTURE

The main goals of IFOS are (1) to generate a plan automatically for construction equipment that performs field operations such as stripping, pushing, hauling, spreading, and compacting of soil or solid waste materials in continuously changing environments, (2) to rationalize quality control corresponding to the execution by construction equipment, (3) to provide a seamless means of cooperation between construction equipment, and (4) to reduce worker requirements and improve worker's safety. IFOS generally consists of three sorts of principal sub-systems as shown in Figure1: task planning sub-system (TPS), task execution sub-system (TES), and human control sub-system (HCS). Following is a brief description of each sub-system.

➢ Task planning sub-system (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 field 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 IFOS.

➢ Task execution sub-system (TES)

TES is responsible for performing field 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 field 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), uncompleted tasks are added into a rework list.

➢ Human control sub-system (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 IFOS 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 IFOS. 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.

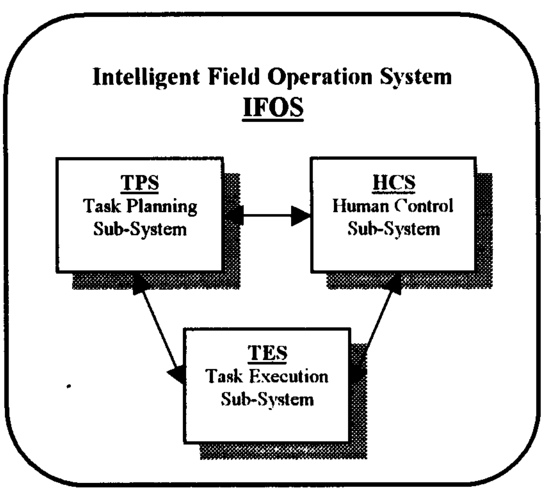

Figure1. Principal Sub-Systems of the IFOS

All sub-systems in IFOS are mutually connected with radio LAN. Using the latest information telecommunication technology, each kind of required information on field operations such as control of work volume, control of operation process, quality control, etc., is shared seamlessly. IFOS is on the evolutionary link between the pre-programmed operation system and the fully autonomous operation system.

3.1 Agents of Task Planning Sub-System (TPS)

The principal sub-systems and their corresponding agents for IFOS are presented in Figure 2. TPS consists of a master database (MDB) and a task planning agent (TPA). Each element of TPS is described next.

➢ 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 field 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) tasks 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 is being processed in task planning and executions. Whenever the field operation tasks are done by equipment agents, this database is updated.

➢ Task planning agent (TPA)

TPA extracts information on topological and terrain data, site-specific parameters, work quality, and constraints from MDB to determine field operation tasks. It performs automated volumetric calculations to find out the amount of materials removed, placed, and compacted for each cell, and then identify tasks for field 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 Agents of Task Execution Sub-system (TES)

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

➢ 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 field 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 IFOS with lower-level decisions for the task execution unless critical situations occur.

➢ 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, craw 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 field 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* 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 can be added or dropped.

➢ Equipment agent browser (EAB)

EAB is responsible for finding all EAs queried by the interface agent (IA) 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 Agents of Human Control Sub-system (HCS)

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

➢ Interface agent (IA)

IA provides human operators with interactive tools that are used to visualize data, to monitor status of IFOS's 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 human operator's requests, and resolves conflicts and inconsistencies in information, current tasks, and environmental models, thus improving decision-support capability of IFOS. Humans can be able to control the amount of agent autonomy through IA.

➢ Human operator (HO)

IFOS is neither always under the control of humans or agents in IFOS, 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 IFOS.

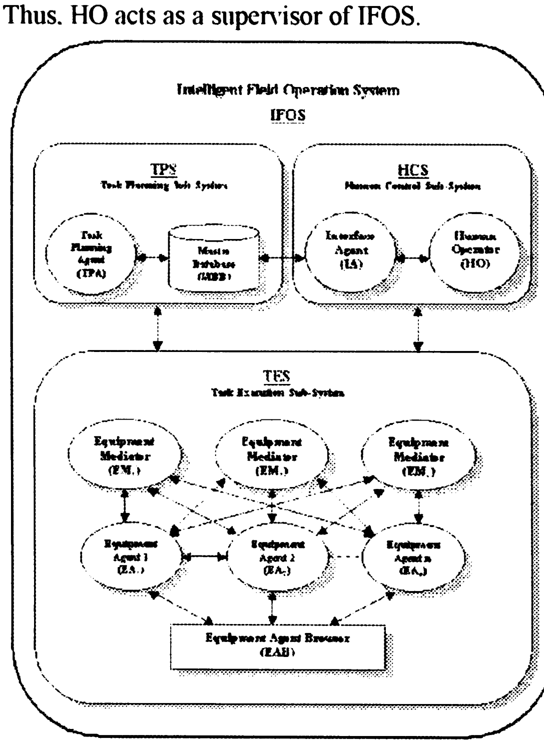

Figure 2. Agents of Sub-systems

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, heterarchical 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 heterarchical control approach have a high degree of autonomy. However, even with a complex control such as centralized control approach, it is hard to predict system behavior and performance, it takes relatively long time to do decision making, and it is difficult to realize global optimization [7].

The system control strategy for IFOS should be capable of adapting to emerging tasks and changing environment, and managing uncertainty such as equipment brake-down in order to meet the needs of field operations. To achieve this adaptability and reconfigurability, hybrid control approach which is a partially hierarchical and partially heterarchical approach is used for IFOS. This control approach aims at ease of extension and modification, more flexible decision-making, and more effective error recover. The functional layers of IFOS control approach are presented in Figure 3. Each layer can be composed of various agents, which collaborate and negotiate with each other to execute field 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 IFOS' agents are used in the system: a vertical relationship and a horizontal relationship.

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 field operation tasks and globally schedules them based on information gathered from EDB and HO. EMs are obliged to attempt to announce tasks identified by TPA and make a contract with EAs to assign field 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.

Horizontal relationship means interaction among a group of EAs. EAs can exchange information on field operations, their locations, and their availability. This exchange is not performed hierarchically; rather it is associated with the aspects of conflict and cooperation. Each agent is responsible for its own movements and actions it should take on the basis of interaction with other agents.

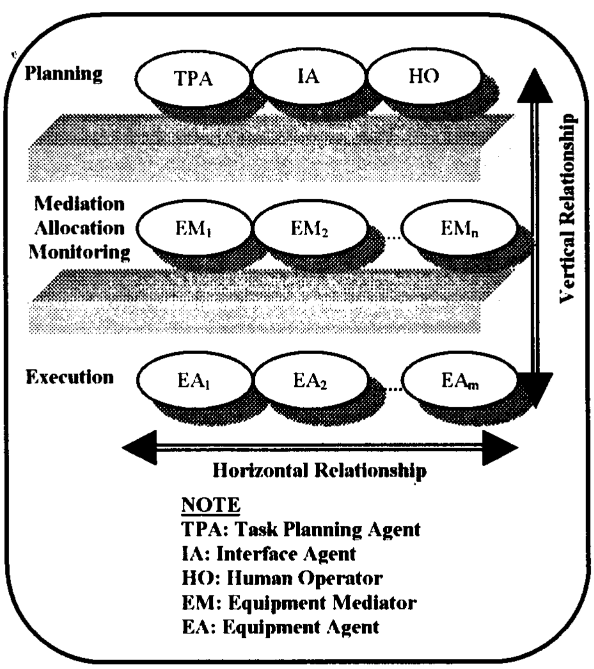

Figure 3. Functional Layers of the IFOS Control Approach

5. INFORMATION FLOW

IFOS 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 and monitoring. The flow of information between functions has to be modeled in a precise manner to maintain the soundness of the proposed system. Figure 4 briefly represents the conceptual information flow model and the interaction between system functions of IFOS. To implement a real system, the interactions between functions can be more complex to represent all microscopic information flow and controls of an intelligent construction system.

The graphical model in Figure 4 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 IFOS' 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.

(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 pre-established rules or criteria, the task identification and planning function performs several sub-activities. This function processes information and data from input for task planning to decompose a construction site into several cells, which are designed for effective field 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 IFOS. 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 IFOS. Input to this function is provided by task allocation function activity. To perform various sub-activities, 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 re-task allocation support, equipment productivity calculation, and feedback data collection.

6. SUMMARY

This paper has briefly reviewed three available technologies to help implement an IFOS such as GPS, sensor and sensing technology, and wireless communication technology. For the full-implementation of an IFOS, the three technologies mentioned above is not enough. Thus, more advanced technologies should be developed and applied. This paper has also described the system architecture of IFOS in detail. It consists of task planning sub-system (TPS), task execution sub-system (TES), and human control sub-system (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 IFOS and the functional layers of the IFOS control approach are presented here. The flow of information between functions is modeled.

The methodology of automated task planning for IFOS is discussed in another paper submitted by the authors to ISARC 2001.

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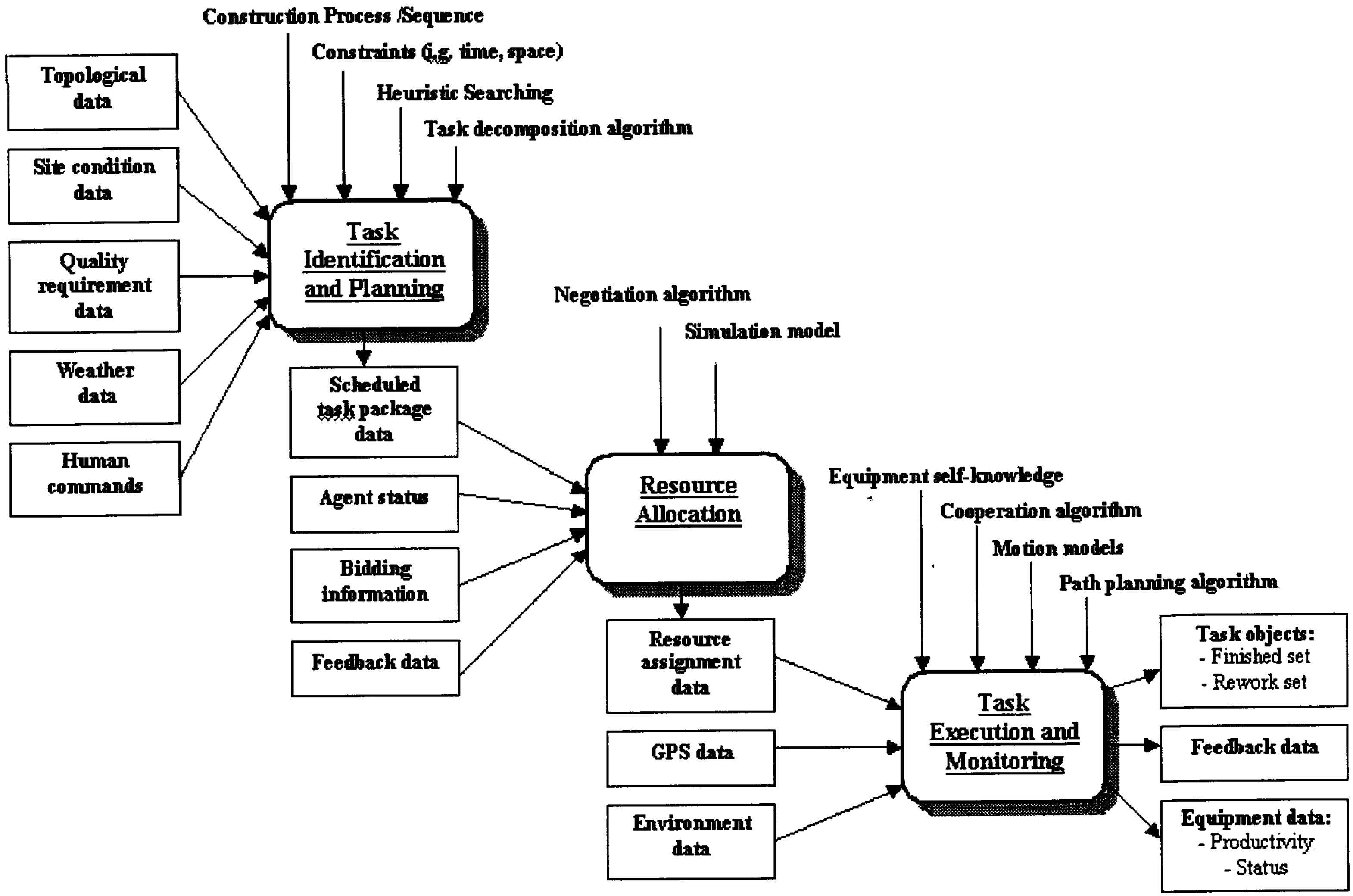

Figure 4. Overview of Information Flow in IFOS