William L. WHITTAKER
Esfandiar BANDARI
Construction Robotics Laboratory
The Robotics Institute
Carnegie Mellon University

A Framework for Integrating Multiple Construction Robots

Abstract

This paper presents a speculative framework that embodies multiple robots carrying out construction tasks. We first discuss the nature of construction tasks and the need for multiple automatons. We then present the major elements of our framework: host, automatons, and human interfaces. Finally, we explain how the framework enhances modeling, interpretation, and strategic and tactical planning.

Introduction

Robots are emerging in construction as a way to increase productivity, improve quality, and decrease hazards to human workers. To date, construction implementations have been predominantly teleoperators and programmable machines. The ideal construction robot senses, models, moves and acts purposefully to synthesize a built facility within the work environment, but this capability is a distant ideal. Research has speculated on the forms, architectures, issues, and agenda to challenge individual construction robots, and implementations are emerging that address these challenges.

However, these individual robot forms, though necessary, are not sufficient to achieve typical construction goals. For example, a common construction task, asphalt paving, requires the cooperative capabilities of three types of equipment: trucks for material delivery, a paver for asphalt placement, and a roller for compaction. The requirement for multiple capability at the automated work site must be served by multiple cooperative robot agents.

The introduction of multiple robots to the work site raises issues distinct from those for individual machines. Central coordination by a host is necessary to plan, monitor and optimize communal construction goals. Protocols and methods of interaction are necessary for the flow of plans, commands, and information between the host and the robotic construction fleet. As with individual robots, human interfaces are essential for intervention when complex operations frustrate a multiple robot system's ability to cope with challenges. Thus individual cognitive automatons, which in the past interacted with the human supervisor and the work site only, must now cope with the added interactions of a coordinating central host and robot peers.

Given multiple robot agents at the work site, we need to speculate a framework to embody the multiple robot pursuit of a construction goal. In the remainder of this paper, we propose such a framework and describe its elements, interrelations, and utility to construction robotics.

Architecture and Interfaces

Construction consists of complex and concurrent activities in an unstructured, rugged environment. Because of the special demands of such work sites, construction automation requires an architecture that can address, among other issues, coordination of cognitive machines, strategic planning and optimization, local tactical planning, and machine-machine interaction.

While we are chiefly concerned with the domain of construction robotics in this paper, it should be noted that the architecture we propose is not domain-specific. It is easily applicable to unstructured tasks in other fields, including subsea activities, mining operations, and hazardous waste cleanup.

Figure 1 shows a simplified representation of our speculative architecture. The major elements are a *host* for global planning and optimization, a fleet of repair *robots* for local planning and task execution, and *human interfaces* for supervision and operator intervention.

Host

The host is the central decision-maker of our architecture, a counterpart to a human superintendent. Its principal elements are a global model for representation of the domain, planners for setting sub-goals, evaluators for assessing progress, communication links to the construction fleet, and human interfaces for supervision and input. The primary objectives of the host are global optimization of construction tasks and coordination of agents to achieve communal goals.

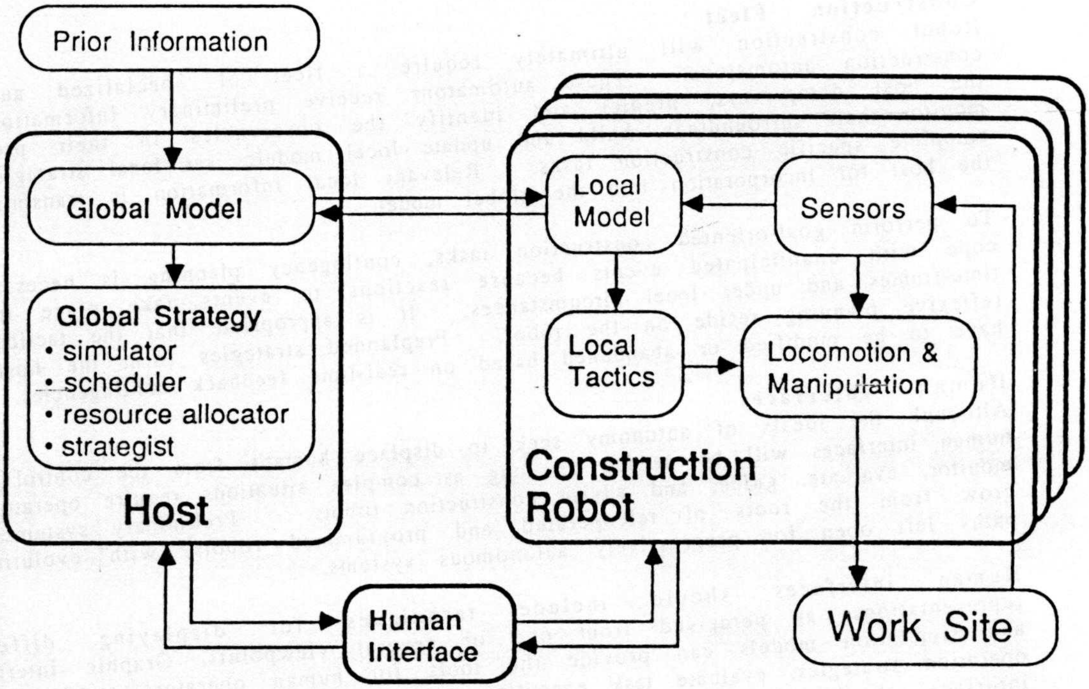

Figure 1: System Architecture

The global model is the principal representation of the real world to the host and its robots. Global modeling is initiated by prior information from designs and site characterization. The model is a dynamic knowledge representation of the real world with access and updating to absorb information gathered during construction operations. The host accesses the physical, geometric, symbolic, and logical representations of objects and relationships in the global model to: evaluate construction operations, conduct high-level planning and optimization, and monitor and control the status of work. By evaluating the status of construction needs from continuously evolving knowledge, the host partitions the construction activities into tasks and determines the criticality, duration, and resource requirements of each operation. Subsequently, the host conducts effective planning, sequencing of operations, and final delegation of machine responsibility. By monitoring the construction progress and machine performance, the host re-evaluates its strategic planning and schedules to develop alternative approaches when appropriate.

To summarize, the host retains a global model of the site and the status of operations in progress. It evaluates global construction repair activities, formulates global plans and schedules, optimizes the sequence of operations, delegates robot responsibilities, monitors performance and progress, and reevaluates its decisions. As the repository of the global database and dataservers, the host can also assist robots in global navigation, resource evaluation, and generation of local models. Other host responsibilities extend into determination of machine preservation for fault recovery and contingency planning.

Construction Fleet

Robot construction will ultimately require a fleet of specialized automated construction automatons. These automatons receive preliminary information from the host dataservers, predict and identify the observables in their proximity, monitor their surroundings, build and update local models, set local strategies, and complete specific construction tasks. Relevant local information is transmitted to the host for incorporation into the global model.

To perform goal-oriented construction tasks, contingency planning is necessary to cope with unanticipated events because reactions to events take place in fast time-frames and under local circumstances. It is appropriate that the tactical and reflexive planning reside on the robot. Preplanned strategies form the host may have to be modified or abandoned based on real-time feedback contingencies.

Human Interfaces

Although the ideals of autonomy seek to displace humans from the control loop, human interfaces will be needed as long as complex situations require operators to monitor, evaluate, guide, and advise construction robots. Preliminary systems will grow from the roots of teleoperated and programmed robots, with evolutionary paths left open for progressively autonomous systems.

Human interfaces should include techniques for displaying different representations, as perceived from one or several viewpoints. Graphic interfaces and simulation models can provide the tools for human operators to investigate operation strategies, evaluate task execution, and analyze local tactics. The human interface should also support hardware devices such as joysticks, mice, and keyboards. The resulting system should enable the human operator to select the appropriate level of abstraction to interact with the system, to select what aspect of the world to see, and to input parameters and commands when necessary. Human intervention can increase the reliability, fault tolerance, and overall performance of the system.

In general, human intervention may take any of the forms of: onboard operation, remote teleoperation, supervisory control at the tactical level, or access to the global strategy for high-level supervision. Each mode has its own virtues and may prove desirable under different circumstances.

Machine Interfaces

The host-machine interface is an essential link for information exchange and optimization. The repair robots communicate with the host through telemetry (radio, microwave, infrared, or leaky coax), and interact with each other through the use of markers, gestures, or direct telemetry.

The host views each individual automaton as a black box or virtual machine able to execute commands, and views the automatons collectively as a network of distributed computing units. A primary responsibility of the robots is to report the dynamic changes in the environment. Each automaton is capable of specific construction operations and only transmits relevant information about its location, job progress, and local model of its environment. Methods for low-level task execution, such as local model building, generation of alternative execution schemes, minimization of manipulator motion, prevention of tool collision, and force-predicated actuation, can be kept transparent to the host without loss in efficiency.

The robots view the host as a global coordinator, database, and file server. Much like management on a need-to-know basis, the host issues commands while keeping its decision-making process a mystery to its subordinates. However, it provides the necessary information to facilitate the machines' operations.

Robot-robot interaction would be adequate for many construction activities, but the central host facilitates automaton interaction and maximizes overall productivity. Direct interaction by automatons, however, removes an unnecessary burden from the host and also serves as a back-up when the host or its communications are debilitated. Automaton-automaton interaction can also be facilitated through the use of physical markers or tokens. This would in turn reduce (or eliminate) automaton dependence on the central host, and reduce the burden on communication channels and sensory units. Tokens can be implemented in the field on a permanent or temporary basis. Permanent tokens, such as embedded magnets or preplaced landmarks, can be used to guide numerous tasks including calculation of position and orientation, calibration of devices, and evaluation of resources. Other uses of tokens may include marking of work space or navigation routes.

Whether the scope of the operation is global (e.g., evaluation, synthesis or optimization) or local (e.g., obstacle avoidance, excavation, or painting), the host and the automatons must model and understand their respective domains and formulate the appropriate strategic and tactical plans for execution.

We now move from a discussion of what the elements of the architecture are to what they do and how they interact. In the next two sections we address modeling, interpretation, and strategic and tactical planning.

Modeling and Interpretation

The ability of a system to operate efficiently is dependent on how high-level abstractions are explicitly represented, understood, and processed. For high-level planning, the global model must provide the host with the necessary physical, geometric, and symbolic representations of the domain. Even more detailed abstractions may be required by the automatons for lower-level tactical planning and manipulation purposes.

While symbolic properties may be represented by schemas, semantic nets, and physical properties, the data should be quickly accessible, adequately detailed, easily understood, and readily updated. Successful construction robots must exhibit local cognition because no motion preplan is final; the work site is dynamic, the work proceeds by discovery, and actions are dictated by needs and contingencies.

Figure 2 illustrates the flow of information and control proposed in this framework. Geometric information is extracted from sensor data as two-dimensional and three-dimensional features and a local model is constructed from the fusion of feature information inputs from the global model. A knowledge source combines the sensor data and identifies physical objects in the scene. Cognition then addresses higher level semantic and cognitive functions such as generating plans for navigation, communication, and task pursuit.

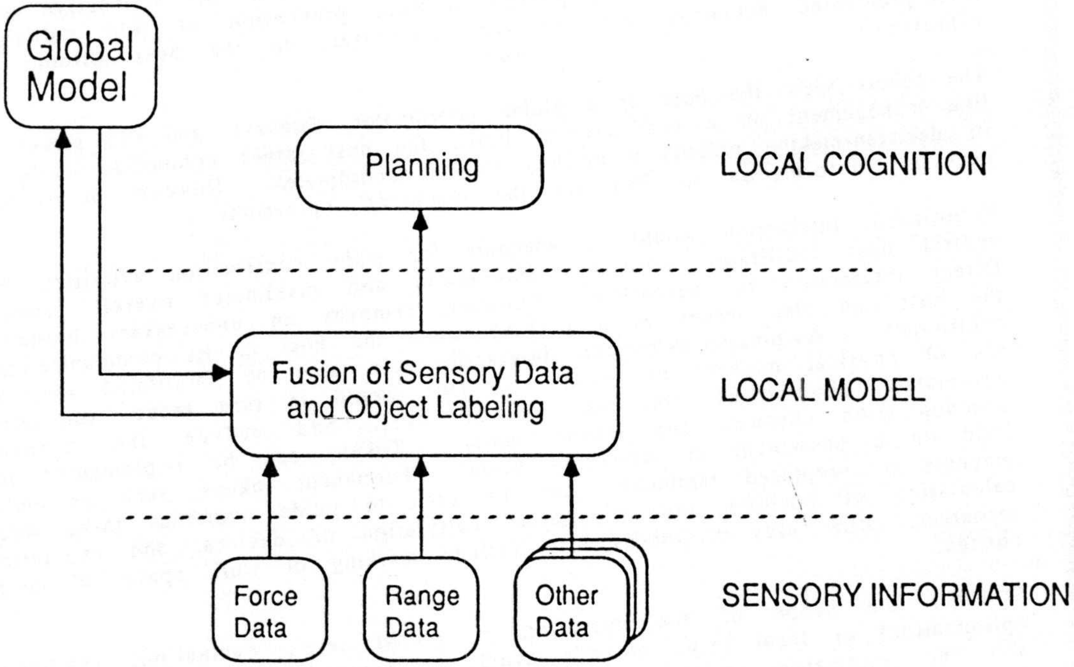

Figure 2: Onboard Abstraction and Planning

Strategic and Tactical Planning

An important function of the host is the strategic planning and orchestration of the autonomous fleet. A host-resident simulation of the construction environment can incorporate data descriptions of the work site, strategic construction goals, and operation planners. Using a knowledge base and simulation or optimization algorithms, the host generates efficient sequences of activities.

Machines are allocated to each construction activity and their location and progress is monitored to update the global model and schedule. Additionally, robots may extract information from the global data base as needed to maximize their own efficiency.

An automaton's software utilities, such as sensor drivers and host interfaces, are generic and modular, facilitating the site integration of multiple machines. However, the local models, reflexes and tactics are specialized to every type of machine. Autonomy requires that each machine embrace resident tactics for the specific tasks of its abilities. Contingency planning and strategic decision-making must also be imbued in the robot for those instances when host-machine relationships fail or are in conflict. These tactical specializations are essential to individual machine effectiveness. The capabilities of the elemental robots within a system govern the effectiveness of the construction system taken as a whole.

Conclusion

Construction provides both the economic incentives and the technical challenge to push the limits of machine autonomy into unexplored dimensions. Beyond the need to develop individual robots that are capable in the unpredictable, unstructured, and dynamic domain of construction, there is a need for a framework that integrates multiple robots on the construction work site. We present such a framework here.

Technical and economic issues will force the construction sites of the future to exhibit a form of organizational structure. At minimum, strategic and tactical planning of operations and optimization of task pursuit will have to be centralized. Toward the goal of cooperating construction machines, we are researching the enabling technologies and the system framework for integrating multiple construction robots. Promising technologies, such as the application of communication and human interfaces to construction subsystems, should be developed with the premise of eventual integration into working systems of multiple construction robots.

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William L. Whittaker
Esfandiar Bandari

Construction Robotics Laboratory
The Robotics Institute
Carnegie Mellon University
Schenley Park, Pa. 15213 USA
Phone: 412-268-2952