Multitask Motion Planning for Material Handling in Construction

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Abstract: This paper describes a proposed system, Multi-Task Motion Planning (MTMP) for planning and modeling operations of large material-handling equipment typically found in construction. The system will provide the capability to effectively plan conflicting multiple tasks to be performed concurrently and also provide a mechanism to directly output code to automate the overall process. MTMP aims at integrating structural dynamic behavior of the equipment at the path-planning stage to resolve conflicts. A geometric/graphical approach is proposed that considers equipment constraints and degrees of freedom. The system is conceived within a three-dimensional computer-aided design (CAD) animation and simulation graphics package, which allows modeling of the environment and provides an interactive tool for motion planning. A capability to store motion variables for individual objects will allow for automatically generating code for automation. The system has been envisioned to meet the demand for automation to improve planning and operational safety in the construction industry. However, the underlying concepts can be useful for a variety of material-handling operations and off-line programming of robots.

Introduction

Developments in technology have resulted in complex structural design and an increased demand to improve planning and management in the construction industry. There is a need to increase automation in the construction process and at the same time increase reliability and safety.

One of the main areas where automation could significantly improve the efficiency of the construction process is material handling during fabrication and installation. The use of robots and other automated material-handling devices in the construction industry has been limited. This is because of the size of both the payload and the manipulating mechanisms. Also, several activities are performed simultaneously in a typical construction environment.

Construction and large-scale manufacturing have multiple material-handling equipment (cranes, loaders, hoists, etc.) that cross each others' paths. This material-handling equipment exhibits significant structural dynamic behavior (deflection, swaying, etc.) under load conditions. If advances in automation for these industries are to occur, a system to model multitask material handling with structural dynamic behavior is required.

A common example of conflicts caused by the operation of multiple equipment is the operation of tower cranes at a construction site. These

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tower cranes working independently have overlapping areas of reach and may interfere or collide during routine material-handling operations. This is a serious safety issue. Effective planning of multiple tasks to be performed concurrently will improve the safety and efficiency of the material-handling process.

Extensive research has been done in the area of path determination. Several approaches have been proposed for planning a collision-free path for a moving object among fixed obstacles. Exact cell decomposition was proposed by Kedem and Sharir (1986). Zhu and Latombe (1991) use hierarchical approximate cell decomposition based on constraint reformulation and hierarchical search for path planning. Kant and Zucker (1989) proposed a two-level hierarchy for path planning that permits velocity alternations but not path alternations. Fujimura and Samet (1989) use an accessibility graph, Shih et al. (1990) use graph search and linear programming for the space-time configuration of free space.

Collision-free motion-planning schemes for multiple objects have been researched by Lee and Bien (1990) and Chang et al. (1990). When the task requires movement of two objects concurrently, collision may occur between the objects if the trajectories are planned independently. Lee and Bien (1990) noted that, when the task requires more than two robots, the collision-free path of each robot may not be determined explicitly by the methods for moving a single object. In particular, the coordination of designated paths is not easily accomplished. Extension of the existing methods for more than two robots is either impossible or too complicated to render any practical solutions. Heuristic methods allowing one robot to move at one time or proposing safe robot trajectories to avoid conflicting space between robots can be used for the collision avoidance of multiple robots. These schemes can be easily implemented, but usually do not take advantage of the capabilities of multiple robots satisfactorily (Chang et al. 1990).

No effective tool has been developed that can effectively model a multitasking system with more than two moving material-handling components. The target industries have many material-handling operations, all performing concurrently. Multi-Task Motion Planning (MTMP) is a novel system that will provide the tool to better plan, model, and control this multitasking environment.

The ability to better plan multitasking material handling lies at the heart of reaching feasible, reliable, and safe work environments. The ability to not only plan the construction sequence but also to plan the actual manufacturing process will be of significance. Given the technology, continuous simulation of the processes will identify areas of conflict, potential delays, methods to alert for critical safety considerations, and an overall planning environment not available at present.

This paper presents a conceptual system MTMP. The paper describes the fundamental philosophy of the system, specifically, the strategy of the required path-planning and dynamic behavior modeler. Current work in these areas is presented. However, full disclosure of these components is left to the references (Morad et al. 1992; Dal 1991).

MTMP System

The MTMP system has been conceived as a complete motion-planning system with extensive graphic-stimulation capabilities. MTMP will provide a tool to model, simulate, and test construction plans and output control code to automate the construction process.

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The MTMP system will incorporate the following:

- A structural dynamics behavior modeler
- A dynamic motion planner capable of resolving multitasking motion conflicts
- The integration of the aforementioned into a simulator that will provide control data for automation/robotics

A broad overview of the MTMP is shown in Fig. 1. The flow of data between the various segments of the system can be visualized from the same. The process of motion planning using MTMP will be as follows:

1. The three-dimensional structural modeler (upper left quadrant of Fig. 1) will allow the user to interactively define equipment degrees of freedom based on the computer-aided design (CAD) model. These will be used to define the objects' relations and constraints and to set up parent-child hierarchies, based on motion dependencies between components.
2. The algorithms for dynamic behavior analysis will be executed. These algorithms will utilize available information on geometry, constraints, and physical properties to predict structural deformations. Parameters that affect dynamic behavior will be stored.
3. The path finder (right half of Fig. 1) will then generate acceptable collision-free paths for each operation, while taking into consideration the limits on motion and the results of the dynamic behavior analysis.
4. A time-based simulation of activities will help identify potential con-

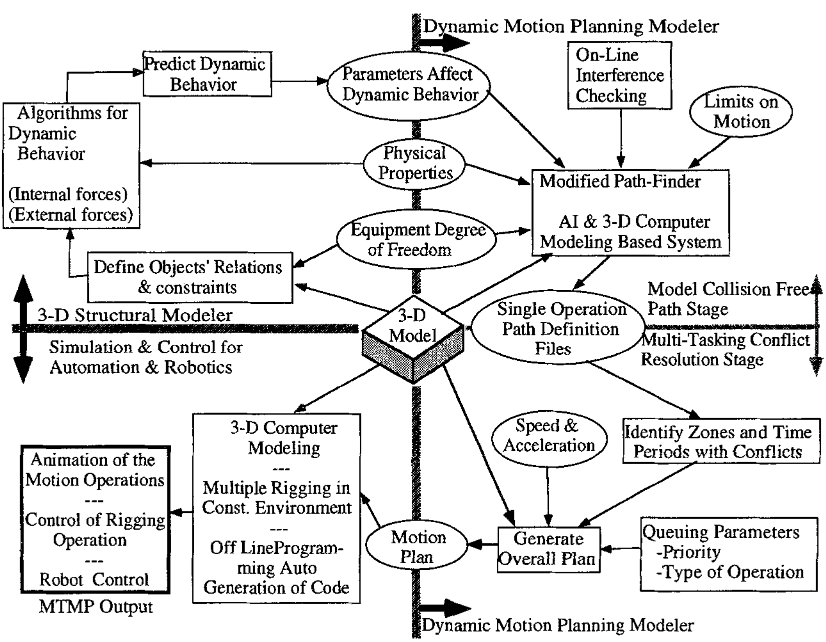

FIG. 1. Data Flow for MTMP System

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flicts. Strategies to resolve these conflicts will be executed based on information on the type of operation and scheduling priorities to obtain an overall plan.

5. Steps 3 and 4 will be iteratively executed to resolve all conflicts and generate an optimized motion plan. The motion plan will then be simulated, checked, and refined, if necessary.

6. The final plan (lower left quadrant of Fig. 1) will enable animation of the proposed work, control for multiple-rigging operations and for off-line programming of robots and equipment.

Three-Dimensional Structural Modeler

Modeling structural dynamic behavior is an essential component of MTMP. The goal is to obtain insight into actual behavior, leading to visualization of real-life performance.

Stringent technological problems, increasing demands for more sophisticated equipments, and an increasing need to visualize real-life performance have generated a growing interest in the development of reliable approaches for the dynamic simulation of systems (Dal 1991).

There has been a steadily increasing interest in self-formulating generalized computer-based programs that can simulate a broad range of mechanical systems such as vehicles and manipulators (Richard et al. 1986). The spectrum of desired capabilities in a general-purpose dynamic design problem is very large—i.e., large element library, static, free vibration and transient response analysis, nonlinear analysis, use of composite materials, and efficient pre- and postprocessing facilities (Rajan and Bhatti 1986).

The objective of the structural dynamic behavior modeler required for the MTMP system is not to develop a large general-purpose design program with such a wide range of capabilities. The main goal is to perform dynamic simulation for computer animation that is essential to accurately model the dynamic response of material-handling equipment (such as mobile crane and tower crane) found in construction. The achievement of this goal ensures realistic visualization and simulation required for efficient and effective multitasking motion planning for equipment.

The specification of motion for computer graphic sequences has traditionally been controlled explicitly by an animator. Also, objects in a scene are looked upon as geometric shapes devoid of dynamic properties. The result is that the animator is forced to use intuition about the physical world in planning the motion of objects in the scene (Hahn 1988). However, motion occurs in the physical world due to forces acting on objects that have shape and mass. There is a need to think of objects in a scene as real objects having mass, moment of inertia, elasticity, friction, etc. To achieve a satisfactory degree of realism, the motion of the objects must be simulated by the physical principles of dynamics governing the motion.

As Isaacs and Cohen (1987) stated, the term *simulation*, rather than *animation* denotes a shift in control from the animator to the underlying physics of the environment. One would like a system for specifying motion that combines the realism of dynamic simulation without removing control from the animator.

General systems for dynamic simulation of linked mechanisms have been described in the literature relating to robotics and biomechanics as well as computer graphics. Wilhelms and Barsky (Wilhelms and Barsky 1985) described a system for dynamic simulation without incorporating the kinematic

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constraints and the associated control strategies. Armstrong and Green (1985) also described a system based on alternative dynamic formulation. Isaacs and Cohen (1987) introduced a system, DYNAMO, based on dynamic simulation for computer animation. Witkin et al. (Witkin et al. 1990) aimed to use physical simulation as an interactive medium for building and manipulating a wide range of models. Schroder and Zeltzer (Schroder and Zeltzer 1990) implemented an algorithm for rigid-body dynamics that unifies the advantages of linear recursive algorithms with the advantages of earlier linear algebra–based constraint force approaches.

Although similar in concept, the major difference between the various methods is the approach to formulating and solving the equations of motion. Among various methods, the system introduced by Isaacs and Cohen (1987) is the most appropriate approach to deal with the problem being tackled in this work. The structural dynamic behavior modeler described in this section relies heavily on their work. One of the drawbacks of their system is that they have only dealt with the dynamic-motion aspect of the dynamic behavior. However, the response (i.e., displacements) due to dynamic loading should also be considered in dynamic simulation. This issue was addressed in the structural dynamic behavior developed for the MTMP system (Dal 1991).

The structural dynamic behavior modeler developed for the MTMP system has been structured to perform dynamic simulation on mechanisms, such as mobile cranes and robots that are or can be involved in material-handling operations in construction. In addition to performing dynamic simulation for computer animation, the modeler contains three means for achieving control. The three means are:

1. The imposition of kinematic constraints permits traditional animation systems to be embedded within a dynamic analysis. Motion of portions of an object can be explicitly specified while allowing the remaining sections of the body to react to the dynamic forces created by this motion.
2. The ability to define behavior functions allows the object to react to surroundings. Behavior functions relate the momentary state of the dynamic system to desired forces and accelerations within the object.
3. A process of inverse dynamics provides a means of determining the forces required to perform a specified motion. Thus, a previously specified action can be transformed into equivalent forces for development of behavior functions or evaluation of stresses within linkage.

The strategies provide control without disrupting the dynamic integrity of the resulting motion.

The structural dynamic behavior modeler requires as input the physical and behavioral characteristics of a linked object placed in an initial state. The initial state of the system contains the starting position and the velocity of the links and an initial time. The physical model includes descriptions of all links and joints, as well as their connectivity. Each link has size, shape, and mass and, thus, a center of gravity and moments of inertia. Each link possesses one joint at which it is attached to its parent link and may possess one or more joints where child links are attached. Links move relative to each other via one to six translational or rotational degrees of freedom associated with each joint. A key to dynamically creating virtual physical objects lies in the proper treatment of joints. Joints provide the glue that combines simple objects to form complex ones. There are several types of joint, and each has different kinematic constraints. Each joint may have associated springs and/or dampers that act to exert internal forces or torques within that joint. Joints may also have associated limits that act to keep the degrees of freedom from moving beyond some point, e.g., the boom of a crane can only rotate within a defined arc about the base of the crane. The links, joints, forces, and position and the velocity of the degrees of freedom form a complete description of the state of the dynamic system at any given time.

The dynamic simulation is treated as an explicit time series analysis. A simultaneous solution is performed at each time increment for the accelerations of each degree of freedom of the dynamic system. These accelerations are integrated with the current state to determine a new set of positions and velocities. The solution is checked to see if any constraints have been exceeded and to see if the accuracy is within a tolerable range. If these tests are passed, the new state becomes the current state and the process is repeated for the following time increment. Time increments corresponding to frame times are recorded for display and playback. Preliminary design and implementation of the structural dynamic behavior have been done (Dal 1991).

At a later stage, a finite element modeler can be interfaced with the MTMP system to yield greater accuracy in computing deflections. At the initial stage, approximate estimates can be obtained to get an insight into actual behavior. The implementation of the finite element modeler will enhance MTMP from a planning tool to a complete system for overall automation of the construction process.

Dynamic Motion Planning Modeler

The dynamic motion planning modeler has been conceived based on the extension of PATH-FINDER (Morad et al. 1992), a joint research effort by Virginia Polytechnic Institute and State University and Bechtel Software. Motion planning is an intermediate step between process planning and process execution in manufacturing, distribution, construction, maintenance, transportation, and many other industrial functions.

The dynamic motion planning modeler will provide multitask planning for the movement of all material-handling equipment within the environment. The motion-planning process should consider the predictions of the structural dynamics behavior modeler and the constraints on the degrees of freedom of manipulating equipment while determining a collision-free path.

MTMP proposes a novel geometric/graphical approach for the path-planning process. The pathfinder is based on an artificial intelligence (AI) approach that uses the state-space transformation representation with a heuristic (directed or ordered) search strategy. The system defines an evaluation function based on minimizing cost (Morad et al. 1992) that improves and expedites the search process by providing a directed-search approach.

The path-finding strategy involves moving the equipment incrementally along available degrees of freedom. A relationship is established between the members of the material-handling equipment and the objects to be moved. For example, if the boom of a crane is moved, the cable and pulley system will also move along with the boom. These relationships are stored within the system in the form of parent-child hierarchies. Such established parent-child hierarchies within the CAD model will result in moving related parts of the equipment and the material. Incremental frames describing the geometry of the changing environment can be computed at short intervals

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of time. Collision detection can be done with the help of an on-line interference detection capability build within the system for each individual frame to detect conflicts. The motion to be performed can therefore be considered a sequence of stationary frames. This helps to reduce the continuous nonlinear time-varying problem of multiple objects in motion to a finite number of static problems. Besides, the path definition obtained will be in the form of joint values (change in position and/or orientation, depending on the type of joint), at short intervals of time, which eliminates the need for an inverse kinematic solution. This is because the frames are generated using forward kinematics for increments along the degrees of freedom of the equipment, which can be stored. The path-finding strategy provides a sequence of incremental values along the available degrees of freedom. This is actually the order in which the joints responsible for performing motion along these degrees of freedom are to be manipulated to achieve the collision-free path.

The path-finding strategy described here will exploit graphics capabilities currently available to obtain a solution based on iteratively executing motion along available degrees of freedom, until an acceptable solution is reached. The use of heuristics provides an objective function to perform a guided search.

A conflict-resolution mechanism needs to be developed to produce a feasible scenario for performing several material-handling processes in a congested environment. The conflicts can be resolved by building mathematical, logical, and graphical models and using a simulation approach. The factors that will influence the conflict-resolution process are:

- Identifying space and time zones where conflicts exist
- Establishment of priorities of processes
- Analysis of processes in terms of continuity (some processes cannot be stopped once they have started)
- Safety considerations based on velocity and acceleration analysis
- Development of a queuing model
- Existence of alternative paths

Simulation and Control for Robotics

A real-time simulation system will form the backbone of the proposed MTMP system. An ideal simulation system should provide the necessary tool for modeling the environment, displaying and storing object motion, and storing object hierarchies, degrees of freedom, and motion constraints. A capability to use models created on commercial computer-aided design/computer-aided manufacturing (CAD/CAM) systems, through direct interfaces or via International Graphical Exchange Standard (IGES), will be an added advantage. Commercially available simulation software can be modified/extended to achieve the required capabilities. An example of such software is the WALKTHRU software marketed by Bechtel Software Inc. (Cleveland 1989).

MTMP has been conceived as a tool developed around a simulation software. The aim is to integrate the structural dynamics behavior and path-planning into one CAD simulation system. This integration will provide the capability for realistic modeling of real-world situations. Such a model can be exploited for automatically generating control data for the manipulating equipment.

The simulation system should provide an on-line interference-detection mechanism to assist the path planner. The interference-detection strategy can be hierarchical and will vary from a primitive proximity search using bounding boxes to a more accurate interference detection at the surface description level. Since the tessellation (subdivision of a complex surface into polygons for a graphics display) of surfaces in the model and the interference detection are both variable, accuracy can be controlled by the user interactively. The capability to vary the exactness of the interference detection will enable the user to maintain the required balance of accuracy versus speed of execution, depending on the application.

Using the capabilities of the simulation system, incremental frames of the changing environment can be computed based on the output of the dynamic analysis. Path planning can then be performed interactively until a feasible solution is achieved.

Once the analysis is performed, the stored frames can be used to create a time-based animation of activities. This may be seen as three-dimensional color-shaded images of objects in motion. Linear interpolation between key frames will make display in real-time possible. It is important to note that the linear interpolation performed will improve speed and will not reflect on actual accuracy of the solution, which has been computed previously. Within the limitations of current technology, the simulation can be presented in real-time although the computation is not.

The simulation system should provide MTMP with suitable libraries for standard equipment and robots along with tools such as grippers and hooks. These libraries must be extensible to allow the user to add more objects if required. Such libraries will provide a complete, robust system for efficiently modeling material-handling operations.

A further goal is to automatically generate control code for material-handling operations. The path-finding strategy, by virtue of its design, will store the incremental steps along the available degrees of freedom for the manipulating equipment. This information can be exploited for automatic generation of code.

There is no universally accepted neutral language for robot programming. MTMP proposes to incorporate two-way interfaces with popular robot programming languages. These will transfer the object motion information recorded within the system to generate control code. Alternatively, existing code can be input to the system and the process can be verified by a simulation.

To achieve reliable off-line programming, a provision will have to be made to incorporate workplace sensors to overcome minor inaccuracies between the computer model and the actual environment. This process is called robot calibration. Currently, acceptable generic calibration procedures have not yet been resolved and, hence, the MTMP system may not be able to achieve reliable autonomous programs for precision work. However, the system will have wide applications in construction and large-scale manufacturing, which is our primary goal. It is important to note that the MTMP system will be an invaluable asset at the planning stage in any kind of environment.

Applications

Construction and manufacturing processes for large objects are two application areas that will significantly benefit from MTMP.

As an example of a construction application for MTMP, the installation

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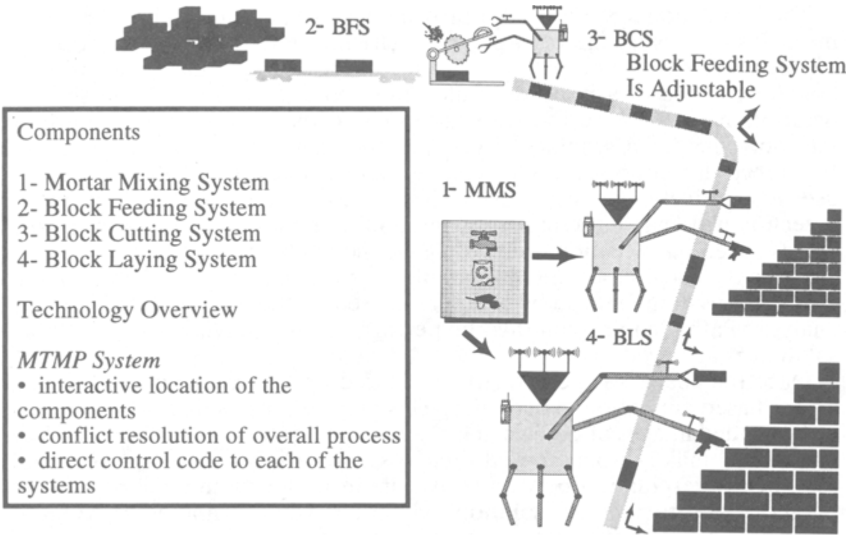

FIG. 2. Multiple Autonomous Vehicle Control for Masonry Construction

of a masonry structure is presented. It should be noted that several strategies can be used for the solution of building a masonry structure; however, only one will be presented here. Consider a case where a project consists of two automated block-laying machines, a block-feeding system, a block-cutting system, a mortar-mixing system, and a mortar-delivery system. A starting location for the first block to be laid is required. All goal states are defined by the final location of each block. The system described here is shown in Fig. 2.

MTMP would be used to interactively locate the components of the operation to plan a strategy for conflict resolution of the overall process. Location for each system and subsequent relocation during operations will be analyzed and a feasible solution would be provided. MTMP would then provide direct control code to each of the systems to meet the goals of building the masonry structure. Finally, sensor technology, for fine adjustments of positions, would be needed for a fully automated process.

Similar examples can be visualized in the area of multiple tower cranes for concrete-placing operations, large steel fabrication cranes, and control of multiple equipment in the hazardous-waste cleanup industry.

MTMP is of significance for construction applications in that it will improve the constructability of construction facilities. The improvement is accomplished by visual simulation of the construction process during the design phase to avoid future constructability problems.

To avoid constructability problems that may result in construction rework, it is necessary to evaluate constructability of each component at the planning stage, within the constraints of the equipment to be used. This will ensure that the scheduling process will generate a feasible sequence (Morad et al. 1991).

With MTMP, design professionals can test their initial sequencing of activities for constructability and future sequencing due to out-of-sequence components. MTMP will help the designers efficiently organize complex construction operations where a lot of material-handling equipment (such as tower cranes, mobile cranes, and forklifts) is involved. MTMP will provide collision-free paths for this equipment and enable designers to achieve significant improvements in the performance of the construction operations. Accidents and rework will be reduced, while safety and productivity will be improved and timeliness will be ensured throughout the construction process.

MTMP is a multipath modeler for multitasking operations. It determines the collision-free routes for the material-handling equipment involved in a construction environment based on position and time. Therefore, if a conflict arises, e.g., if two mobile cranes will interfere with each other, MTMP will provide a strategy to avoid the conflict. This can be done by assigning priorities to the equipment that performs the more critical activity. After the conflict is resolved, MTMP will continue to determine the most feasible routes for other equipment.

MTMP will provide significant advances toward application for multirigging operations. It will help in analysis and planning of multirigging operations where safety is an important issue. Having a feasible solution while maintaining safe tolerances is a significant contribution.

An example is the construction process of installing a reactor core in a submarine assembly. No method exists where deformations can be modeled for each component of the material-handling process, as multiple devices are rigged together. The forced rotations, tilts, lift, etc., of this process exert potentially dangerous loading conditions. There is a need to simulate a feasible solution while maintaining safe tolerances. The direct output of control information can serve to provide user-augmented control, and with limited real-time sensing a significantly improved multirigging planning process will be provided.

Apart from construction applications, MTMP will be able to identify bottlenecks in the movement of material and operation of robots in most engineering environments. Alternatives for the shop-floor layout can be simulated and compared to reduce these bottlenecks. Hence, the system will be able to help in designing an efficient shop-floor layout that will reduce conflicts and increase productivity.

Advances in technology will widen the scope of applications of MTMP. MTMP has the potential to provide an efficient tool for material handling and robot operations in all industrial applications as generic calibration procedures evolve, MTMP will eventually provide an ideal environment for off-line programming of robots. The use of a finite element modeler to predict deflections will enhance the accuracy of MTMP, thereby enabling it to be used in precision manufacturing applications and in the aerospace industry. As speed of computing and animation continues to grow, a real-time strategy for computing and animation with a finite element modeling capability is envisioned.

Conclusion

MTMP will provide a robust tool for multitask motion planning with several applications, typically in the construction industry. This research introduces a novel AI–based geometric/graphical approach to the path-planning problem. This approach reduces the continuous nonlinear time-varying problem of multiple objects in motion to a finite number of static problems and negates the need for an inverse kinematic solution for the selected path.

MTMP considers structural dynamic behavior, equipment constraints on

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degrees of freedom and overloading. Paths determined without considering these issues may not be achievable in practice because of equipment constraints and deflections. This is particularly true for material handling of large objects, because deflections in manipulating equipment are large and, hence, are a primary issue in path planning. A path generated by MTMP will always be feasible.

The proposed MTMP system will automatically generate code to control material-handling equipment. The system can also be used to check the correctness of existing and old programs or to avoid conflicts when two previously distinct programs need to be combined at a later stage.

Work continues on the various components of MTMP at Virginia Polytechnic Institute and State University. The overall system is a long-range effort. The ultimate goals are targeted for a future computing platform. Intermediate results will provide useful tools for the construction and manufacturing industry. MTMP will be a valuable asset in all motion-planning operations.

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