# A HEURISTIC APPLICATION-SPECIFIC PATH PLANNER FOR ROBOT MOTION PLANNING

David G. Alciatore

Department of Mechanical Engineering
Colorado State University
Fort Collins, CO 80523

## ABSTRACT

This paper presents the development and simulation results of a Heuristic Application-Specific Path Planner (HASPP) that can be used to automatically plan trajectories for a manipulator operating around obstacles. Since the implementation of HASPP is inherently application-specific due to dependence on heuristics, the application of HASPP to an eight degree of freedom Pipe Manipulator is presented as an illustrative example. This development and simulation was implemented on a Silicon Graphics Personal IRIS with the aid of WALKTHRU, a 3-D simulation and animation tool, and software developed in C. HASPP uses extensive knowledge of the manipulator's workspace and makes certain assumptions about the environment in finding trajectories. The algorithm also makes use of the manipulator's redundant degrees of freedom to avoid obstacles and joint limits during the trajectory while obtaining a heuristic near-optimal solution. The algorithm is rule-based, governed by heuristics and well-defined geometric tests, providing extremely fast results. It finds "good" trajectories that are optimal within the defined heuristics. When a trajectory is not feasible for the given geometry, the algorithm offers a diagnosis of the limiting constraints.

The Pipe Manipulator HASPP implementation has been tested thoroughly with the computer graphics model and it has demonstrated the ability to reliably determine near-optimal collision-free erection trajectories completely automatically. No other planning techniques available in the literature have demonstrated the ability to solve problems as complex as the example presented here. The use of HASPP with simulation offers many application opportunities including plant design constructability studies, assembly and maintenance planning, pre-planning and pre-programming of equipment tasks, and equipment operator assistance. This work was the result of construction automation research sponsored by the National Science Foundation.

## INTRODUCTION

Finding collision-free pick-and-place trajectories for an articulated manipulator is a very difficult problem. A path must be found for the payload, and at the same time, each of the robot links must be kept free from obstacle interference. A complete discussion on currently available path planning techniques can be found in Alciatore (1989b), Barraquand and Latombe (1989), Lumelsky and Sun (1987), Herman (1986), and Lozano-Perez (1981).

Unfortunately, none of the general algorithms discussed in the literature, with the possible exception of Barraquand and Latombe (1989), are practical in planning paths for realistic applications such as the Pipe Manipulator example presented here. The Pipe Manipulator is a large construction manipulator used for piping construction as found in the building of process industry plants and power facilities (Alciatore, et al., 1989a). The difficulty is due to the large number of degrees of freedom (eight), the complexity of the pipe-rack structures with its many long slender members, and the difficulty of handling 3-D space. HASPP deals with these complexities by utilizing application-specific knowledge of the manipulator kinematics and the environment configuration. The HASPP approach has been successfully applied to the Pipe Manipulator (Alciatore, 1989b) providing a good illustrative example of the method. Although this development is application-specific, the methodology can be readily applied to other manipulators and environments provided adequate rules and heuristics could be ascertained.

It should be pointed out at this time that the HASPP path planner assumes that an accurate world model of the environment exists. This makes it easy to develop and test the developed algorithms in a simulated world where everything is precisely defined, but this assumption is not valid in the "real world" where there may be uncertainties in the environment, in equipment operation and performance, and especially in sensor data. A world model is appropriate if the environment is certain to be completely structured and unchanging as in a well-controlled manufacturing environment, but this is often not the case. Most path planning work discussed in the literature (Barraquand and Latombe, 1989; Lumelsky and Sun 1987; Herman, 1986; and Lozano-Perez, 1981) assume that a world model exists, although some researchers are investigating the development of sensor-based intelligent control systems which deal with uncertainty (Smithers and Malcom, 1987; Lumelsky and Sun, 1987), but an application as complex as the Pipe Manipulator is beyond the scope of these developments. Justification for using a world model in a simulated environment for the Pipe Manipulator example, despite the obvious difficulty involved with on-line control implementation, is that there are many useful simulation applications including plant design constructability studies (Fisher, 1989), assembly and maintenance planning, pre-planning of equipment tasks, and equipment operator assistance.

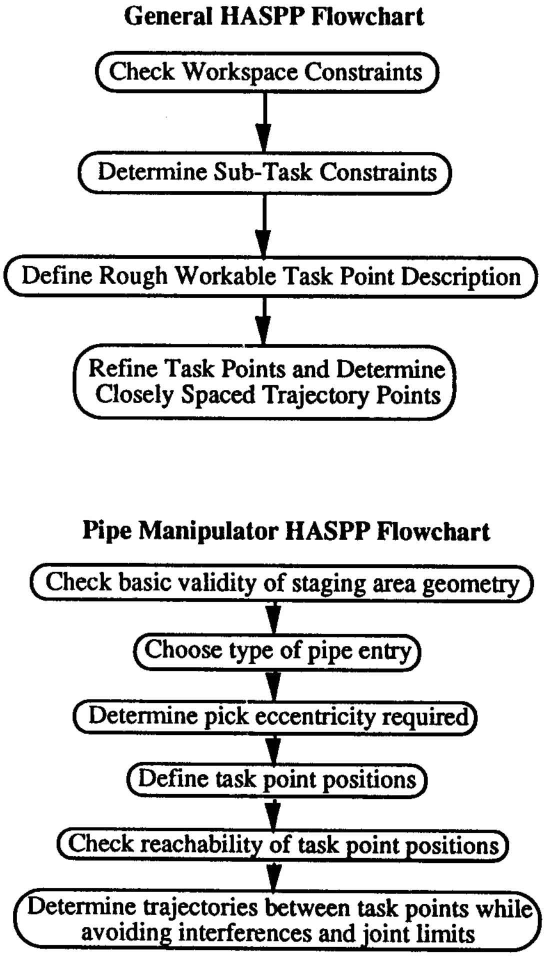
## HASPP STRUCTURE

HASPP is "heuristic" because it is based on a set of geometric rules and guidelines which shape the trajectory. Therefore, the solutions are by no means optimal – the solutions are only as good as the heuristics and rules used. HASPP is "application-specific" because it must be developed specifically for each application. In the example presented in this paper, the application is the Pipe Manipulator erecting straight pipes in a rectangular pipe-rack environment. The HASPP approach uses knowledge of the manipulator kinematics and the environment configuration to define a series of task points (positions of the pipe in space for the Pipe Manipulator) which roughly define the trajectory requirements. Heuristics and geometric analyses are then used to refine these task points and generate intermediate trajectory points and manipulator configurations which define interference-free trajectories between the task points. This series of trajectory and task points are essentially a list of point to point and configuration to configuration motion commands for the manipulator. The general flowchart summarizing HASPP implementation is shown in Figure 1.

Figure 1 also summarizes the flowchart for HASPP as applied to The Pipe Manipulator. Input to the algorithm is a complete geometric description of the staging area world model as illustrated in Figure 2. The staging area geometry is defined by the 24 parameters listed on the figure which completely locate and orient the environment and the manipulator. The assumptions concerning the staging area are that the pick location and manipulator are in front of the rack bay access window plane, that the place location center is within the rack bay volume otherwise the pipe would be installed from an adjacent bay, and that all objects are free from interference. The first step in the algorithm is to verify that these assumptions are met. If an assumption is not met, the algorithm detects it immediately and requests a change in geometry. The rest of the flow chart steps are based on the following geometric rules and heuristics:

- choose the type and direction of pipe entry based on the pipe length, rack geometry, and manipulator placement. This choice will dictate how the pipe enters the pipe-rack access window during the trajectory.
- choose the grip eccentricity, the amount the pipe is picked up off center, as close to zero as possible to avoid torsional boom loads. The specific choice for eccentricity is based on wrist pivot constraints, column obstacle avoidance constraints, and pipe and jaw geometry.
- determine the preliminary trajectory task point locations and check for reachability based on manipulator placement constraints and workspace considerations.
- determine the intermediate task points and manipulator configurations which avoid obstacles, joint limits, and the use of excessive motion.
- avoid rack front-plane interference during swing-past-rack trajectories between task points by constantly changing the pipe orientation and/or by reducing the manipulator boom radius either by lifting and/or telescoping in.
- avoid rack beam interference during access window entry by keeping the boom penetration point in the center of an interference-free zone.

The next section briefly discusses some of the analyses necessary to implement these heuristics. The complete documentation of these and other analyses can be found in Alciatore (1989b). The purpose of these combined analyses and resulting heuristics is to find a trajectory, or determine that a trajectory is not possible, given the task represented by the 24 unknowns illustrated in Figure 2.



**General HASPP Flowchart**

**Pipe Manipulator HASPP Flowchart**

Figure 1 HASPP Flowchart

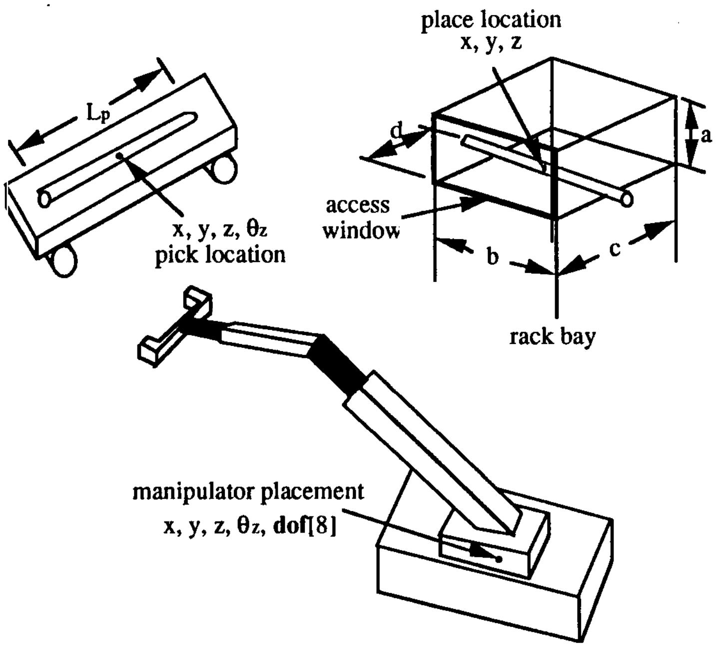


Figure 2 Pipe Manipulator Staging Area Geometry

## HASPP ANALYSES

The analytical description of the manipulator workspace boundaries is a fundamental step in implementing some of the path planning heuristics used by HASPP. The workspace describes the working volume of the manipulator which basically describes what positions the manipulator can and cannot reach in space. The half volume of the Pipe Manipulator workspace is shown in Figure 3. The analytical descriptions of the bounding surfaces of this volume are used to aid the algorithm in defining reachable task points.

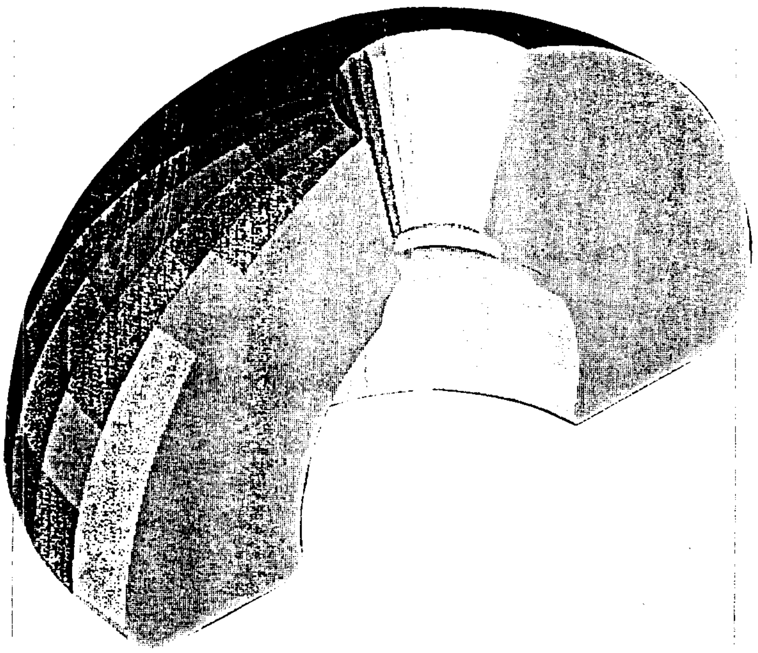
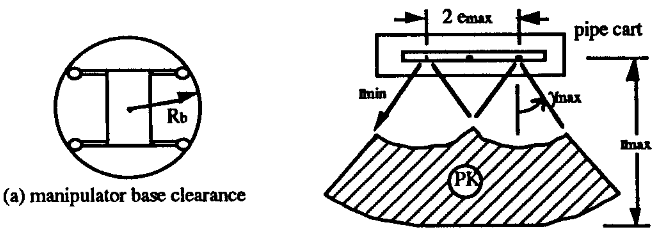


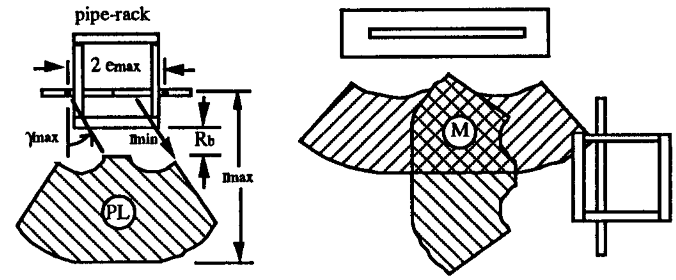
Figure 3 Reachable Workspace

One of the first steps in HASPP is to verify that the given staging area geometry is valid. This validity is based on various constraints which apply to placement of the manipulator in the environment. These constraints are illustrated in Figure 4. $R_b$, the radius of the manipulator's base-enclosing circle, defines the minimum distance the base can be from any object such as a pipe cart or rack and still avoid interference (see Figure 4a). The region "PK" defines where the manipulator must be positioned in order to reach the pipe pick position (see Figure 4b). $r_{min}$ and $r_{max}$ define the workspace reach limits, $g_{max}$ defines the maximum horizontal pivot limitation of the wrist, and $e_{max}$ defines the maximum allowable pick eccentricity. The region "PL" defines the allowable manipulator placements which satisfy reach and column interference constraints concerning the in-rack pipe placement (see Figure 4c). Region "M" (M = PK « PL) defines the region in which the manipulator can be placed in order to satisfy both the pick and place constraints (see Figure 4d). If



(a) manipulator base clearance

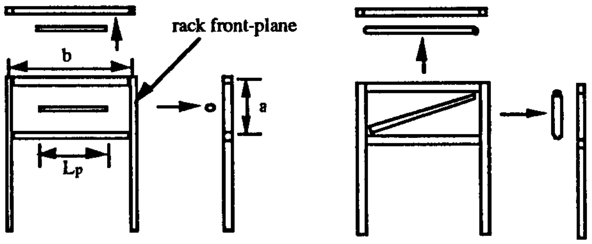
(b) allowable pick locations



(c) allowable place locations

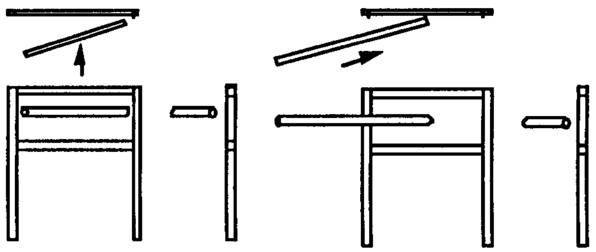
(d) allowable manipulator placement

Figure 4 Manipulator Placement Constraints



(a) straight entry

(b) diagonal entry



(c) slant entry

(d) angle entry

Figure 5 Catalog of Pipe Entry Types

there is no "M" (i.e., $M = \Delta$), then the staging area represents an impossible erection task. In this case the manipulator and/or pipe cart and/or pipe-rack placements would have to be modified in order to install the pipe.

Another HASPP step is to determine task points defining the type and direction of pipe entry. Pipe entry refers to the movement of the grasped pipe through the pipe-rack access window into the center of the pipe-rack bay. The type of entry and resulting task points are selected from a catalog of four predefined entry types illustrated in Figure 5.

Another important variable in defining the trajectory is the grip eccentricity. This is the amount that the pipe must be picked up off center to make the erection task feasible. Factors which influence this choice are torsional loading of the boom, pipe and jaw geometry, wrist pivot joint limit constraints, and obstacle avoidance. An example of an obstacle avoidance constraint is illustrated in Figure 6 where a minimum eccentricity of x is required to maintain a clearance of d between the boom and rack column. The eccentricity constraints are considered by HASPP in defining the key preliminary trajectory points and the choice for eccentricity is made before a complete trajectory definition is attempted. If there is no eccentricity which will allow the installation, HASPP detects and reports this along with the reason. An example diagnostic message provided by the algorithm is: "pipe cannot be installed because the eccentricity exceeds the allowable limit at the in-rack place position".

Another obstacle avoidance problem involves penetration of the manipulator boom through the rack access window. Interference with the rack beams is avoided by controlling the rack plane penetration point as illustrated in Figures 7a and 7b. A safe distance is kept between the manipulator boom and rack beams by utilizing the boom's self-motion capability. Self-motion refers to the fact that even if the pipe position is fixed in space, the boom's configuration can be varied utilizing the redundancy of the degrees of freedom. Four extreme positions of the self-motion configurations are shown in Figure 7c.

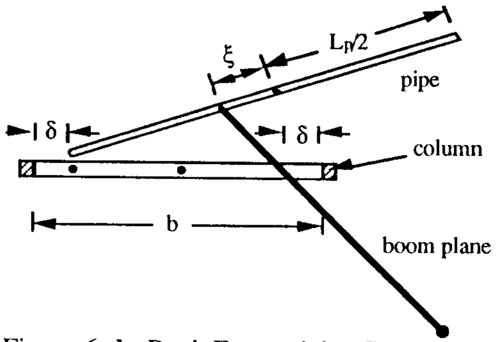
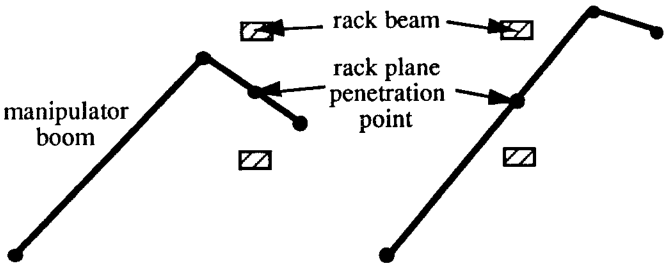


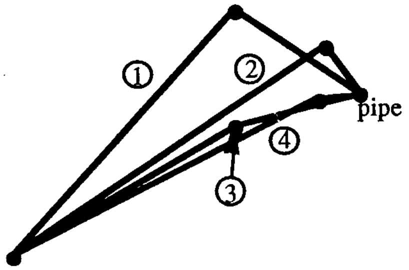
Figure 6 In-Rack Eccentricity Constraints

EXAMPLE

Figure 8 illustrates a sample Pipe Manipulator trajectory that was determined from the HASPP implementation. This is a good example in that many of the HASPP heuristics were utilized in calculating the trajectory. The grip eccentricity heuristics determined that the pipe had to be grasped off center to avoid rack column interference. The swing-past-rack obstacle avoidance heuristics determined that the boom had to be lifted and retracted and the wrist required constant reorientation to avoid rack-front-plane interference. An angle entry from the left of the rack was chosen by the pipe entry heuristics according to the staging area geometry. And finally, the beam interference avoidance heuristics utilized the boom self-motion to avoid obstacles during entry and exit of the pipe-rack.

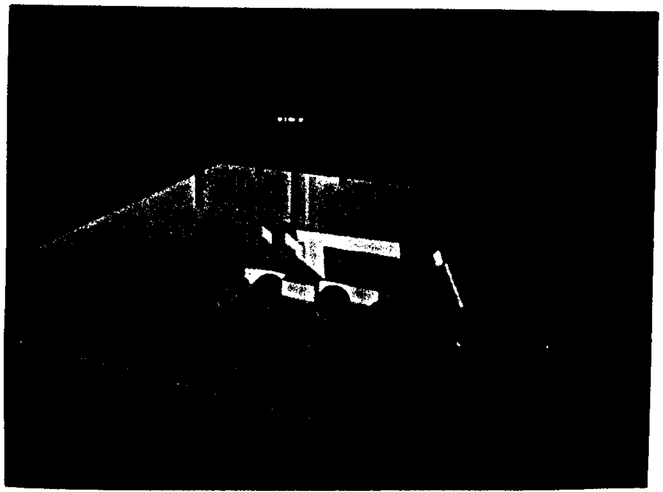


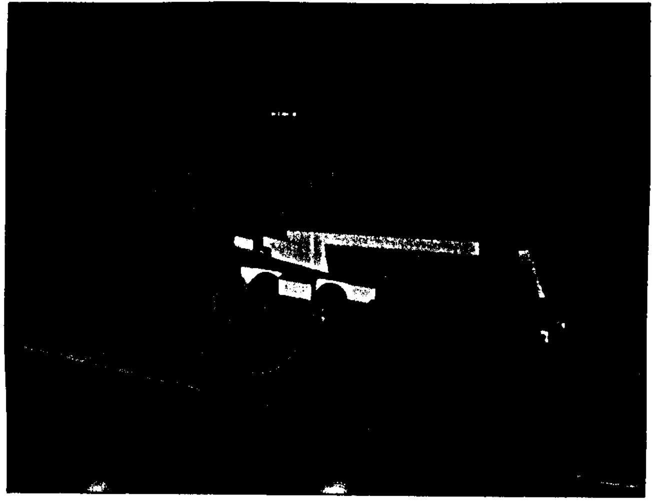
(a) auxiliary boom penetration (b) main boom penetration



(c) boom self-motion

Figure 7 Rack Beam Avoidance





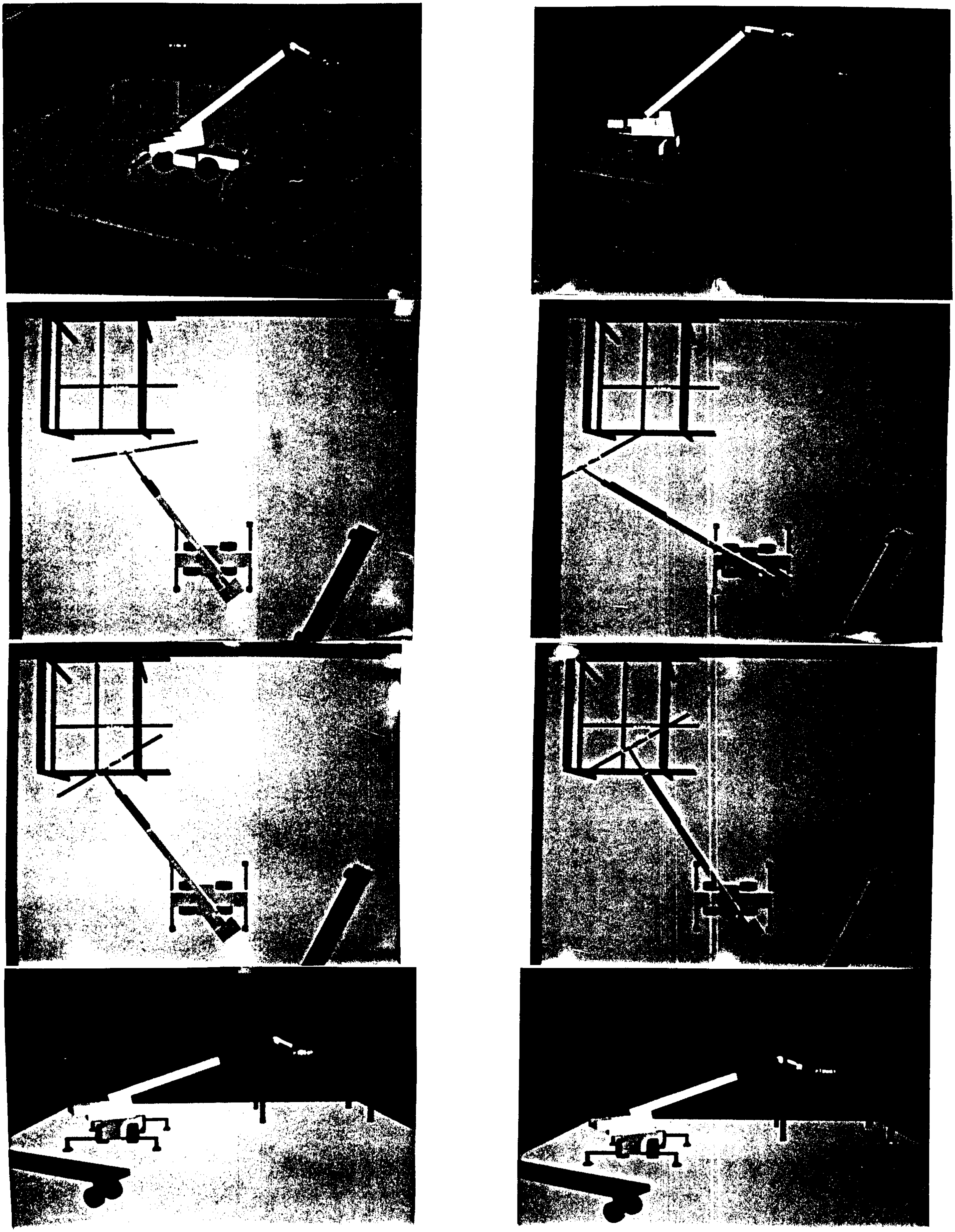


Figure 8 Example HASPP Trajectory

## APPLICATIONS TO SIMULATION

As pointed out in Section 1, there are many "real world" difficulties with implementing HASPP on an on-line control system. This is due to the dependence upon an accurate world model of the environment. There are many uncertainties involved in the "real world" which cannot be reasonably modeled in the simulated world. There are uncertainties in the environment such as unknown obstacles in the field, uncertainties in the equipment operation and performance such as link compliance and joint drift, and uncertainties in sensor data due to sensor mechanical and electrical design issues. However, the development in the simulated world is still useful and has many applications.

One application is in performing plant constructability studies. Fisher (1989) performed extensive studies of pipe-rack structure design for constructability with the Pipe Manipulator. These studies were performed with both a plastic and a computer graphics model where rough erection trajectories were determined experimentally and completely manually. These trajectories were then analyzed allowing for evaluation of structure design alternatives - the ease of generating trajectories is related to the constructability of the designs. With HASPP and a simulation model, this type of work can be completed automatically.

Assembly and maintenance planning is another application for HASPP and a simulation model. As illustrated in Figure 9, the simulator could read data from the CAD database of a facility's design, break the overall construction task into staging area modules, and plan the erection trajectory for each pipe spool in the module. Furthermore, if the machinery is going to be operated by construction personnel, this simulation can be used to illustrate erection strategies to the operator visually providing guidance for the work.

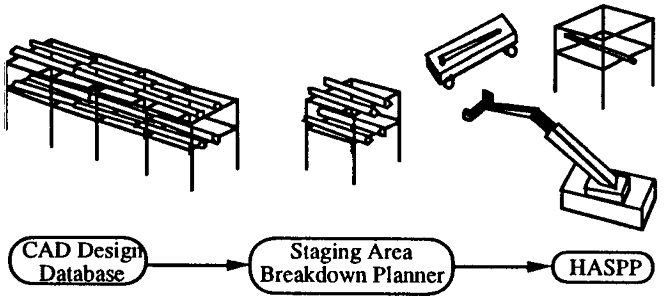


Figure 9 Construction Simulation Using HASPP

## CONCLUSIONS

Presented here was a Heuristic Application-Specific Path Planner (HASPP) for automatically planning manipulator trajectories through an environment with obstacles. The HASPP method was demonstrated by applying it to a piping construction device called the Pipe Manipulator. Computer graphics simulations have shown that HASPP can be used to reliably plan trajectories for the Pipe Manipulator completely automatically and extremely quickly with execution times are on the order of 1/10 sec on a 33 MIP 6 MFLOP computer. For this application, HASPP and the 3-D computer graphics model provides a valuable tool for planning and simulating construction by automatically generating and displaying erection trajectories, for performing constructability studies by determining if pipes can be installed in a rack for a given manipulator placement and rack geometry, for generating instructions off-line for pre-programming the Pipe Manipulator for an automated operation, and for providing assistance to an equipment operator through visual training.

Although the development presented in this paper is application-specific, HASPP and the 3-D graphics simulation tool could be applied to other manipulators and environments. Attributes required for an application to be suitable for a HASPP implementation include: well-defined environment (e.g., consistent rectangular pipe-racks), easy task definition (e.g., pick up pipe, insert pipe through the rack front access window, place pipe, exit rack), "nice" manipulator kinematic structure (e.g., Pipe Manipulator planar boom and simple wrist), and easily ascertainable heuristics to define task points and connecting trajectories (e.g., beam interference and joint limit avoidance analyses).

## REFERENCES

Alciatore, D., Hughes, P.,Traver, A., and O'Connor, J., 1989a, "Development of an Ergonomic Control System for a Large Construction Manipulator," *Proceedings of the Sixth International Symposium on Automation and Robotics in Construction*, June.

Alciatore, D., 1989b, "Automation of a Piping Construction Manipulator and Development of a Heuristic Application-Specific Path Planner," PhD Dissertation, The University of Texas at Austin, December.

Barraquand, J. and Latombe, J., 1989, "Robot Motion Planning: A Distributed Representation Approach," Stanford University Report No. STAN-CS-89-1257, Department of Computer Science, May.

Fisher, D., 1989, "Piping Erection Constructability Issues in a Semi-Automated Environment," Dissertation, The University of Texas at Austin, May.

Lumelsky, V. and Sun, K., 1987, "Gross Motion Planning for a Simple 3D Articulated Robot Arm Moving Amidst Unknown Arbitrarily Shaped Obstacles," *Proceedings of IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 1929-1934.

Herman, M., 1986, *Proceedings of IEEE International Conference on Robotics and Automation*, San Francisco, CA, April, pp. 1056-1063.

Lozano-Perez, T. 1981, "Automatic Planning of Manipulator Transfer Movements," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. SMC-11, No. 10, October, pp. 681-698.

Smithers, T. and Malcolm, C., 1987, "A Behavioural Approach To Robot Task Planning and Off-line Programming," DAI Research Paper No. 306, Department of Artificial Intelligence, Edinburgh University.