DEVELOPMENT OF A HEURISTIC APPLICATION-SPECIFIC PATH PLANNER FOR PIPING CONSTRUCTION

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ABSTRACT

This paper presents the development 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, the application of HASPP to an eight degree of freedom Pipe Manipulator is presented as an illustrative example. 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 a computer graphics model and it has demonstrated the ability to reliably determine near-optimal collision-free erection trajectories completely automatically.

1.   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 (a large construction manipulator used for piping construction as found in the building of process industry plants and power facilities [Alciatore, et al., 1989a]). This 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.

2. 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 this case, 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) which roughly define the trajectory requirements. Heuristics and geometric analyses are then used to refine these task points and generate intermediate trajectory points (manipulator configurations) which define interference-free trajectories between the task point configurations.

The Pipe Manipulator HASPP basic flow chart is summarized in Figure 1. Input to the algorithm is a complete geometric description of the staging area as shown 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 (i.e., neither object penetrates the rack), 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 (i.e., how the pipe enters pipe-rack access window) based on the pipe length, rack geometry, and manipulator placement.
- choose the grip eccentricity (i.e., 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 task point locations (positions of the pipe in space) 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].
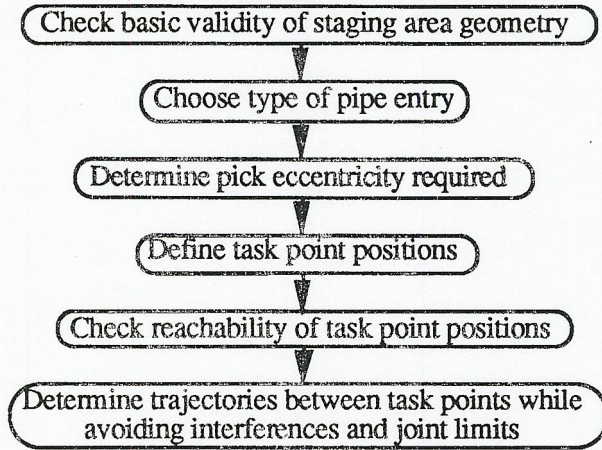
Check basic validity of staging area geometry

Choose type of pipe entry

Determine pick eccentricity required

Define task point positions

Check reachability of task point positions

Determine trajectories between task points while avoiding interferences and joint limits

Figure 1 Pipe Manipulator HASPP Flowchart

L_p

x, y, z, θ_z
pick location

manipulator placement
$x, y, z, \theta_z, dof[8]$

place location
x, y, z

d

a

access
window

b

c

rack bay
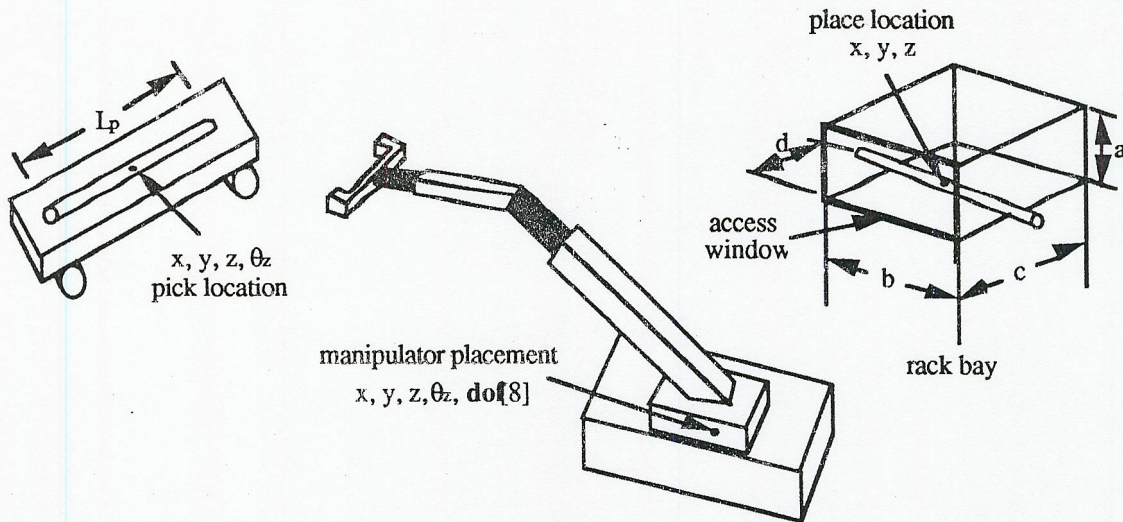
Figure 2 Staging Area Geometry

3. 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 Pipe Manipulator workspace is shown in Figure 3 (note - only half of the volume is shown since it is symmetrical). The analytical descriptions of the bounding surfaces of this volume are used to aid the algorithm in defining reachable task points.
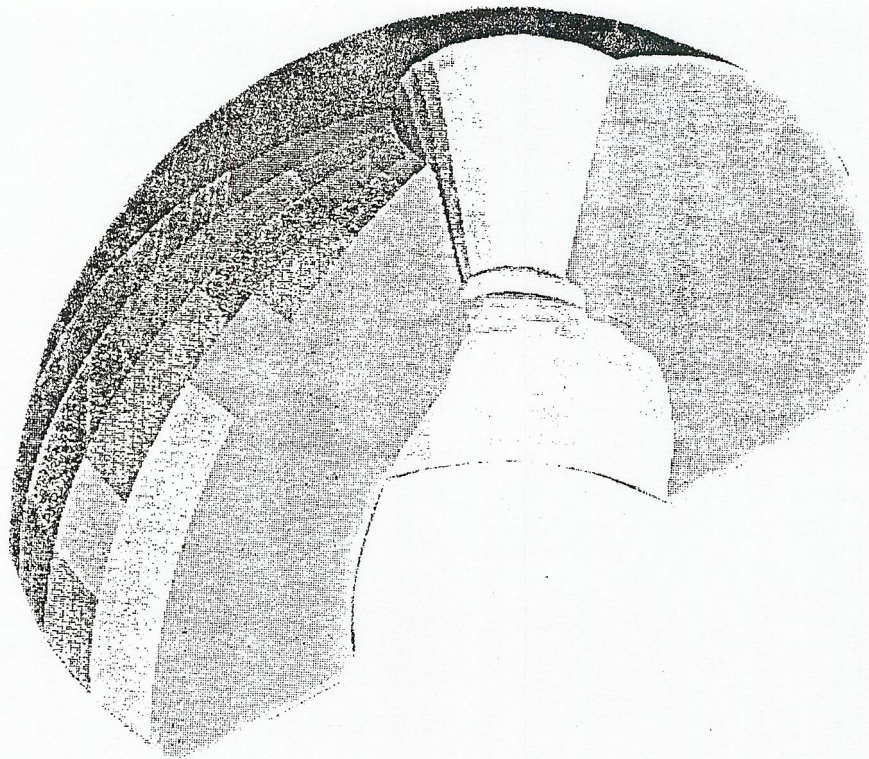
Figure 3 Reachable Workspace

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, γ_{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" ($M = PK \cap PL$) defines the region in which the manipulator can be placed in order to satisfy both the pick and place constraints (see Figure 4d). If there is no "M" (i.e., $M = \varnothing$), 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.
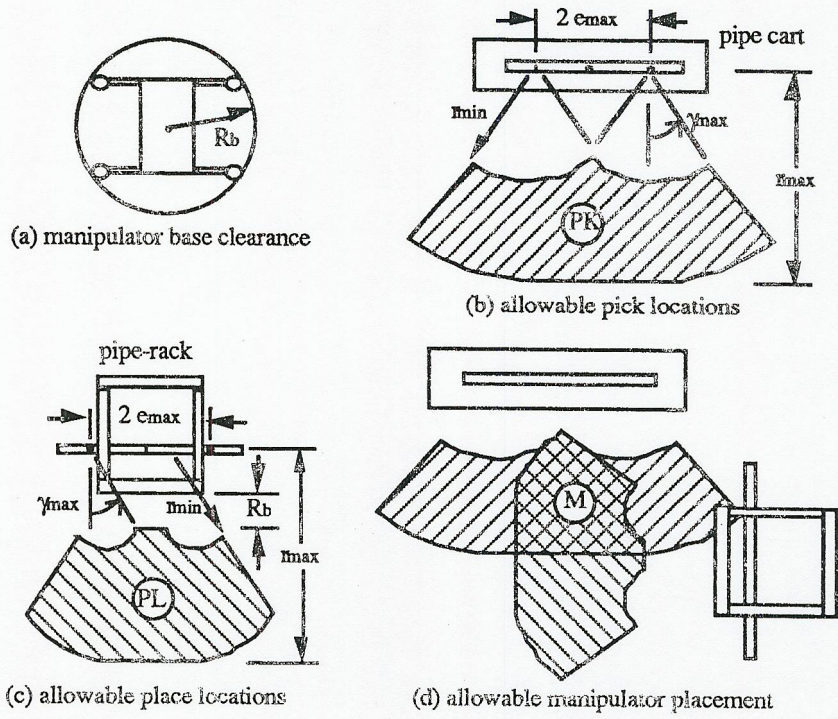
(a) manipulator base clearance

(b) allowable pick locations

(c) allowable place locations

(d) allowable manipulator placement

Figure 4 Manipulator Placement Constraints

(a) straight entry

(b) diagonal entry

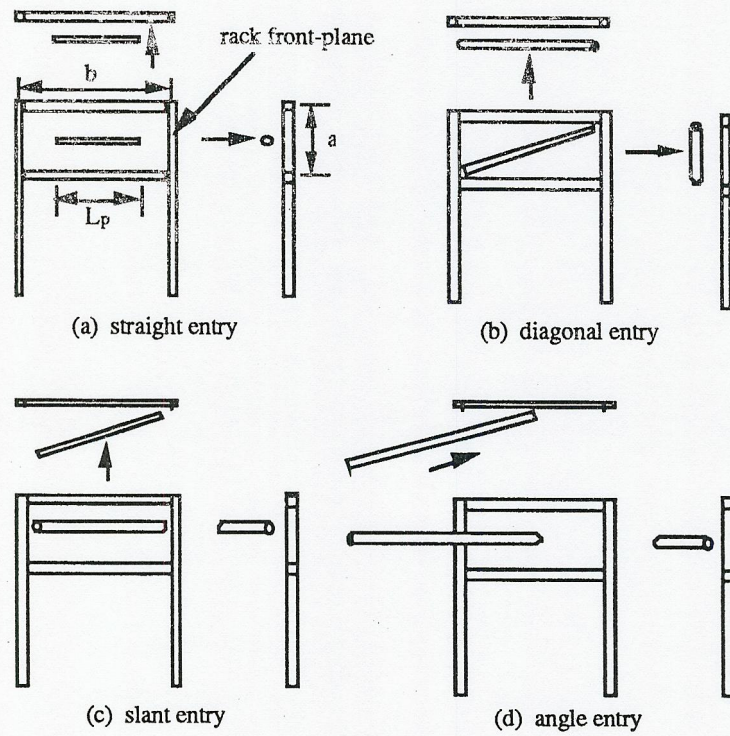(c) slant entry

(d) angle entry

Figure 5 Catalog of Pipe Entry Types

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 ξ is required to maintain a clearance of δ 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 (task point) 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.
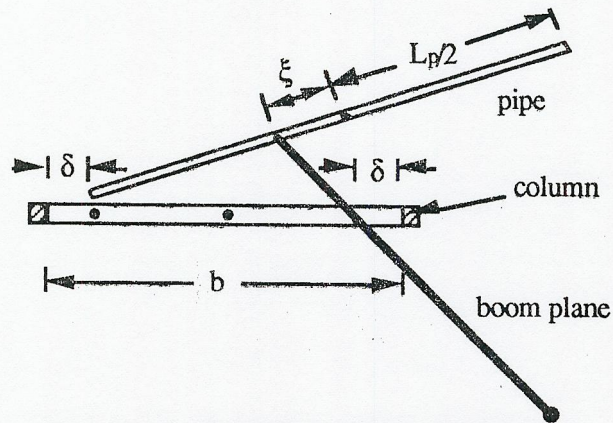

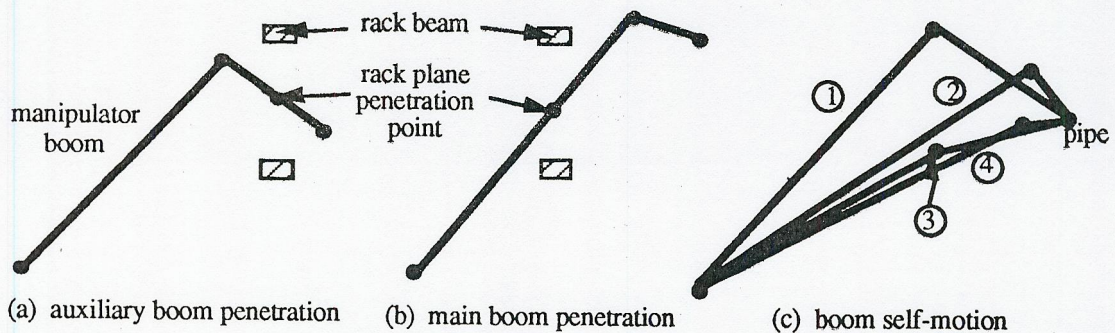Figure 6 In-Rack Eccentricity Constraints

(a) auxiliary boom penetration   (b) main boom penetration   (c) boom self-motion

Figure 7 Rack Beam Avoidance

4. 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.
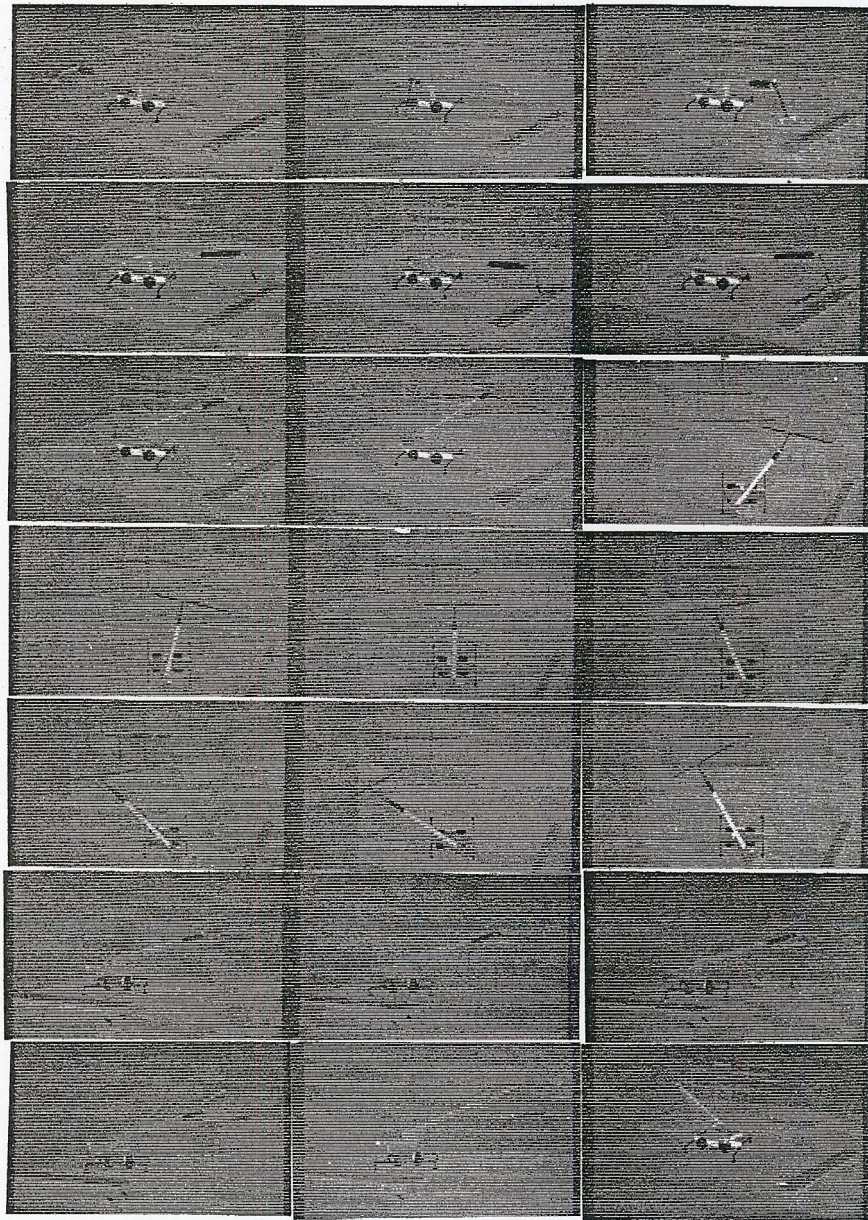

Figure 8 Example HASPP Trajectory

5. 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 (execution times are on the order of 1/10 sec). For this application, HASPP and the 3-D computer graphics model provides a valuable tool for planning and simulating construction (automatically generating and displaying erection trajectories), performing constructability studies (determining if pipes can be installed in a rack for a given manipulator placement and rack geometry), or for generating instructions off-line for pre-programming the Pipe Manipulator for an automated operation.

Although the development presented in this paper is application-specific, HASPP 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).

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