Serpentine Manipulator Planning and Control for NASA Space-Shuttle Payload Servicing

by

Herman Herman

Hagen Schempf

CMU-RI-TR-92-10

The Robotics Institute

Carnegie Mellon University

5000 Forbes Avenue

Pittsburgh, PA 15213

October 1992

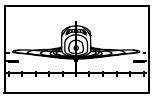
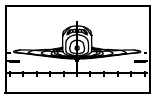


Table of Contents

List of Figures



List of Tables

1. Abstract

The use of a highly-redundant manipulator, so-called ‘serpentine’ manipulator, is proposed as a solution for servicing space-payloads during the payload installation process before launch on the space-shuttle. The staging of the system would be inside a large cleanroom area, the Payload Changeout Room (PCR), which sits on the Rotating Service Structure (RSS), allowing it to be swung into mated contact with the space-shuttle as it sits on the launchpad at the John F. Kennedy Space Center in Cape Canaveral, Florida (see figures in section 2).

This report is not so much concerned with the design and implementation issues associated with a serpentine manipulator, but rather with the planning, control and user-interface issues. We thus present a brief introduction to the actual application environment and its restrictions, followed by the theoretical background and implementation issues of planning and control algorithms developed specifically for a serpentine manipulator operating within the confined spaces of the PCR and the space-shuttle cargo-bay.

The approach used to generate a continuous path is to develop and use a minimizing continuous energy curve for the manipulator, and then fit the discretized link-sections to that curve. The operator is then able to modify this curve directly, allowing for shaping of the serpentine, and for the placement of obstacles that can then be avoided. This algorithm can be implemented in real-time, and curve-parameters can also be adjusted such as flexibility and curvature of the curve. An A* method is used to search for the shortest distance between two goal points, in order to construct the curve. In order to avoid obstacles (real and artificial), available from a database or which can be placed by the operator using the operator interface display, we use an obstacle potential field FIRAS function.

This report outlines the NASA applications background and the technical research and implementation issues of the different planning and control algorithms. The entire system was simulated on an SGI IRIS, and a video-tape has been made of the different operational modes of the planning and operator control displays, showcasing the different capabilities of the serpentine manipulator motion planning and control system.

2. Applications Background

The application of a highly dexterous serpentine manipulator for NASA servicing tasks, was deemed most beneficial in servicing space-payloads during the installation of the payloads into the space-shuttle orbiter [7], while it is on the launch pad at Cape Canaveral Air Force Station at Kennedy Space Center in Florida. A drawing of the launch-pad facility is shown in Figure 2.1. The launchpad is used as the location where most payloads are loaded into the space-shuttle right before take-off (see Figure 2.3). The payload installation and checkout all occur within the Payload Changeout Room (PCR), which is mounted on the Rotating Service Structure (RSS), which is used to mate and demate the PCR to/from the shuttle (see Figure 2.1). The description and purpose of the PCR are explained in more detail below.

2.1 Payload Changeout Room (PCR)- Facility Configuration and Attributes

The PCR is used to service payloads while they are at the launch pad. It is part of the Rotating Service Structure (RSS) [8], the main movable part of the launch pad. The PCR is used to service payloads which will be installed vertically into the orbiter at the pad. The PCR is defined as a class 100,000 clean room, and its high efficiency particle accumulator (HEPA) filters provide a class 100,000, non-laminar flow air supply. The temperature is maintained at 70 deg F, with relative humidity at 50% maximum.

The vertical payloads are transported to thc pad in the vertical position in payload canisters on the payload transporter. The canister is positioned under the RSS while the RSS is in the retracted position. The payload canister is lifted from the transporter to the PCR doors and is unlocked in position. The PCR environmental seals are inflated and the area between the PCR and the orbiter is purged. The PCR-to-orbiter /canister seal system encloses the orbiter payload bay or payload canister doors into the PCR interior without exposing the payload bay, the canister interior, or the payload to contamination by outside elements. The structurally mounted seals are positioned to provide sealing between the PCR doors and the payload canister or the orbiter. Aluminum strongbacks provide support for the inflatable seals around the orbiter interface surface. A bird’s-eye view from the top of the PCR room, with shuttle mated to the PCR, doors open, and a payload being positioned inside the cargo bay, is shown in Figure 2.4.

The doors to the PCR open allowing access to the outside of the canister doors which are opened into the PCR. The Payload Ground Handling Mechanism (PGHM) in the PCR is extended and attached to the payload trunnions and the entire payload is withdrawn from the canister into the PCR. First the doors to the canister, then the PCR doors, are closed and the canister and transporter are removed from the RSS area (see Figure 2.5).

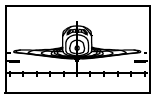
After the orbiter has been positioned on the launch pad, the RSS is rotated to mate the PCR with the orbiter. First the PCR doors, then the orbiter bay doors are opened and the PGHM is used to transfer the payload form the PRC into the orbiter. As a contingency, the PGHM can also be used to remove payloads from the orbiter (see Figure 2.5).

Payload access via the present extendable platform system (see Figure 2.7) is currently adequate to facilitate known processing operations, but to reach certain payload unique configurations and envelopes and/or access to payload areas between platform levels, the use of special supplemental ground support equipment (GSE) is required. Payload processing in the Payload Changeout Room (PCR) often requires tasks which are very difficult for humans to perform from the perspective of reasonable accessibility. Payloads in the shuttle bay create long, narrow corridors where processing tasks are required. In some cases the payload has to be removed to allow access for these tasks. The current handling mechanism and platform systems (see Figure 2.5) do not provide flexible access to all payloads and critical shuttle bay locations. Thus human technicians must assume hazardous positions on specialized fixtures, scaffolds and lifting devices. These alternatives all increase cost, possibly increase payload exposure to potential damage, reduce efficiency, flexibility and overall cleanliness. For this reason it is desirable to have a tool for performing processing tasks in locations which are difficult or impossible for humans to reach. With a special telerobotic or semi-autonomous robotic arm, it will be possible to decrease orbiter flow time, improve task quality, and decrease risk to payload and human safety. The focus of this effort is on the conceptual design, planning, and control issues of such an arm (greater than 6 DOF) relevant to PCR payload processing, although it may be applicable to other shuttle processing facilities as well.

2.2 Serpentine Manipulator for Payload Servicing

A cleanroom serpentine manipulator could be the solution in order to perform payload processing tasks such as inspection, insertion and removal of small items. Namely, this proposed manipulator should be able to perform the following PCR tasks, (ordered in ascending degree of difficulty):

1. Closeout Inspection/Photography



2. Configuration Inspection
3. PCR Cleanliness Inspection
4. Radiator Inspection/Cleaning
5. Sharp Edge Inspection
6. Remove-Before Flight Items
7. Insert/Remove Quick Disconnect
8. Line Insertion/Removal

This arm should also be designed to enhance payload access in the PCR environment. A redundant arm (greater than 6 DOF) will likely be required due to the large, extremely cluttered and constrained workspace that exists when there is a payload in the PCR or payload bay area.

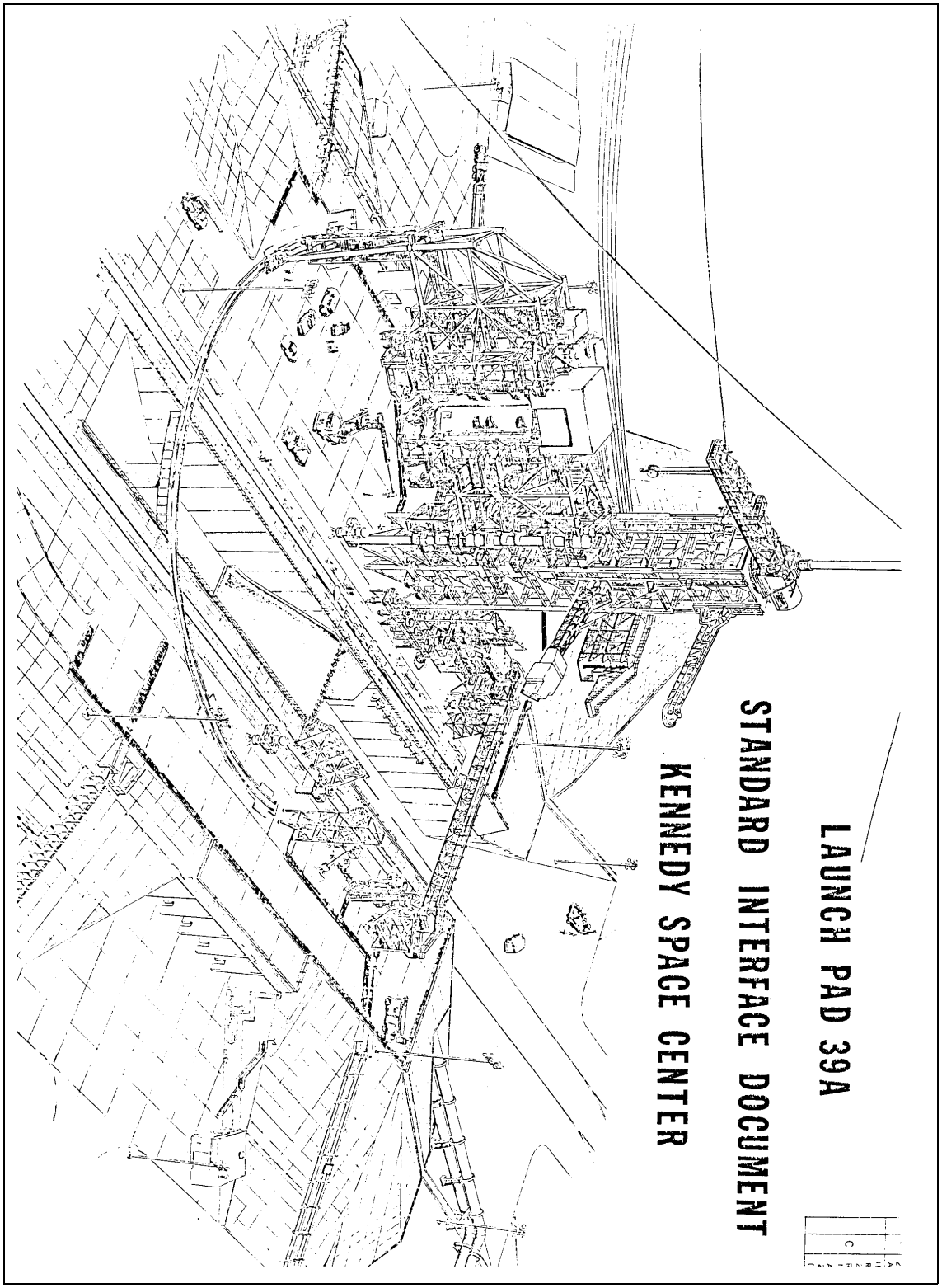


Figure 2.1: Space-Shuttle launchpad facility at John F. Kennedy Space Center, Cape Canaveral, Florida

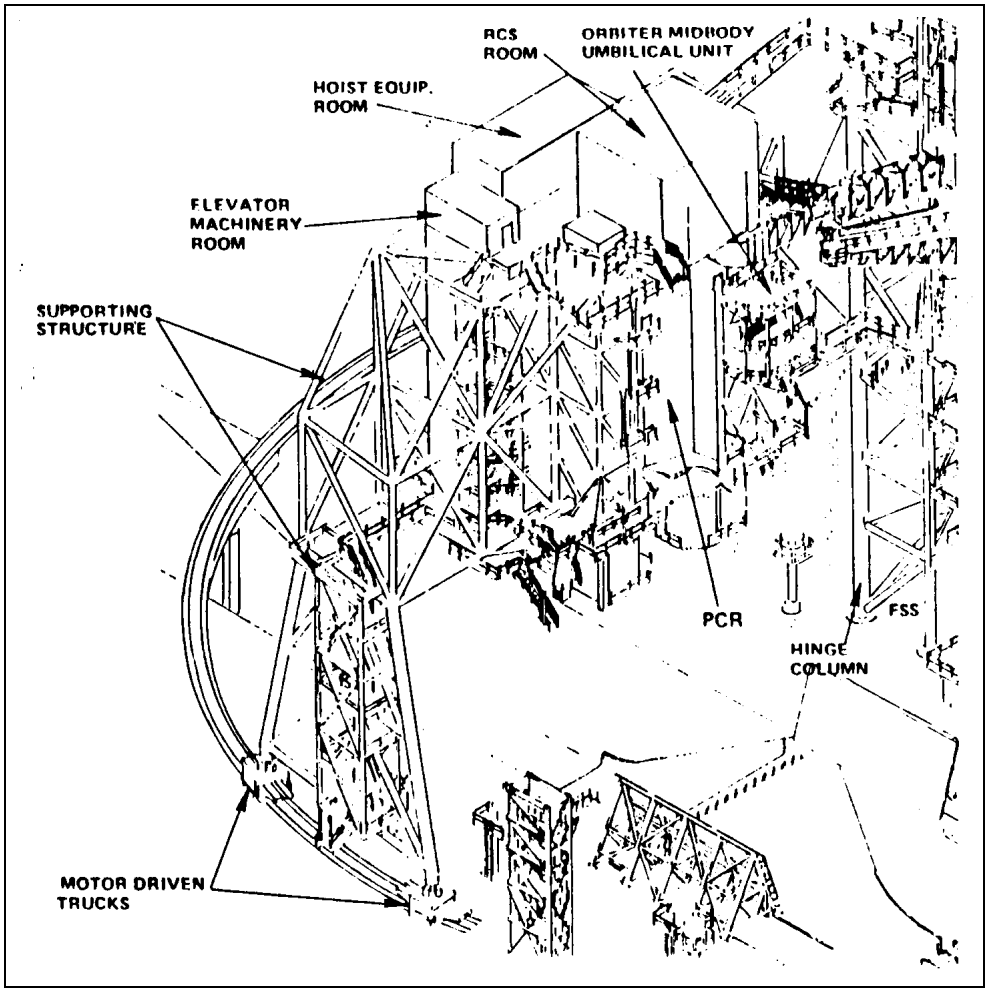


Figure 2.2: Detailed View of Rotating Service Structure (RSS) and the Payload Changeout Room (PCR)

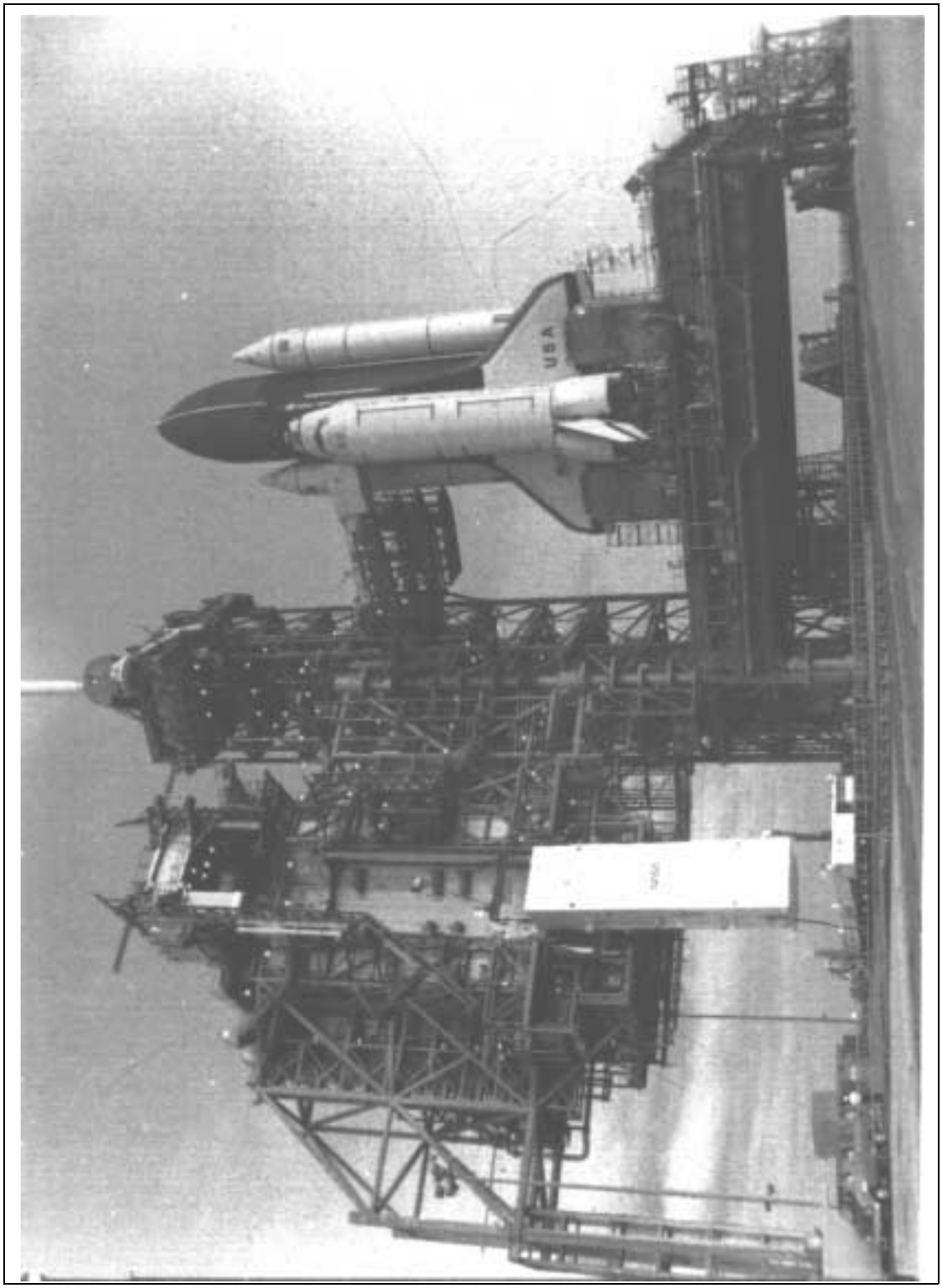


Figure 3: Space-Shuttle launchpad showing the Space Shuttle, the Rotating Service Structure, the Payload Changeout Room, and a payload being hoisted.

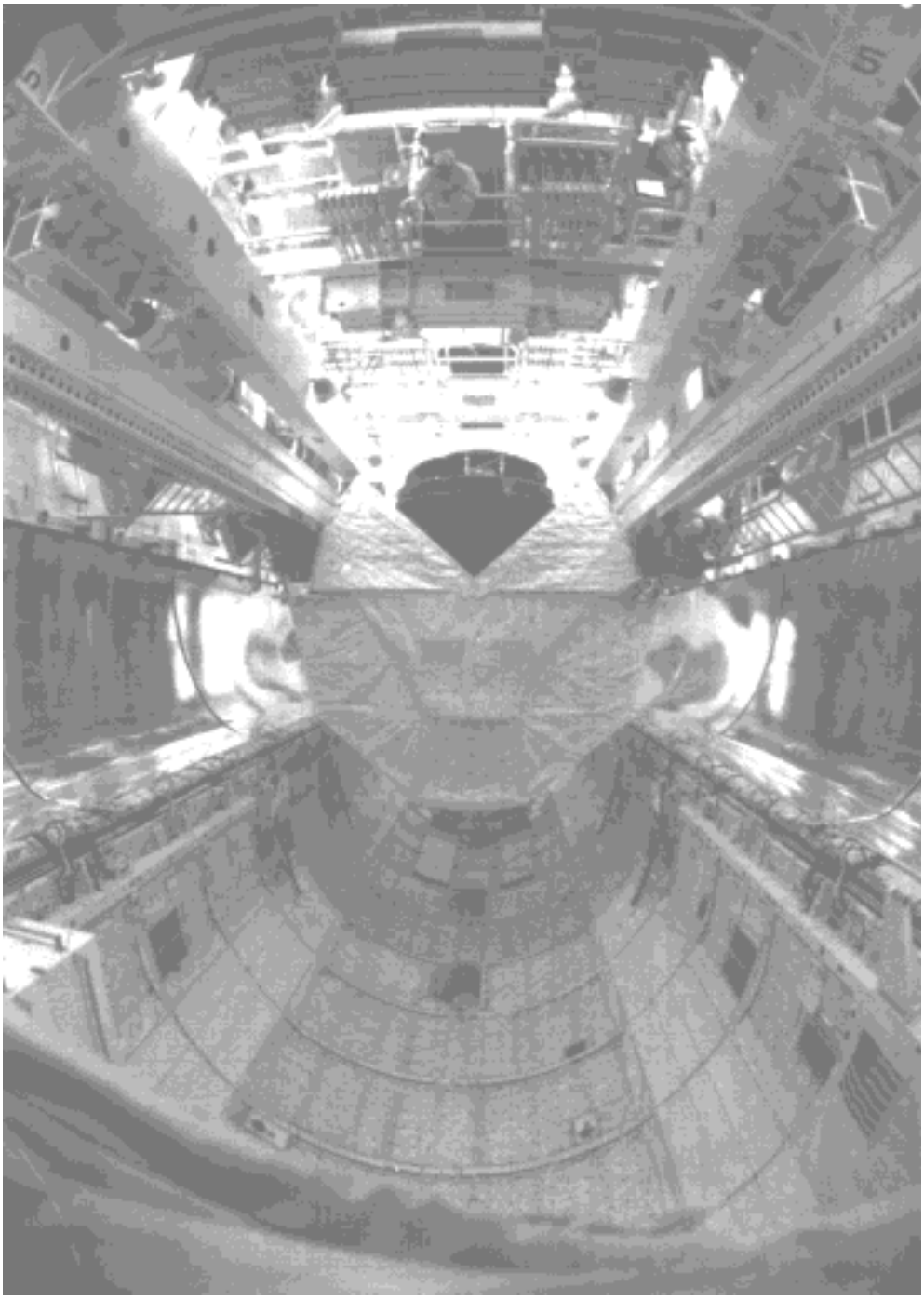


Figure 3: Birds'-eye-view inside the PCR, showing a payload being maneuvered into the cargo-bay of the space-shuttle mated to the PCR doors.

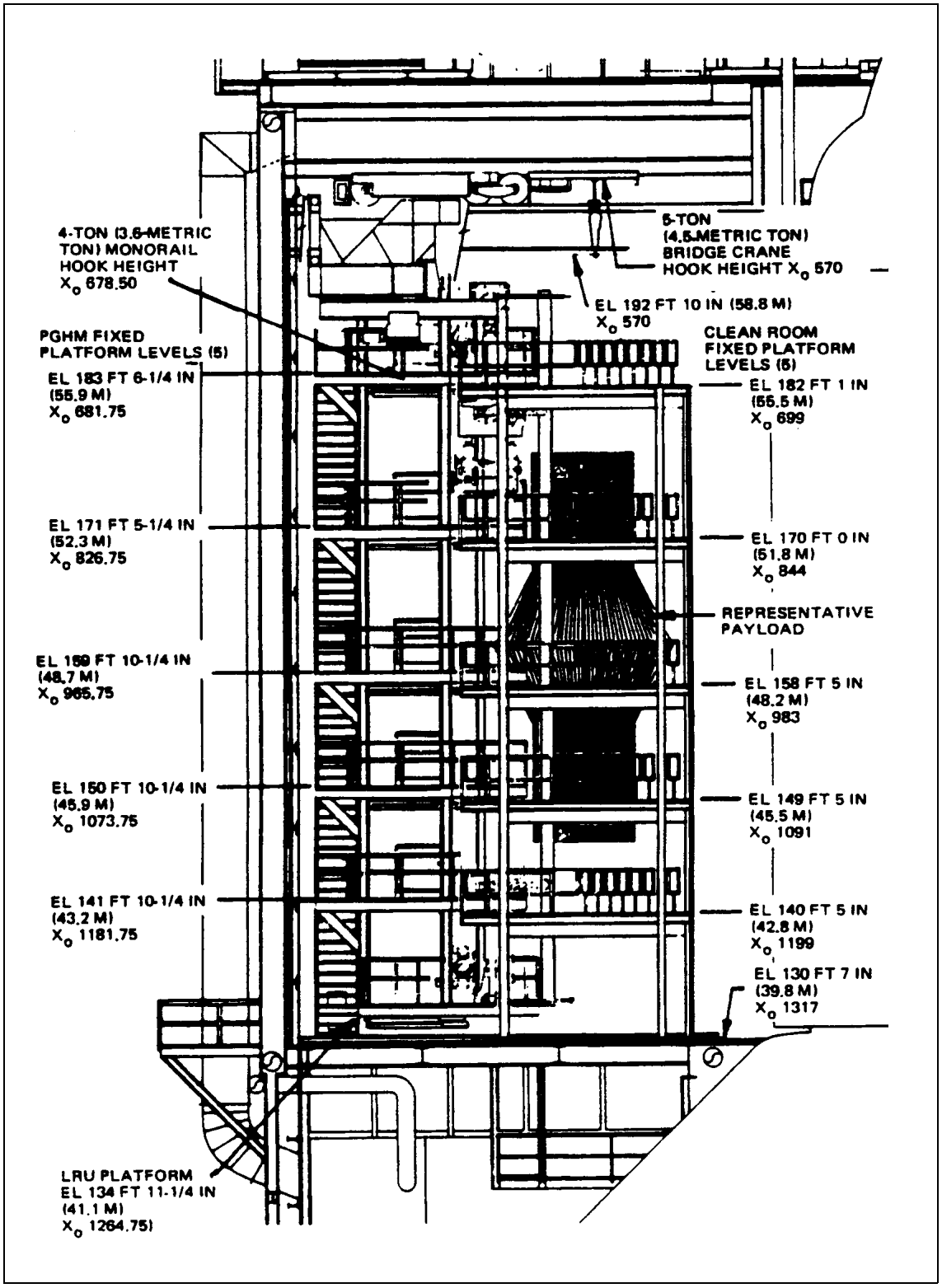


Figure 3: Structure of the platforms and the PGHM inside the PCR, used to access and transport payloads, respectively

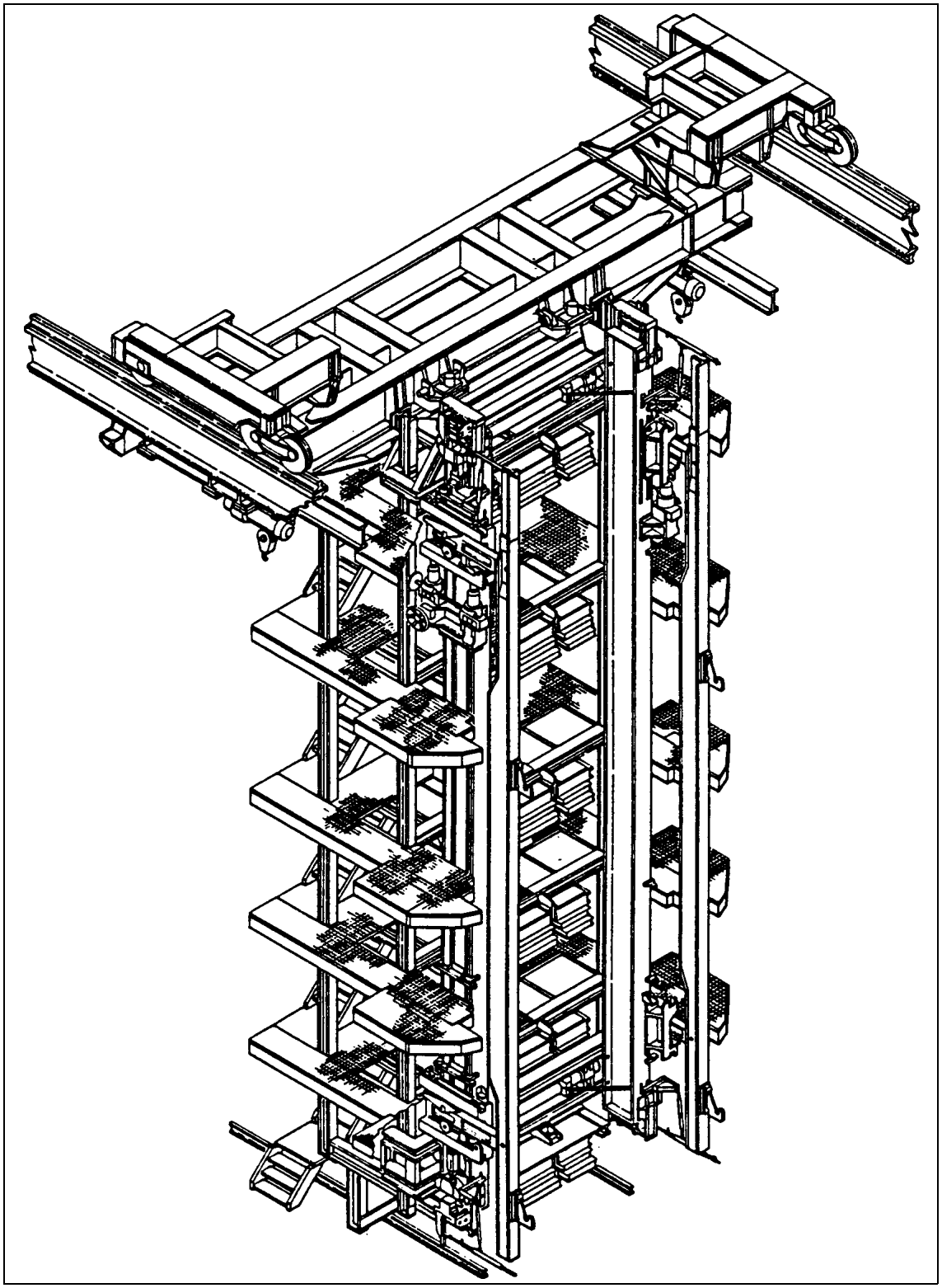


Figure 4: Elevated View of the platform and PGHM systems

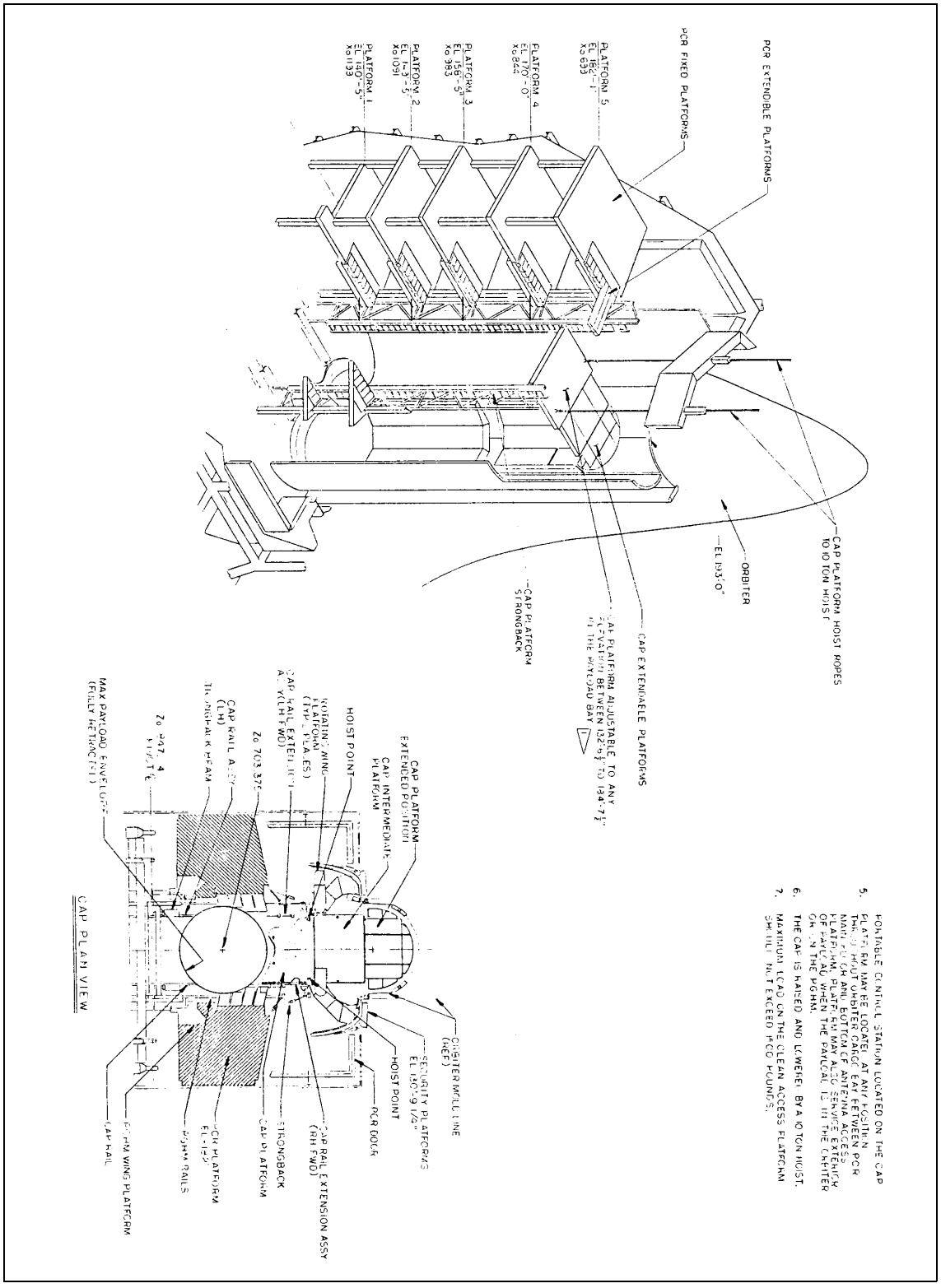
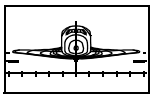


Figure 3:Detailed views of inside PCR structures and reaches



3. Technical Background

3.1 Introduction

There is a need for path planning and control of highly redundant manipulators in real time. There are ongoing efforts that have been concentrating on planning for highly redundant manipulators, but almost all of them could not be executed in real time. There is also a need to manually control the highly redundant manipulator configuration, specifically for teleoperation. It would be extremely complicated for a human operator to directly control each joint concurrently, while avoiding obstacles in the workspace. We have developed an approach that can generate a path automatically in sparsely populated environments, and semi-automatically in densely populated environments and thus allow the operator to easily modify the path or control the robots' endeffector/links directly. All this can be done in real time, allowing the teleoperation of the highly redundant robot. The system we have developed can be used on a highly redundant serial-link manipulator or a mobile robot. The highly redundant serial manipulator in this case must be able to adjust the length of the exposed manipulator in the workspace or have enough room to wrap the unnecessary length of the manipulator around a freely rotating base.

The planning system presented here was developed specifically for the space shuttle bay servicing robot. The robot in this case is a hyper-redundant serial-link robot and the operation space of the robot is the narrow space between the payload and the space-shuttle's cargo-bay. Space between the payload and the cargo-bay is sparsely populated by obstacles.

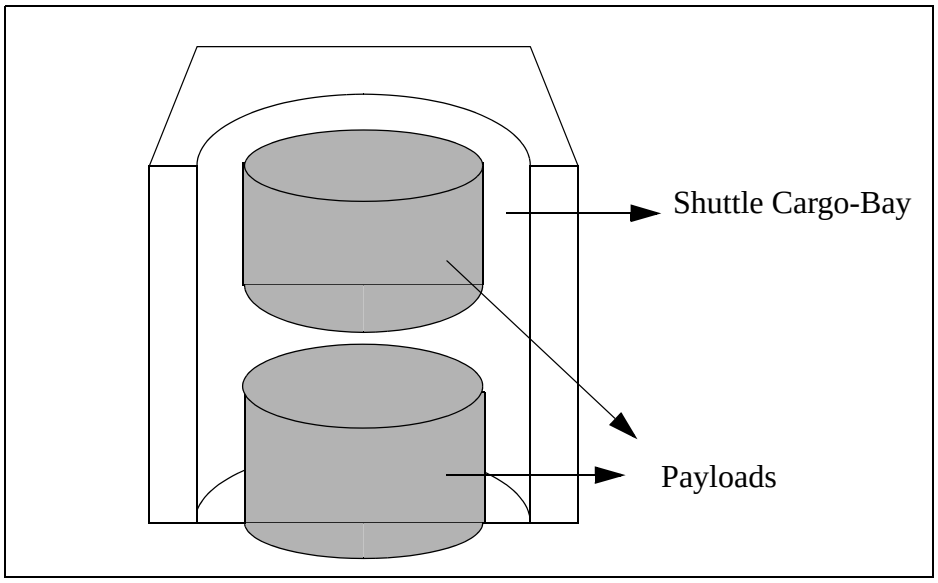
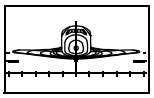


Figure 3.1: The workspace of the space shuttle servicing robot

The approach that we use puts more emphasis on the ability to operate the robot semi-automatically and in real time. Even though the system might not be able to find a suitable path if the obstacle-density is very high, it will be possible for the operator to correct the path. The system also enables the operator to teleoperate the robot easily without having to deal with all the degrees of freedom of the manipulator.

3.2 Approach

One of the problems in developing planners for hyper redundant manipulators lies with solving for system redundancy. There are many proposed solutions that can resolve redundancies in a myriad number of ways. In order to solve this issues more readily, we need to impose more constraints on the manipulator.



The approach that we use to create the path uses an energy minimizing continuous curve as an approximation to the manipulator shape. This curve is used to create a smooth and collision-free path for the manipulator. It also allows the operator to easily modify the path or put constraints on the path itself. In the teleoperation mode the operator can manipulate this curve directly by applying forces to the curve or by putting a constraint on the curve. Joint angles of the manipulator can be calculated by fitting the manipulator to the curve. Since the fitting process is done locally, no difficult inverse kinematic problems exist (except where the manipulator has more DOFs than needed - another criteria needs to be used then to choose the solution).This approach is similar to Hayashi[4], except that we are using a different kind of continuous curve, which offers much more functionality.

The curve that we are using is part of the family of energy-minimizing curves called '*snakes*', which were introduced by Kass, Witkin and Terzopoulos[1]. *Snakes* can be used to construct a smooth curve for a path and thus provide a 'natural' continuous model for the manipulator. Another important reason for using a *snake*, is that we can apply forces at any point along the *snake* and also put hard constraints on the *snake*. Also, no interpolation is necessary between the current and the final path, since we can adjust the step-size of the *snake* to move in small steps from the current to the final path. Because of these reasons, *snakes* are much more versatile than the splines used in Hayashi[4]. *Snakes* are applicable in 3D as well as 2D situations without too much modification.

After the *snake* has defined the path, we use it as a guide for mapping the manipulator. We can think of it as a flexible hose within which the manipulator can be pushed and pulled. In this case, this 'hose' is always trying to be as straight and short as possible, while reacting to the outside forces that are applied to it. Its rigidity and elasticity are adjustable by modifying the respective parameter in the energy equation.

The approach used here is to first find a path to the goal using a known search method, such as the A* search. The problem with the resulting path is that it tends to be very closed to known and specified obstacles. Several other methods can be used to alleviate this problem, such as using the skeleton of the free space (or voronoi diagram of the free space) as the path. Here we use the *snake* to construct a smooth, short and safe path that is at a safe distance from the obstacle. So once we found a path to the goal, we lay down the curve (*snake*) on that path and let the obstacles' repulsion-forces and the internal force of the *snake* shape the final configuration. The end point of the *snake* are fixed at the start and the goal point, so that external and internal forces will not be able to modify their location. The external forces, namely the obstacle repulsion forces, will try to repel the *snake* away from the obstacles to a safer distance. The internal forces, on the other hand, will make the *snake* as straight and short as possible. As a result we will have a path that is smooth, short and located safely away from obstacles.

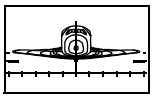
In a densely populated workspace, the shortest path might have a curvature that exceeds the maximum physically achievable curvature for the manipulator. If this happens, the operator could pick another path or modify the path by applying forces to the *snake* or fix some points of the *snake* at certain locations, in order to arrive at an achievable curvature configuration.

After the *snake* has reached a stable configuration, the manipulator can be mapped onto the *snake*. To move into a new goal position, we extend the *snake* from the current goal to the new goal. More on this later in section 3.3, because sometimes we do not want a path that has the shortest distance to the current goal, but rather a path that has the shortest distance from the base or from some other point on the manipulator to the current goal.

3.3 Generating the initial path

As we mentioned earlier, the A* search is used to look for the shortest path to the goal, leaving one more variable to be determined: the origin of the search. We could look for the shortest path from any point on the manipulator. There are two values that we can minimize to choose the origin of the search:

1. The distance that the tip of the manipulator has to travel to the next goal (synonymous with time/energy minimization)
2. The length of manipulator that is extended/unfolded into the workspace (synonymous with cantilever load and potential collisions minimization)



For some of our selected tasks, such as continuous scanning, we want the robot to minimize the distance that the tip of the manipulator has to travel to the next goal. For other tasks it is desirable to keep the length of the manipulator in the workspace as short as possible so as to minimize the possibility of collision and reduce cantilever loads. In the first case, we just extend the current *snake* to reach the new goal. In the second case the manipulator is retracted until it can safely move to the new goal (point-and-shoot). Then the *snake* is connected at that point to the new goal. Figure 3.2 shows these two paths. In sub-figure (a) the manipulator has already reached its old goal. In (b) the manipulator is shown reaching the new goal through a path that minimizes the distance the end point of the manipulator has to travel. Sub-figures (c) and (d) show how the manipulator reaches its new goal by minimizing the length of the manipulator that is inside the workspace.This approach may have the drawback that the manipulator might be too short to reach a goal by following the path that resulted in the shortest distance from the tip of the manipulator. In this case, we can minimize the length of the manipulator that is extended into the workspace.

In both cases the distance that the tip of the manipulator has to travel is minimized as much as possible. Therefore, if the length of the extended manipulator is to be minimized and the manipulator is to be retracted, we have to figure out how far we should retract the manipulator. Due to the characteristics of the *snake*, two paths can result in the same final modified path as long as there is no obstacle between them. This is always true since the starting point and the end point of the *snake* will be at the same locations and there is no obstacle between the two paths to prevent the *snake* from moving from one path to the other. Specifically, the *snake* will always move to the path that will minimize its internal energy.

To clarify this situation, look at Figure 3.3. The manipulator has reached the old goal and now we command it to move to the new goal. From position 1 through 7 of the manipulator, we execute the A* search to look for the shortest path to the new goal. Since there is no obstacle along the path between positions 1 and 2, they will result in the same final path.This means that if we put the *snake's* initial position on path 1 or path 2, the *snake* will end up in the same final configuration. We can then check for interference between paths 2 and 3, 3 and 4, and so on, until we find (an) obstacle(s) between paths n and n+1. In this case, the obstacle is found between paths 5 and 6, which means that the resulting path will be different if we initialize the *snake* on path 6 rather than path 5, since the *snake* could not pass through the obstacle.

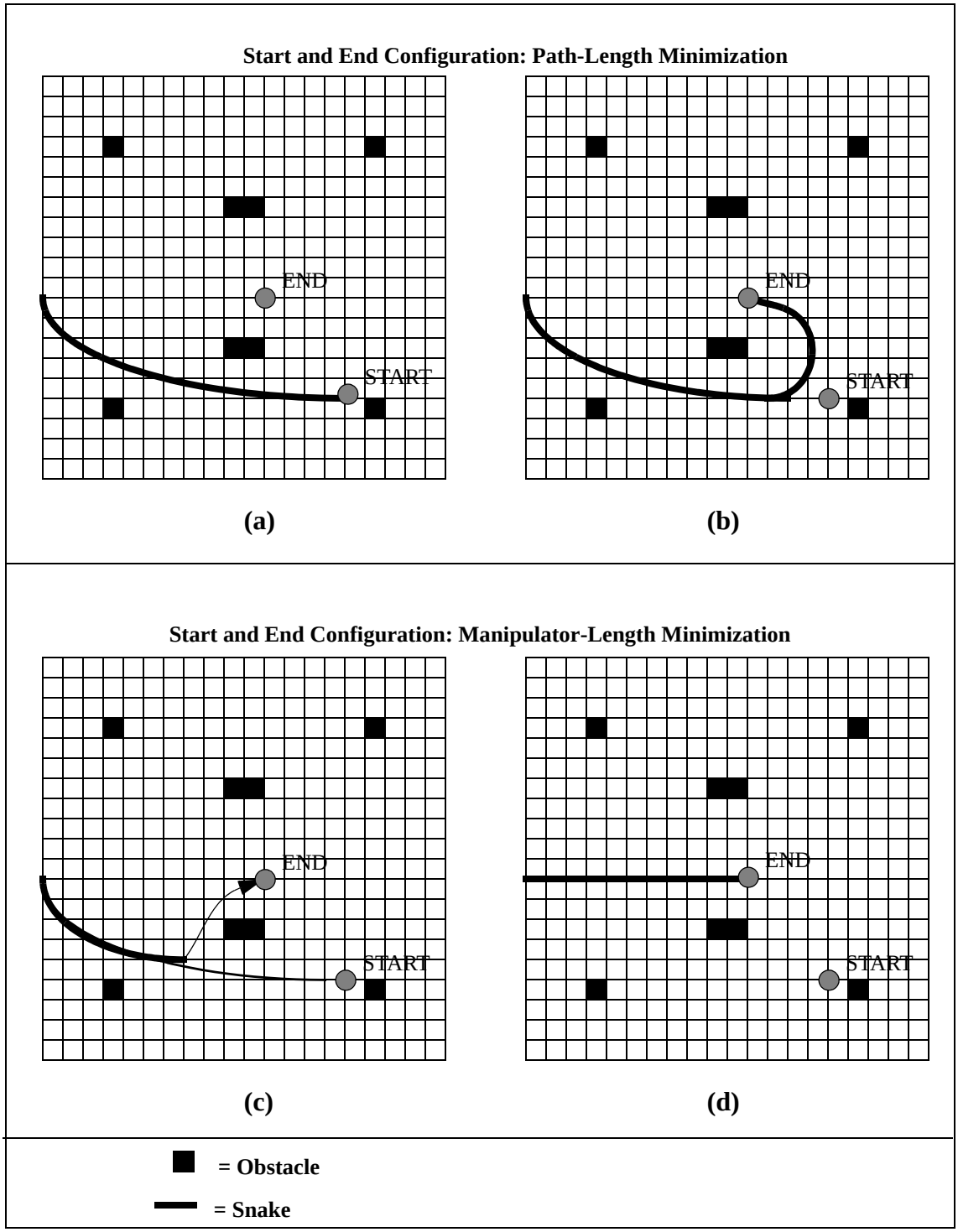


Figure 3.2: Two ways of moving to a new goal

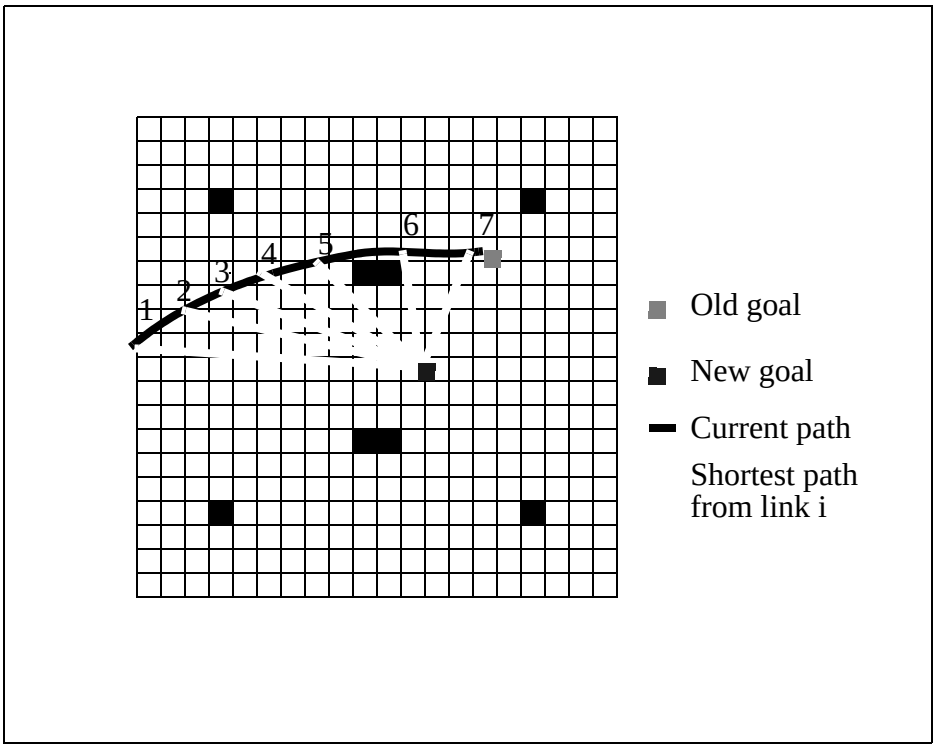


Figure 3.3: Choosing a path to a new goal

3.4 Snakes

Once we found the initial path to the goal, we use a *snake* to create a modified path that is located a safe distance away from obstacles. In addition, this path will be smooth and short due to the energy minimizing characteristics of the *snake*.

Snakes are first described by Kass at al.[1] and were used to extract information from images. In this case, the *snake* is used to generate a smooth path for the manipulator. For a detailed description on *snakes* and the method to solve the resulting finite difference equation, consult the original paper [1]. Here we present only a short description of the *snakes*.

The energy that we try to minimize for the curve is the weighted sum of the first and the second order term of the curve.

$$E = \int_0^1 (E_{int} + E_{ext}) \tag{3}$$

$$E_{int} = \alpha(s)\left|v_s(s)\right| + \beta(s)\left|v_{ss}(s)\right| \qquad 0 \le s \le 1 \tag{4}$$

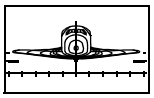
The first order and second order of the internal energy are weighted by $\alpha(s)$ and $\beta(s)$ respectively. Note that these weights are parameterized by s also, which means we can have different values of α and β for each point on the *snake*. The first order term of the energy gives the *snake* elasticity and the second order term gives it rigidity. E_{ext} are the external forces that are applied to the *snake*, for example the obstacle forces or the forces that the user applies to control the configuration of the *snake*.

To solve the above equations, (3) we transform the equation into a finite difference equation and then we solve the corresponding Euler equation for that finite difference equation. The solution can be computed very fast since the resulting matrix in the linear equation is a pentadiagonal matrix and therefore can be solved using a Cholesky decomposition

We added one more feature to the *snake*. The *snake* has discrete points along the curve since we solve the energy minimization problem by a finite differences method. The spacing of its points will influence how it behaves in terms of rigidity and elasticity. Its behavior will change as it gets longer and if it keeps the same number of points. So we have to keep the spacing between two adjacent points within a certain range. This is done by creating a new point between two adjacent points that are too far apart and deleting points that are too close together.

The reason that we choose to use this energy minimizing curve is that it has several desirable characteristics:

- The internal force makes the *snake* as short as possible (due to the minimization of the first order derivative)
- The internal force makes the *snake* as straight as possible (due to the minimization of the second order derivative)
- The curve can be manipulated so that any point on the curve can be nailed at any position.



- The curve also allows for application of external forces at any point on the curve

The first two characteristics are very important for creating a smooth and short path, and the last two characteristics are very important for controlling the manipulator indirectly by manipulating the *snake*.

3.5 Manipulator behavior

This section explains how we transform the path that is created by the *snake* into joint angles for the manipulator.

3.5.1 Extension and retraction of the manipulator

Once a path is created by the *snake*, the manipulator can be extended and retracted along this path. Below is the prescription we use to decide if we should extend or retract the manipulator:

- If the *snake* is not close to a stable condition then do not extend or retract the manipulator.
- Once the *snake* is close to a stable condition (meaning it is in or close to reaching its minimum energy) then extend the manipulator until it reaches the new goal.
- If the end of the manipulator protrudes from the end of the *snake* during the movement of the *snake*, then retract the manipulator until it does not protrude anymore.
- If during any movement, the manipulator can not be fitted onto the curve due to the excessive curvature, then retract the manipulator until it can be fitted onto the curve.

3.5.2 Fitting the manipulator onto the snake

There are two methods of fitting the manipulator onto the *snake*. One method solves for each joint angle directly. This is done locally, so no difficult inverse kinematic problem exists. The disadvantage of this approach is that we have to develop the fitting procedure manually for different types of manipulators.The second method is an iterative method where we attach the manipulator to the *snake* using springs. The joint angle is then calculated based on an iterative method using the Jacobian transpose instead of the inverse Jacobian. The second method is more flexible in the sense that it can be used for different manipulator configurations and it only requires the forward kinematic model of the manipulator. It is an iterative method, so it requires more time to fit the manipulator to the *snake,* however we have been able to perform these calculations in real time for a manipulator with up to 20 links (without much problem).

3.5.2.1 Fitting the manipulator directly to the snake

Fitting the manipulator directly to the *snake* is done by solving the inverse kinematics for each joint locally. For example a hyper-redundant robot that consists of n 2-DOF joints, we can compute each joint separately. In a manner similar to tracking a path for a mobile robot each joint-angle is computed so that the links that are connected to that joint are pointed in the direction of the *snake* that is located at the distance ‘l’ from the origin of the link. The variable ‘l’ is the length of the link. So the joint angle is calculated one by one from the base and moving towards the endeffector.

3.5.2.2 Fitting the manipulator to the snake with an iterative scheme

The manipulator is modeled by using a system of geometric transformations which form a kinematic model of the manipulator. Each degree of freedom is modeled by using a rotation or a translation matrix. The link is modeled as a collection of points with unit mass. This allows the system to be used with manipulators of different designs. For this particular task, a multi-link manipulator with 2DOF joints is used. Figure 3.3 shows a kinematic model for a 2-link manipulator with 2 rotating joints.

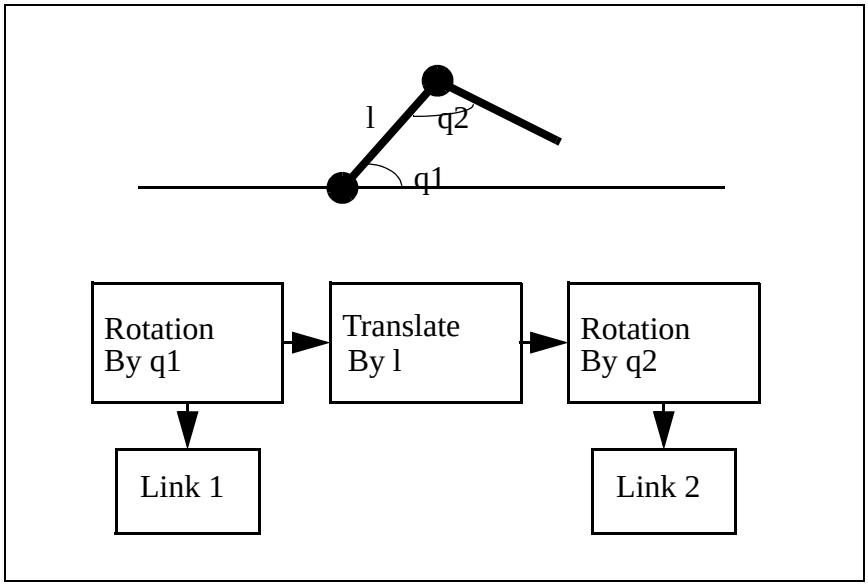


Figure 3.4: Kinematic Model for a 2 DOF serial manipulator

The joint angle computation is done by transforming the forces in cartesian space to joint torque in the joint space. Since this is a kinematic model, only the first order system is used, which means that force is equal to mass times velocity, not acceleration. So the moment the applied force is stopped, the velocity becomes zero.The transformation can be easily done since we only need the jacobian transpose, and not the inverse jacobian (avoiding singularity and ill-conditioning problems).

Here are the basic equations for transforming joint velocity to cartesian velocity, and cartesian force to joint force:

:
$$\tau = J^T F \tag{5}$$

$$J = \frac{d}{dq} x \tag{6}$$

$$x = Mp \tag{7}$$

where ‘p’ is the local coordinate of the mass points for the links, ‘x’ is the coordinate of the mass points in global coordinates and ‘M’ is the transformation matrix modeling the joints.

Each link can have an arbitrary number of mass points, which serve as a place where forces can be applied. The forces are also propagated back to the previous link, so the joint torque is a function of forces further down from that joint. So if there are three joints, modeled by matrices $M_{1,}M_2,M_3$, each is a function of joint parameter $q_{1,}q_2,q_3$ respectively, the joint torques are computed as follows:

$$\begin{aligned}\tau_1 &= \Sigma_i\left(\left(\frac{d}{dq_1}M_1\right)M_2M_3p_i\right)^T f_i \\ \tau_2 &= \Sigma_i\left(M_1\left(\frac{d}{dq_1}M_2\right)M_3p_i\right)^T f_i \\ \tau_3 &= \Sigma_i\left(M_1M_2\left(\frac{d}{dq_1}M_3\right)p_i\right)^T f_i\end{aligned} \tag{8}$$

The force f_i is applied to the mass point. The summation is done for all forces that are applied to the mass points on the links that are located down from the joint. These calculations are very simple if done recursively. The algorithm itself is *O(mn)* where *m* is the number of joint parameters and *n* is the number of mass points. What is left is to compute ‘q’ from the joint torque. To do this we need some quantity that can be regarded as mass.

Let us compute the kinetic energy for all the mass points of a manipulator with a single joint (the point is assumed to have unit mass):

$$T = \frac{1}{2}\Sigma_i\dot{x_i}^2 \tag{9}$$

$$T = \frac{1}{2}\Sigma_i\left(\frac{dx_i}{dq}\dot{q}\right)^2 \tag{10}$$

$$T = \frac{1}{2}\Sigma_i\left(\left(\frac{dx_i}{dq}\dot{q}\right)^T\left(\frac{dx_i}{dq}\dot{q}\right)\right) \tag{11}$$

$$T = \frac{1}{2}\Sigma_i\left(\frac{dx_i}{dq}^T\frac{dx_i}{dq}\right)\dot{q}^2 \tag{12}$$

Since kinetic energy is half of mass times velocity, we could regard the following quantity as mass:

$$m = \Sigma_i\left(\frac{dx_i}{dq}^T\frac{dx_i}{dq}\right) \tag{13}$$

where x_i is the coordinate of each mass point. It is obtained by transforming the local coordinate of each mass point.

$$x_i = Mp_i \tag{14}$$

Then we could use the value of m to compute the velocity of q from the torque

$$\dot{q}_i = \frac{\tau_i}{m_i}$$

: . (15)

Any forces in the cartesian space can be applied to the mass points. For fitting the manipulator to the snake, we applied forces that pull the manipulator toward the snake. Basically we are attaching springs between the manipulator and the snake.

3.6 The obstacle potential field

The obstacle potential field that we use is a FIRAS function[2]. The potential energy of this function is:

$$U(r) = \frac{A}{2}\left(\frac{1}{r} - \frac{1}{r_0}\right)^2 \qquad 0 < r < r_0 \tag{16}$$

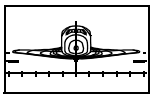
where 'A' is the scaling factor, 'r' is the shortest distance to the obstacle surface and 'r_0' is the effective range of the repulsive potential field. Although it is known that this potential field combined with the attractive potential field can cause local minima[5], it is not a problem in our case since we do not use potential fields to attract the manipulator to the goal. We only use potential fields to repulse the path from known and modeled obstacles.

3.7 Operation of the system

The individual operating modes and the resulting manipulator configurations within the space-shuttle's cargo-bay are outlined below and depicted in Figure 3.5 through Figure 3.8.

3.7.1 Teleoperation

The use of the *snake* allows us to teleoperate the robot easily without having to control all the joint angles individually by allowing the operator to pick which points he/she wants to control. This is possible since the operator controls the *snake* directly, and he/she only controls the manipulator indirectly. Since the *snake* is always repulsed from an obstacle, the operator does not need to worry about collisions. The operator also has one direct control avenue over the manipulator, namely the ability to retract or extend the manipulator along the *snake*. Besides applying forces to the *snake*, the operator can also 'nail' points down on the *snake*. Nailing a point on the *snake* makes that point immovable. The two end points of the *snake* are also always nailed (one to the base and one to the goal), forcing the *snake* to acquire the final goal position with additional constraints.



3.7.2 Automatic Operation

In addition to teleoperation of the robot, the operator can also give the system a goal and it will plan a path to the goal automatically. If the operator wants the robot to approach the goal from a certain opening or access port, then the operator can put an intermediate goal-point near the opening and then set the planning system so the path to the new goal will be the shortest path starting from the old goal. This means that we want the path that minimizes the distance that the tip of the manipulator has to travel. After the manipulator reaches the intermediate goal, the operator can instruct it to go to the real goal. If the manipulator is required to pass through a certain point in the opening, the *snake* can be ‘nailed’ at that point.

3.7.3 Scanning

Sometimes it is necessary for the end point to follow a predetermined path, for example to scan the outside cylindrical surface of a payload installed inside the space-shuttle’s cargo-bay (visual close-out inspection). In this case no path generation is necessary, assuming that the control points in the pre-determined path are located close to one another. To move the endpoint of the manipulator along this path, we just need to move the end point of the *snake* along the path. We move the end point of the *snake* by fixing it to the next control point along the path. The rest of the *snake* will then move accordingly to minimize its overall energy.

Figure 3.5: The manipulator is entering the workspace by following the computed path to the goal[1].

1. Lower left is the 3-D view of the workspace and the manipulator, lower right is the workspace unfolded into a flat surface, upper right is the top view and at the top is the user interface.

Figure 3.6: The manipulator has reached its first goal.

Figure 3.7: The manipulator is retracted in preparation to reach the second goal.

4. References

[1] M. Kass, A. Witkin and D. Terzopoulos “Snakes: Active contour models.” International Journal of Computer Vision 1,1987, 321-331.

[2] O. Khatib “Real-time obstacle avoidance for manipulators and mobile robots.” The International Journal of Robotics Research, 5(1), 1986.

[3] J. Barraquand, B. Langlois and J. Latombe “Robot motion planning with many degrees of freedom and dynamic constraints.”

[4] A. Hayashi and B.J. Kuipers “Obstacle avoidance of the swan’s neck manipulator.” Technical Report AI90-142, Artificial Intelligence Laboratory, the University of Texas at Austin, October 1990.

[5] R. Volpe and P. Khosla “A strategy for obstacle avoidance and approach using superquadric potential functions.”

[6] J.J. Craig “Introduction to robotics.”

[7] NASA/KSC Study, “Payload Processing System Study”, KSC-DM-3489, October 1990, Engineering Development Directorate

[8] NASA/KSC Space Transportation Systems Study, “Payload Accommodations at the Rotating Service Structure”, K-STSM-14.1.10, Rev. B, December 1980, Space Shuttle Payload Projects