MECHANISMS FOR AUTOMATED TOOLHEAD CHANGING IN NUCLEAR STEAM GENERATOR ROBOTICS

by

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Chapter 1 Introduction

Many robotic systems employ interchangeable end effectors. Generally, industrial and field robots have access in the workspace to toolheads for exchange. In areas that lack adequate space to store toolheads within the workspace, they must be changed manually or by an automated mechanism. The need for automation is prevalent when the manipulator must operate in a limited access workspace, because of restrictive geometric constraints. This thesis will discuss the design considerations associated with automated toolhead exchange systems.

The constraints associated with toolhead exchange will be defined and applied to an existing system for steam generator inspection and maintenance in a nuclear power steam generator. The objective of this application is to reduce personnel radiation exposure received during toolhead changes, and to improve the performance of general platform maintenance (toolhead tether handling and parts feeding) by replacing the present manual methods.

1.1 General Discussion of Toolhead Changers

The ability to change toolheads is common in computer numerically controlled (CNC) milling machines and robotic applications [Chubb (1993), McCormick (1986), Owen (1993), Pham (1986)]. In CNC applications, several tools mount on a rotating base that changes the toolhead according to the operation on the work piece. Robotic applications often involve several separate tools that attach to the manipulator by use of a coupler. Couplers mechanically fasten the toolhead to the manipulator, and in many cases, also connect the power source to the tool. These couplers are a relatively mature technology, available commercially.

For common robotic applications, the various toolheads are situated on a tool rack within the workspace of the robot. This allows automated exchange of the toolheads. For an industrial environment, where the workcell is designed around the robot, this provides an effective solution. In field robots, it is generally possible to mount the toolheads on the mobile platform. Therefore, they are always within reach of the manipulator for an exchange. In a limited access workspace there may not be space available for a rack of toolheads within the workspace of the robot. The result is the need for manual or automated toolhead exchange. Although presently the toolhead changes for the specific B&W Nuclear Service Company (BWNS, formerly part of Babcock and Wilcox) case are performed manually, automation would reduce human risk.

A limited access workspace is a particular area of interest that is only accessible through a constricted entrance. Common examples of limited access workspaces, defined and discussed in Shooter (1990), are underground storage tanks, chemical storage vessels and similar spaces opening into a large work area from a smaller entrance. The BWNS manipulator, COBRA, (named for its shape similar to a striking cobra) is this type. COBRA operates in a 59.8 inch (152cm) radius quarter sphere environment accessed through a 16 inch (40.6cm) diameter manway. It is unlikely the toolheads could be placed in the workspace for access by the robot, because of limited space. Manual toolhead changes in a general system are difficult if the entrance is small relative to the human operator.

1.2 Discussion of the Existing BWNS System.

A manipulator is being developed to feed toolheads to the BWNS steam generator manipulator, COBRA. The main purpose of this work is to reduce personnel radiation exposure. The task is defined in relation to constraints that exist in the working environment.

The general problem is to develop a manipulator or other device to automatically feed toolheads through a portal to a robot. To accomplish this, the device must attach and remove toolheads from COBRA. During steam generator service, COBRA uses various toolheads including kinetic sleeving actuator, tube marking, roll-plug installation, drill, TIG welder and several others.

Steam generators are shell-and-tube heat exchangers between the radioactive primary water, from the reactor, and the non-radioactive secondary water that is turned into steam to power the turbine. The generators have between 3,000 and 15,000 tubes through which the primary water flows. These tubes are inserted and welded into a 12 inch (30cm) thick tubesheet that is the cover of the bowl. The bowl is the lower hemispherical pressure vessel end cap, which is divided into two quarter spheres. The primary water flows into half of the bowl through a large pipe, up through the tubes, which are "U" shaped, and down into the other side of the bowl and back to the reactor. The walls of the tubes of the steam generator are the only barrier between the radioactive and nonradioactive water loops. Therefore, it is important for the tubes to be inspected for leaks caused by corrosion, thermal stresses, and other factors.

The tubes must be inspected by COBRA from the bowl of the steam generator. Each half of the bowl, is a 59.8 inch (152 cm) radius quarter sphere with a 16 inch (40.6 cm) diameter portal located 45° down from the top plane and 22° out from the back plane shown in figure 1.1. COBRA and its support equipment are carried to the steam generator and installed manually. The mounting bracket and track extending into the bowl are bolted to the manway. COBRA travels on a motorized trolley, up the track, into position in the middle of the bowl. Figure 1.2 is a view of COBRA in the bowl showing its size relative to a person. The joint axes of this five degree of freedom robot are shown in figure 1.3. COBRA has the ability to tilt its mezzanine (COBRA's support structure, see figure 1.2), and thus reach out through the manway. This position is used during toolhead changes, however, many of the toolheads do not fit through the manway when attached. The shapes and sizes of the toolheads vary, see figures 1.4 - 1.7 (for a size comparison, the coupling is 5 1/2 inches (14

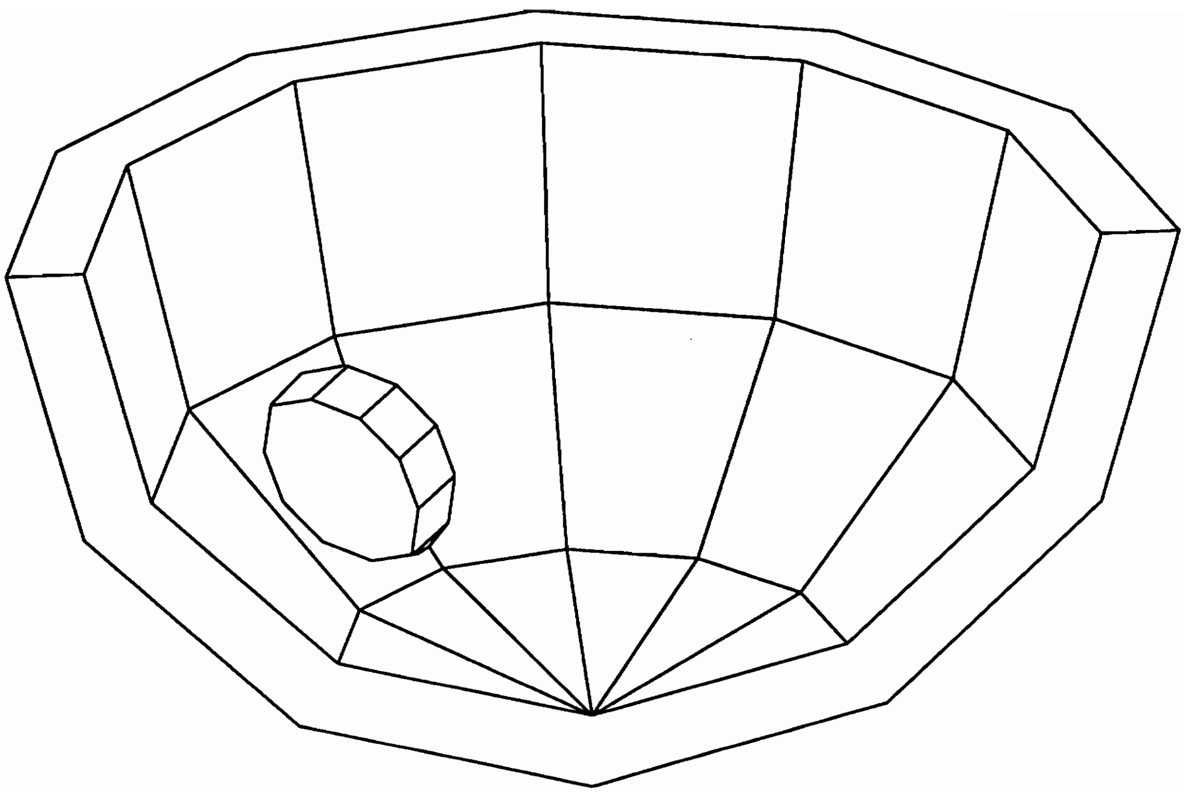

Figure 1.1 Steam Generator Geometry: Quarter Sphere with Manway

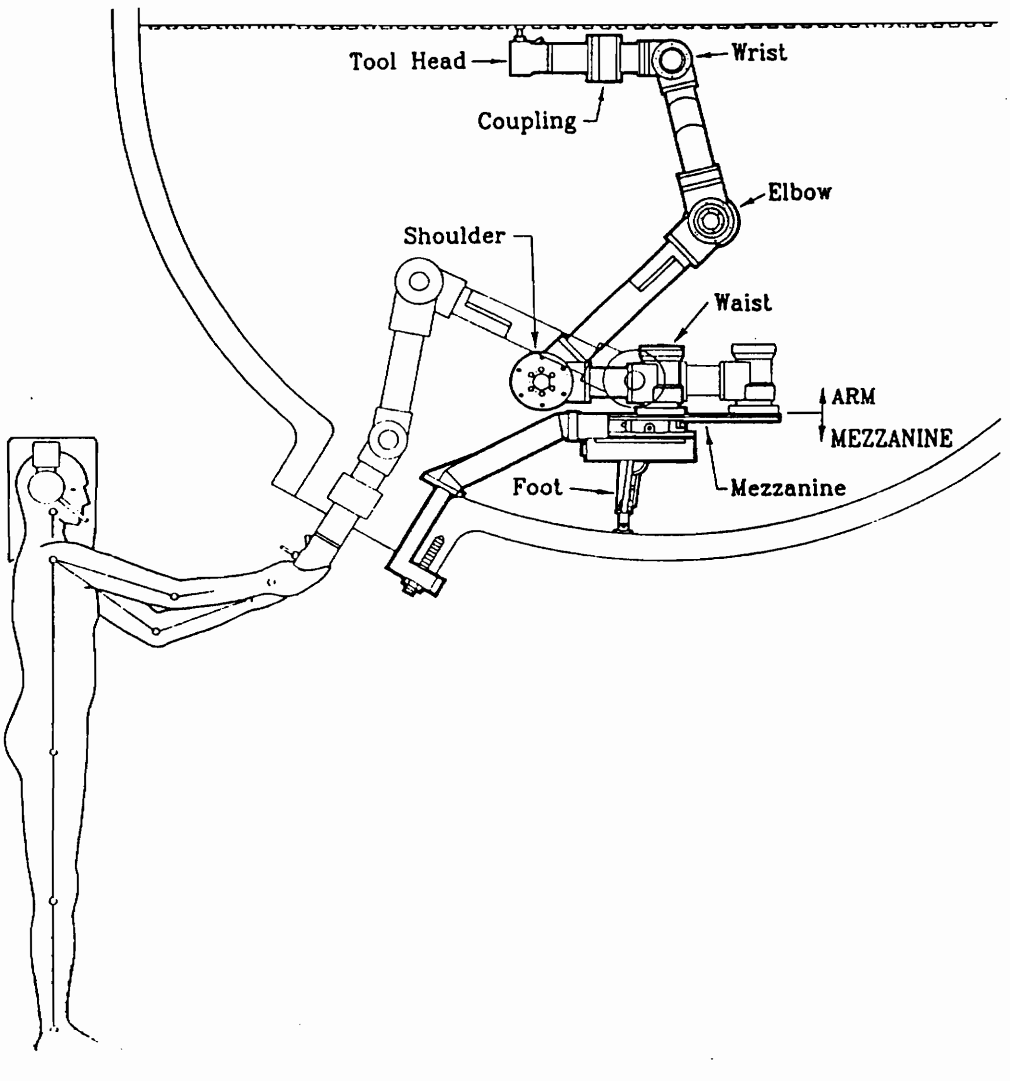

Figure 1.2 Side View of the Bowl with Worker

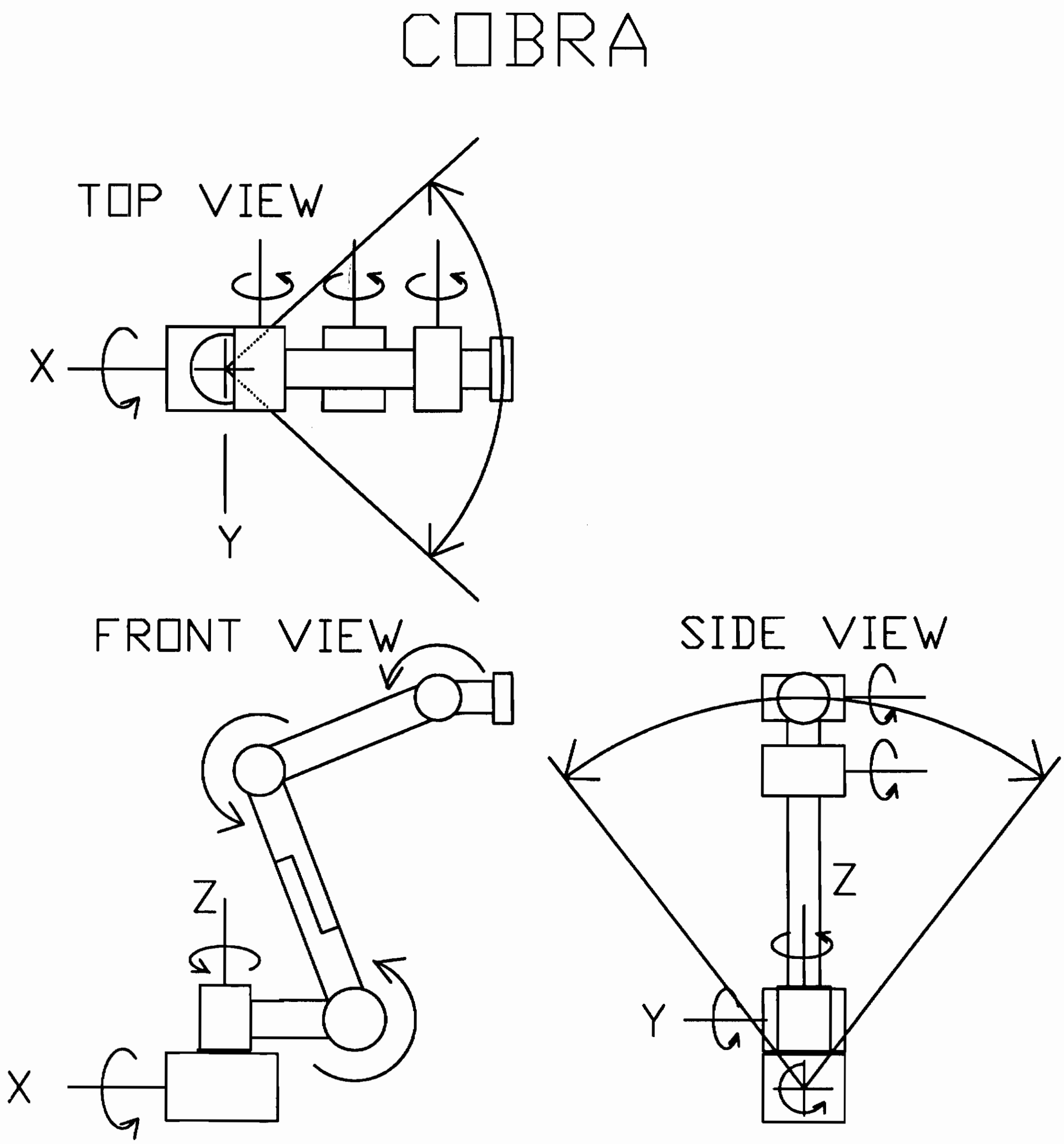

Figure 1.3 Geometry and Rotations of COBRA

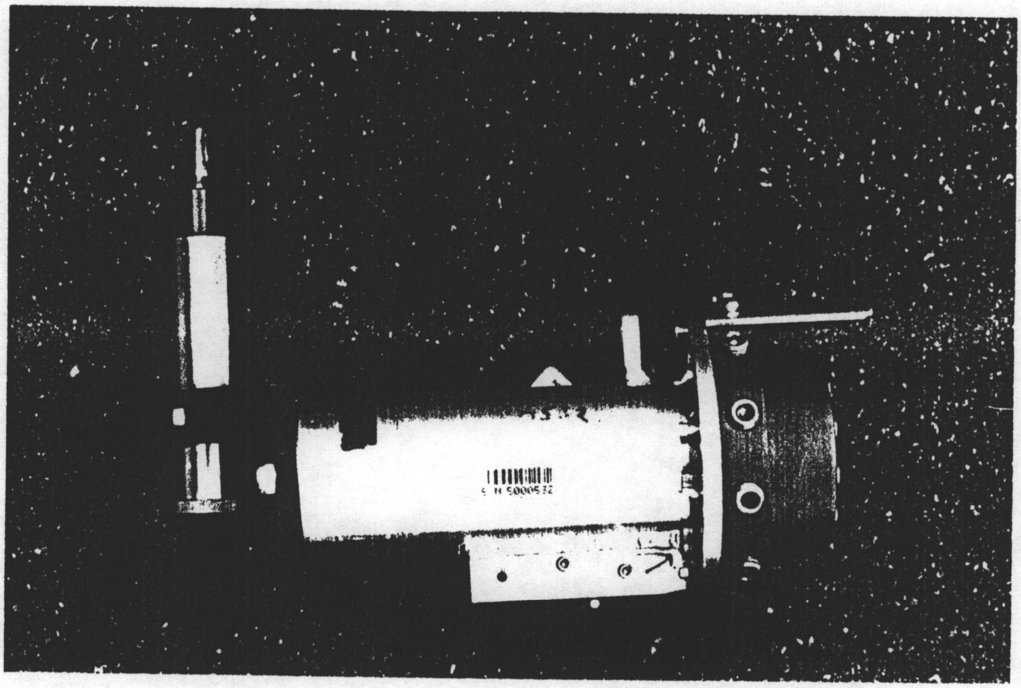

Figure 1.4 Toolheads: Plug Insertion

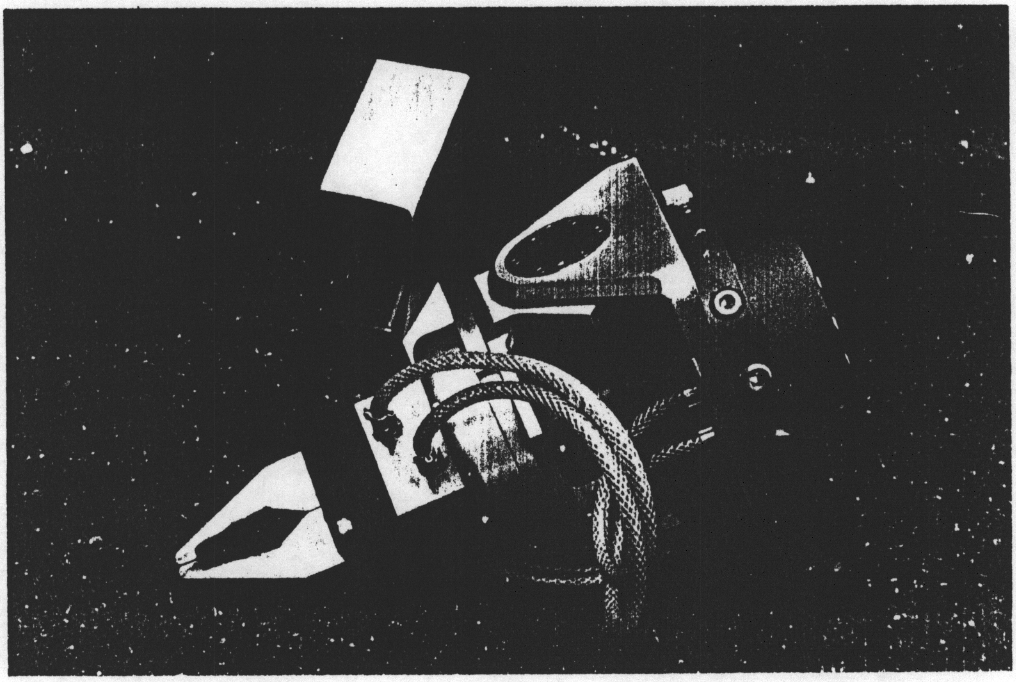

Figure 1.5 Toolhead: Gripper

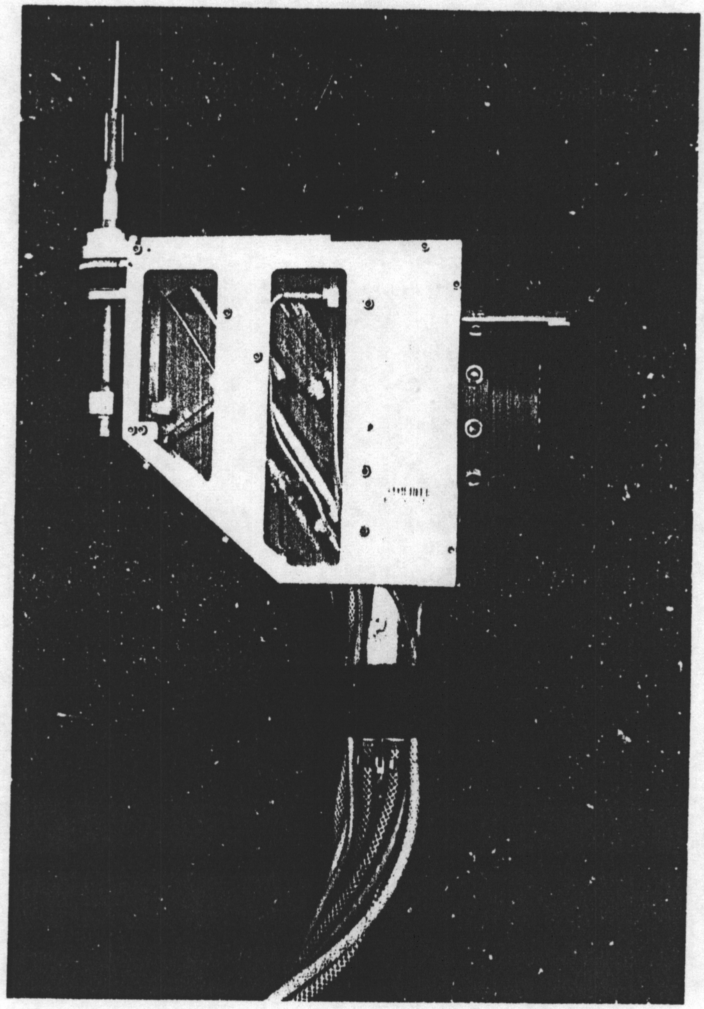

Figure 1.6 Toolhead: Plug Rolling

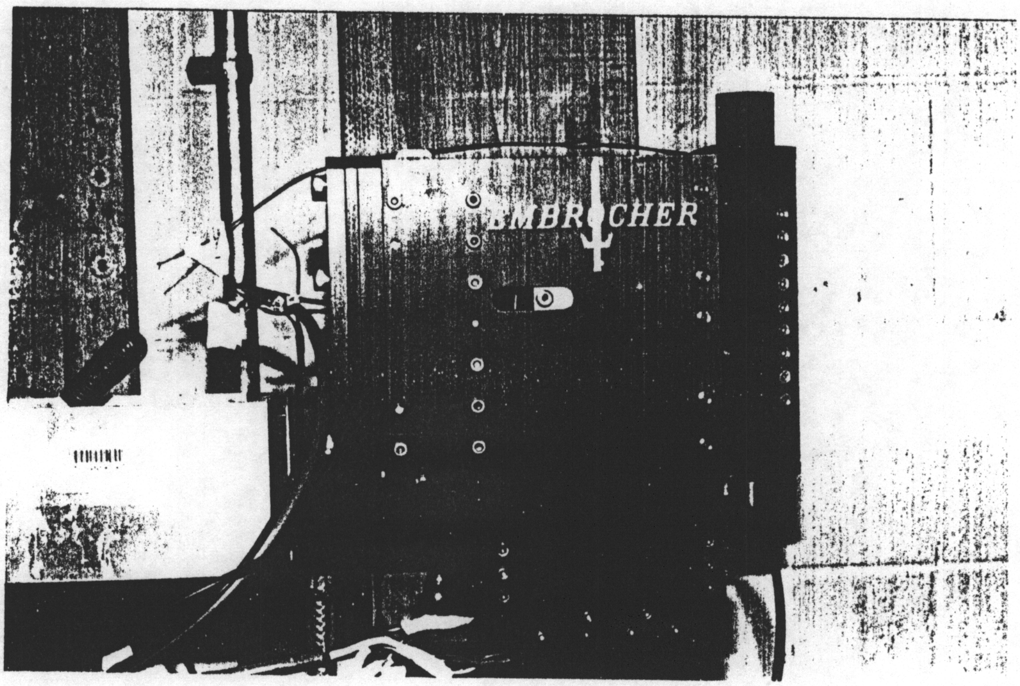

Figure 1.7 Toolhead: Embrocher

cm) in diameter). However, the length from the coupling to the end of the toolhead is constant, which provides consistent positioning of COBRA when locating tubes. Many of the toolheads also have dedicated high current, hyrdraulic and pneumatic lines that extend out of the bottom, clearly illustrated in figure 1.5.

Platform workers perform various maintenance duties including installing and removing COBRA, changing toolheads, feeding sleeves to COBRA inside the bowl and controlling the pneumatic and power lines attached to the toolheads. One of the primary functions of platform workers is managing the tether of lines from the toolhead to prevent tangling and snagging and to feed and remove line from the bowl. Other functions include toolhead changes, see figure 1.2, in which the worker must attach the toolhead to COBRA. For some toolheads COBRA can tilt on the mezzanine and reach out. For larger toolheads the worker must lift the toolhead through the manway to couple it with COBRA. Toolhead changing is a high radiation dose activity, because of the radiation "shine" coming out of the manway. Radiation projects out of the manway of the steam generator in a concentrated beam. Workers are taught to stand to the side of the manway to minimize exposure.

The specific problem is to limit personnel exposure to radiation during the inspection process by reducing the amount of time a worker spends on the platform outside the steam generator in the high radiation environment.

According to Reuben Schilling of Schilling Development, Inc., "Within the nuclear utility industry pressurized water reactor (PWR) steam generators are now responsible for approximately 40 per cent of the exposure accumulated during refueling and maintenance outages." (Shilling 1992a). Personnel exposure is of great concern in the industry for health and safety reasons and because of regulations progressively limiting the level of allowable exposure, discussed by Glass and Kaye (1993). The hazardous environment and the complications of the geometry place a number of constraints on the design of the manipulator.

The environment of the steam generator and its manway place limits on the design of the platform manipulator. First, the device must be carried to and assembled on the platform outside the generator. This limits the weight of the manipulator and its bulk, and may require the design to be modular and assembled on site. The manipulator must also run on the power sources available, namely, electricity and compressed air. It must be able to operate in various workspace envelopes outside the bowl that result from the different types of steam generators and various sites. The platform manipulator may mount on the top quarter of the manway ring and must not interfere with existing equipment, such as the existing camera placements and COBRA's mounting bracket. Finally the manipulator must be an affordable solution. Added to these environmental concerns are the mechanical necessities of the manipulator.

The mechanical design requirements include toohandling, maneuvering, actuation and control, and bowl exterior mobility. Tool handling involves gripping the tool on a common feature. This feature can be existing, such as the coupling, or it may be added to the toolheads. Maneuvering of the toolhead through the manway is a serious problem, because many of the toolheads will not fit through the manway when docked with COBRA. However, it should be possible to insert all toolheads by placing the lengthwise axis of the toolhead parallel to the manway face when inserting the toolhead into the bowl (see Span Entrance Configuration section 3.2). The insertion problem is complicated by the need to control the pneumatic and electric lines connected to the toolheads. These lines must not be pinched or snagged on equipment on the platform or in the entrance to the bowl.

1.3 Review of Literature

Concepts within the scope of this problem are dual-arm robotics, toolhead changers and coupling systems, and robots for hazardous environments. Research in these areas is discussed below.

Dual-arm systems are a relatively new area of research in robotics. Much of the work in this field involves the cooperation of robots to move a single object. Two examples are "Path Planning for Two Planar Robots in an Unknown Environment", by Tung-Ping, C., and Q. Xue, (1992) and "Path Generation for Two Cooperative Puma Robots", by Chen, J. L. and J. Duffy (1992). Both papers examine dual robotic systems moving one object. The systems are closed chain manipulator problems where the object is the link joining the two robots. "Object Handling Using Two Arms Without Grasping" (Yun 1993) discusses holding objects between two manipulators without dropping or crushing them and the control of the motion and forces.

Toolhead changers and couplers are common in the robotics industry. The two terms are interchangeable. Papers typically discuss either the physical coupling between the toolhead and robot or both the coupling and the process by which the robot changes toolheads. Several papers have been written on the subject and describe the uses of toolhead changers in industrial environments. Two collections of papers, Chapter 4 of Robot Grippers, (1986) edited by D. T. Pham and W. B. Heginbotham, entitled "Gripper and Jaw Changers" and Chapter 5 of Developing and Applying End of Arm Tooling (1986) edited by P. McCormick, entitled, "Hand Changers and Interchangeable Tooling", describe systems that use toolhead couplers including the tool rack in the workspace of the robot to change the end effector in use. Tool changing technology is also present in field robotics. Field robotics consists of mobile systems that operate in a dynamic environment. Chubb (1993) describes how a field robot could be outfitted with a coupler and could carry various grippers on its body. It is also common for Computer Numerical Controlled (CNC) machines to have the capability of using various tools, see Owen (1993). In CNC this is typically accomplished by several tools on one mount rotating to change the tool in use. The quantity and age of the papers, as well as the commercial availability of toolhead couplers indicates that this is a well-defined technology.

Industrial and field systems accomplish toolhead changes by having various end effectors within reach. Having the tool rack in the workspace of the robot may be impossible in a limited access workspace due to geometric restrictions. Several tools on one mount may also be ineffective due to the size and weight of the tools. For example, in the case of COBRA, the toolheads at present are designed to fit through the manway with very little radial clearance. The COBRA system was built to be highly portable, and thus lightweight. It must be carried to the steam generator and installed manually, so weight is an important factor. Industrial robots can usually be built to maximize stiffness, which typically results in a heavy arm. This is not practical for COBRA and thus the lighter links result in some deflection due to the compliance of the arm and the toolhead. Adding a larger and heavier multiple-tool-end-effector to this system is impractical. There is a need for a mechanism to feed the toolheads into the workspace to accomplish a toolhead exchange.

Robots are in widespread use in the nuclear industry. Robots perform a valuable service in the inspection, maintenance and operation of nuclear power, processing and production facilities. The extensive use of robotics is the result of several factors the severity of the hazard, the need for careful and repeated inspection and regulation of personnel exposure limits. According to Glass and Kaye (1993), the Nuclear Regulatory Commission has recommended a reduction from the current 5 Rem/year to 2 Rem/year and most utilities will adopt this guideline by 1994. This will drive the development of more robotic systems with greater capability and the need for these systems to operate with little or no direct human contact. Kochan (1992) discusses the state of robotics in the nuclear industry in Europe, describing many different systems. Most of these systems are for reactor core inspection, however, the method of motion varies from suction cup feet to a magnetically attached treaded rover. Robots are also expected to be used extensively in the Decontamination and Decommissioning of nuclear facilities, discussed in Schilling (1992a). The shut down of a nuclear facility will require the removal and disposal of a large volume of highly radioactive material impossible for humans to handle. The clean up of nuclear accidents, such as Chernobyl, is also a subject of much research in robotic application, see Creedy (1993). The areas of inspection, maintenance, fuel handling and Decontamination and Decommissioning encompass the vast array of topics for robotics applications in the nuclear industry.

Chapter 2 Discussion of Degrees of Freedom

2.1 The Generic Problem

In developing the toolhead feeding mechanism an analysis of the kinematics is performed to determine the minimum number of degrees of freedom (DOF) required by the system. The concept is first analyzed for a generic planar problem. The examination begins with two planar manipulators each having one DOF and operating in the same plane. The manipulators are first considered in free space, then with the geometric restriction of the portal. A toolhead is to be passed between two arms. This requires the toolhead to be held by the first arm and docked with the second arm for the exchange. This analysis makes the assumption that toolhead coupling is axissymmetric. Off-axis rotations occur when the axis of rotation is not one of the coordinate axes. The off-axis rotations can cause problems in the typical alignment of the mating parts of the coupling or assist effective positioning with alternative alignment.

In figure 2.1a there are two manipulators each having one DOF. This and all of the figures in this section are kinematic diagrams and are not true scale views. In general, these two manipulators will be able to touch ends. Depending upon the geometry, they may additionally be capable of aligning at a specified point. This case would not allow for a toolhead change, with the exception of the possibility of the one geometry-dependent point. Adding the geometric restriction of the portal, figure 2.1b, the two manipulator system requires an additional DOF

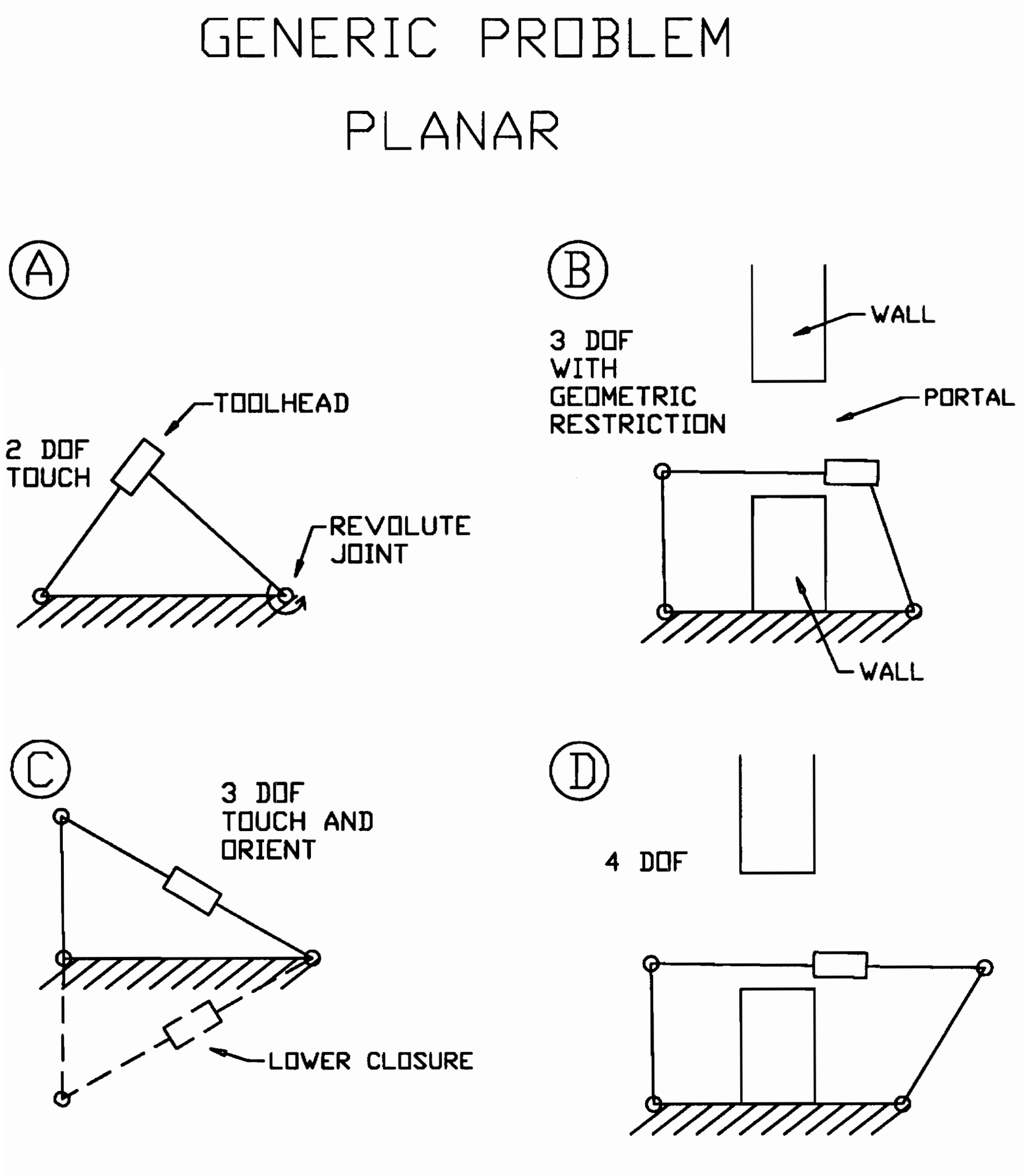

Figure 2.1 Generic Problem: Planar

to touch ends. When the portal opening is not situated on the line between the two arms base points, the complication in geometry made an additional DOF necessary in the system. The system total is now three DOF.

Examine a three DOF system without geometric restriction, the left arm has two DOF and the right arm one DOF, as shown in figure 2.1c. This allows the system to orient to dock a tool. The pair of arms can now dock at two points, upper and lower closures, if free of geometric restrictions. A three DOF system can position and orient in a plane. The addition of the portal again necessitates an additional DOF for the general case. As shown in figure 2.1d, a total of four DOF is needed for the general case including the portal geometry.

Advancing the problem to a nonplanar geometry increases the complexity, see figure 2.2. Consider two nonplanar manipulators. The base point of the arm on the right is moved out of the plane of the left arm by some set distance. Except for the wrist joint on the left arm, both manipulators are independently planar. The intersection of the planes of operation of the manipulators form a line in the vertical. Orientation of a toolhead to dock requires an additional DOF. Three DOF on the left and one DOF on the right for an nonplanar system free of geometric restrictions, in total, a four DOF system. The portal geometry requires an additional DOF to be added to the system, as shown in figure 2.3. If the geometry is not a special case allowing for a configuration-specific alignment, a five DOF system is required for this nonplanar case.

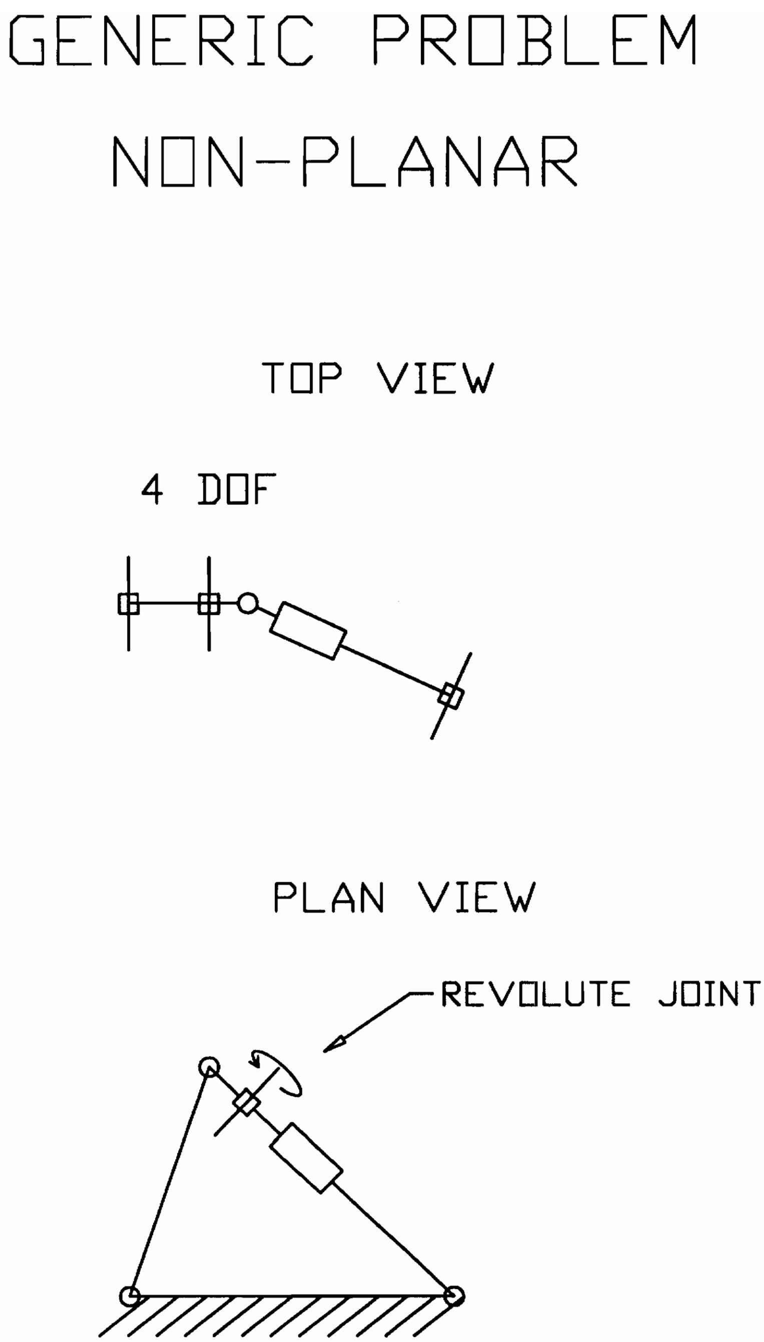

Figure 2.2 Generic Problem: Nonplanar

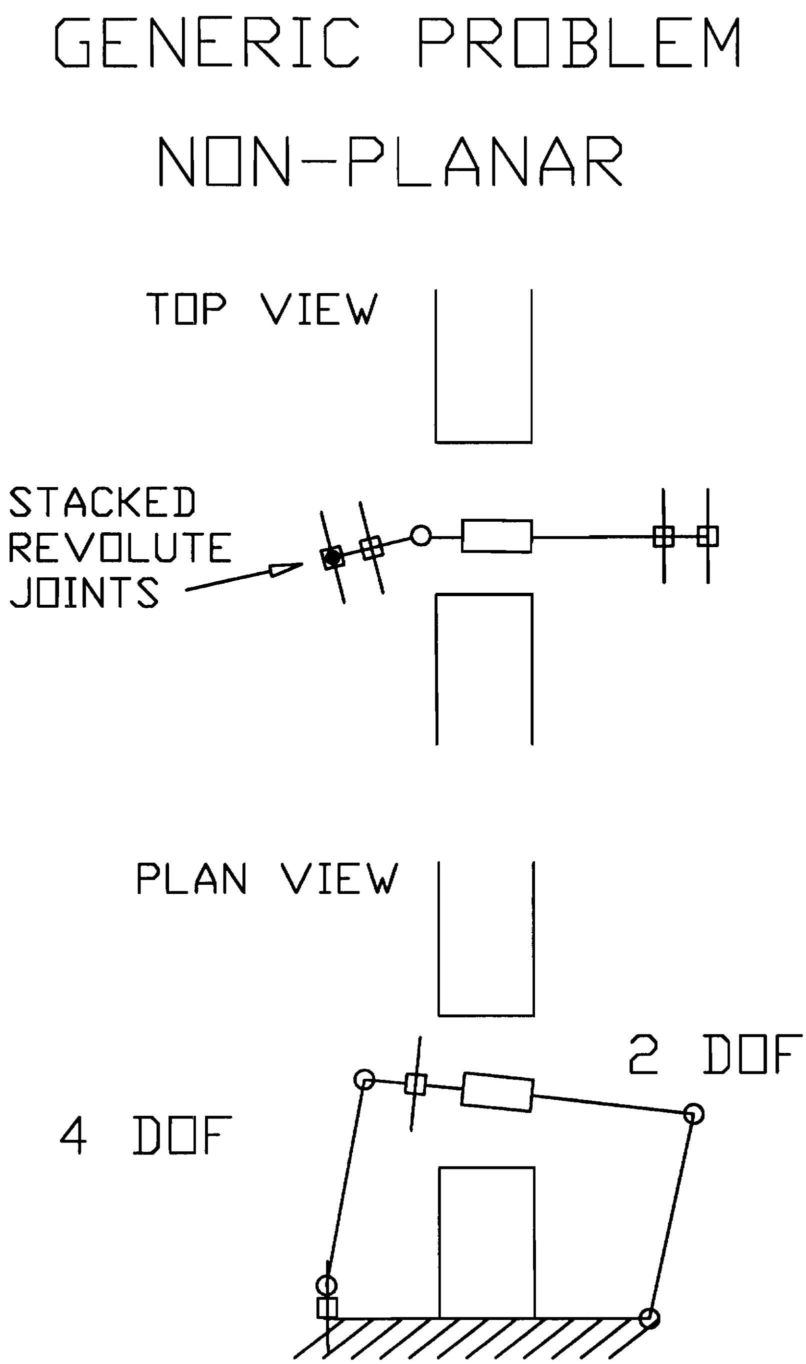

Figure 2.3 Generic Problem: Nonplanar - with Restriction

Continuing to a completely general case, free of geometric restrictions, still considering the axissymetric tool, examine the manipulator system of figure 2.2 previously discussed. As shown in figure 2.4a, in the general case the two planar manipulators would not intersect. The addition of a DOF, shown in figure 2.4b-c, results in a vertical plane of intersection. This is the same vertical intersection case, however, a additional DOF is required to have the manipulators intersect. This is a five DOF system, four DOF in the left arm and one on the right. Again it could be shown that the addition of the portal would necessitate another DOF resulting in a six DOF system, four in the left arm and two in the right, shown in figure 2.5.

Proceeding to the completely general case by adding a nonaxissymetric tool would require a rotation about the tool axis to dock. For the case free of geometric restriction this results in a six DOF system. This agrees with the six DOF of free space, three translations and three rotations. Again the portal necessitates at least one additional DOF and results in a minimum seven DOF system for the general case with the geometric restriction.

To dock a non-axissymetric tool to a robot through a portal requires seven DOF for the general case. Fewer DOF are required for special cases such as planar and vertical intersect systems. This analysis is applicable only for the portal geometry. Other restrictions may necessitate various additional DOF.

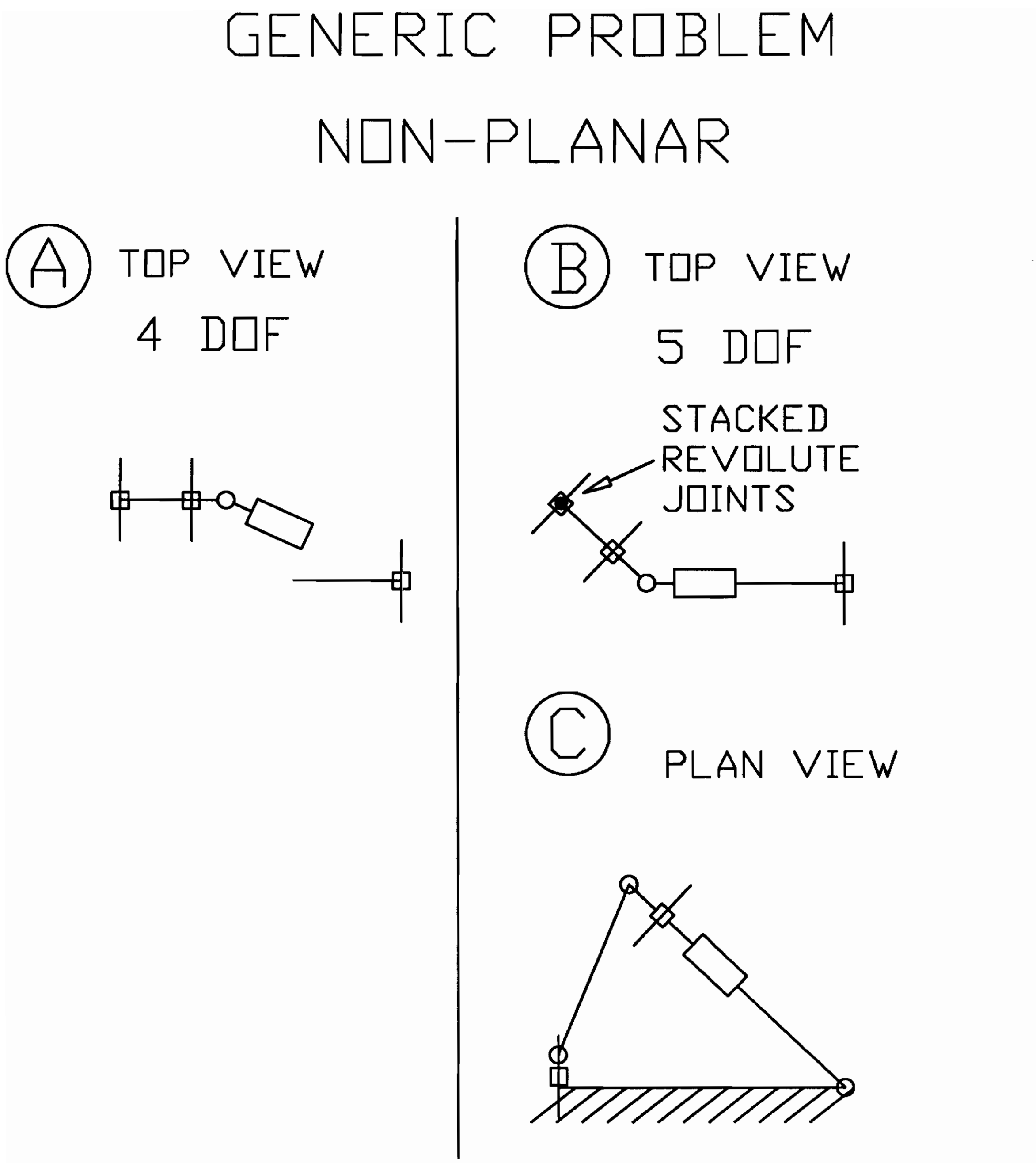

Figure 2.4 Generic Problem: Nonplanar - General Case

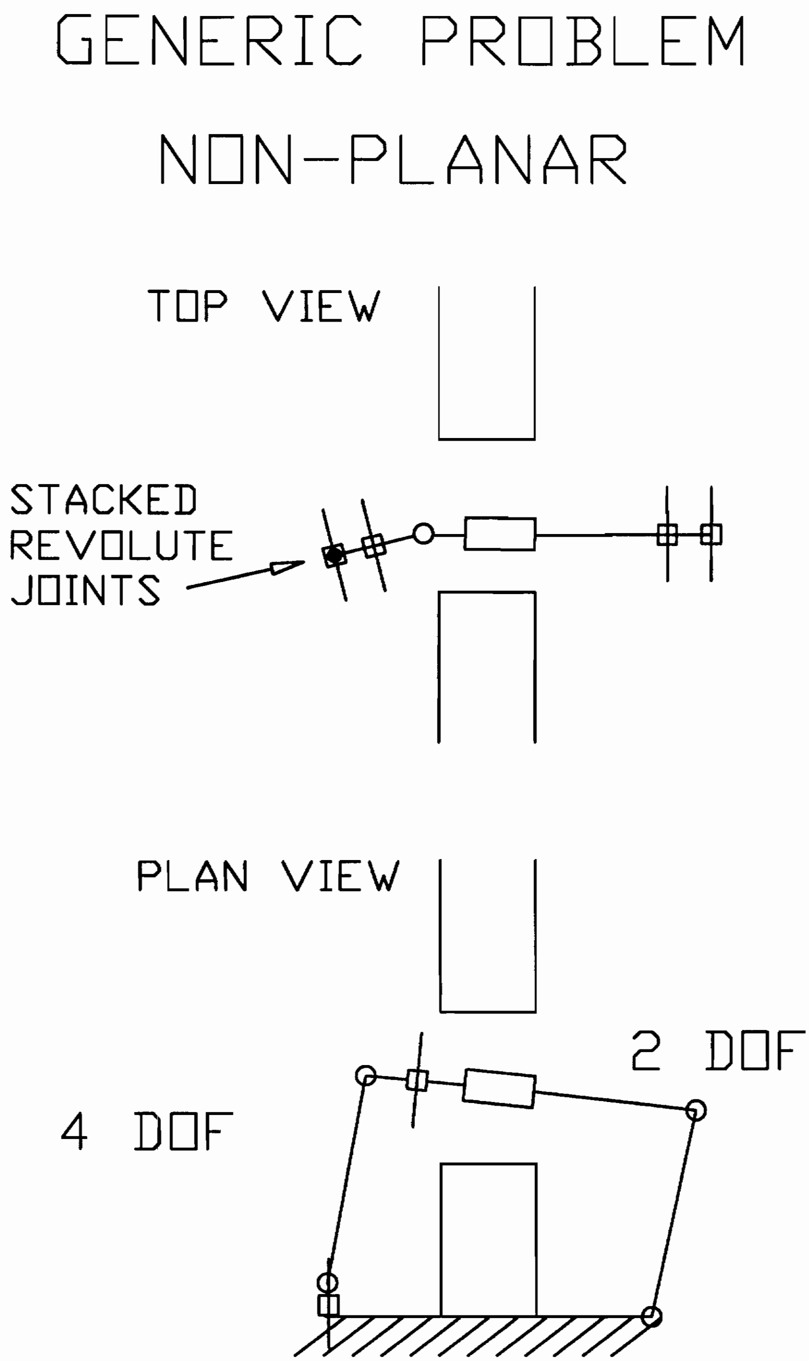

Figure 2.5 Generic Problem: Nonplanar - General - with Restriction

2.2 DOF in the Existing BWNS System

As demonstrated in the generic analysis above, the number of DOF needed by the toolhead-feeding mechanism depends upon the number of DOF in the arm of the existing system. The COBRA manipulator can be viewed as a three-DOF planar manipulator with two additional rotations at the base. The first rotation is the mezzanine tilt, the second is the rotation of the waist joint. The next three axes of rotation are parallel during normal service work.

COBRA's toolhead can translate along the x and z axes and has rotations about the x, y and z axes, see figure 2.6. The rotation about the z axis is of limited usefulness in docking because it is at the base. The z rotation accomplishes positioning, but cannot perform any fine rotations of the end effector useful in docking. During docking, the geometry of the bowl requires the arm to reach toward the manway. The rotation about the x axis is the mezzanine tilt. This rotation is also useful in the positioning of the arm, but of little use in docking because it swings the manipulator out of the plane as it rotates. The mezzanine tilt allows COBRA to reach out the manway. Thus, the DOF useful to docking are x and z translations and the rotation about y.

For a manipulator to reach a point at an arbitrary orientation requires six DOF. To exchange a non-axissymmetric toolhead, with the geometric restriction, the system is required to have a total of at least seven DOF.

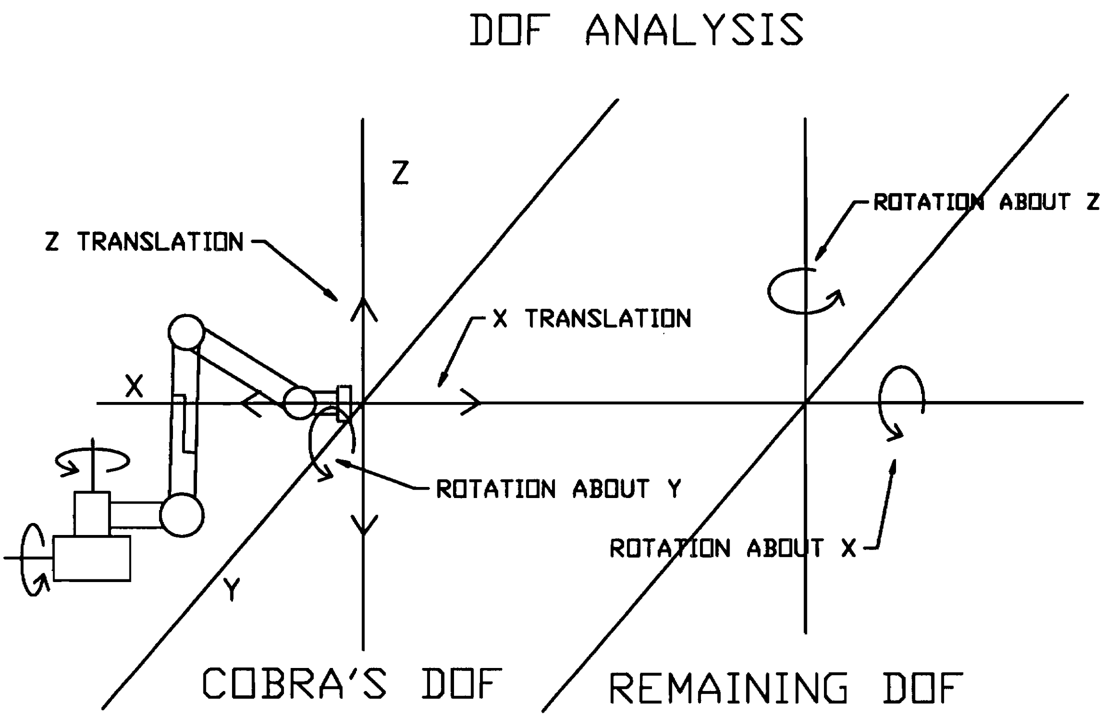

Figure 2.6 COBRA's DOF

Since the mezzanine tilt and the waist joint rotation are of limited use in docking, the DOF needed are rotations about z and x and the ability reach a point inside the workspace of COBRA. These two DOF, plus the five from COBRA result in a seven DOF system between COBRA and the feeding mechanism. Special geometries may reduce the required number of DOF. Examples are discussed later that use the mezzanine tilt to eliminate the need for one DOF.

Chapter 3 Initial Conceptual Designs

3.1 Problem Statement for COBRA

The objective is to develop a mechanism to automatically feed toolheads to a robot through a portal. To accomplish this goal, the mechanism must be able to attach and remove toolheads from the robot. This requires that it move the toolheads into the workspace of the internal manipulator and orient them in a dockable position. Additional requirements include the capacity to reach 10" (25.4 cm) inside the 16" diameter (40.64 cm) manway and the entire manipulator to not intersect the projected cylinder of the portal when not in use. The mounting must not interfere with the manway shield doors and may be mounted either before or after the door support frame. The manway shield is a curtain which covers the opening of the manway during maintenance.

Other constraints exist that are not readily apparent. The toolheads cannot fit through the manway while they are attached to COBRA. Therefore, though COBRA can reach out of the manway, it cannot readily exchange toolheads as part of this action. The toolheads are also various shapes and sizes. A standard method of moving the toolheads inside of the bowl must be developed.

3.2 Presentation of Concepts for Toolhead Feeding

Span Entrance Configuration

Toolheads come in various shapes and sizes. However, some of their features and dimensions are common. All of the toolheads have a robocouplings that allow for rapid tool interchanges. The distance from the robocoupling to the tool tip is a set length. This allows all of the tools to operate identically for positioning on the tube sheet. The overall length of the toolhead along this axis is approximately 13 inches (33.02 cm). Some of the tools are taller than the manway diameter of 16 inches (40.64 cm), especially when they have feeding or pneumatic lines attached at the tool tip refer to figures 1.4, 1.5 and 1.6. Therefore, the toolheads may not fit through the manway with their vertical axis (height in a typical side view) parallel to the manway plane, but all should fit through with the length of the toolhead parallel to the manway plane.

A set method of feeding the toolheads through the manway, the span entrance configuration, is the basis of the concepts presented for the BWNS COBRA application, as shown in figure 3.1. The tool span is defined as the distance from the robocoupling to the tool tip. Orienting the span parallel to the plane of the manway, and orienting the tool vertical parallel to the centerline of the manway, the toolhead can travel through the manway on a linear path. The 6 in (15.2cm) by 14 in (35.6cm) dotted line box is a space that most toolheads would fit through.

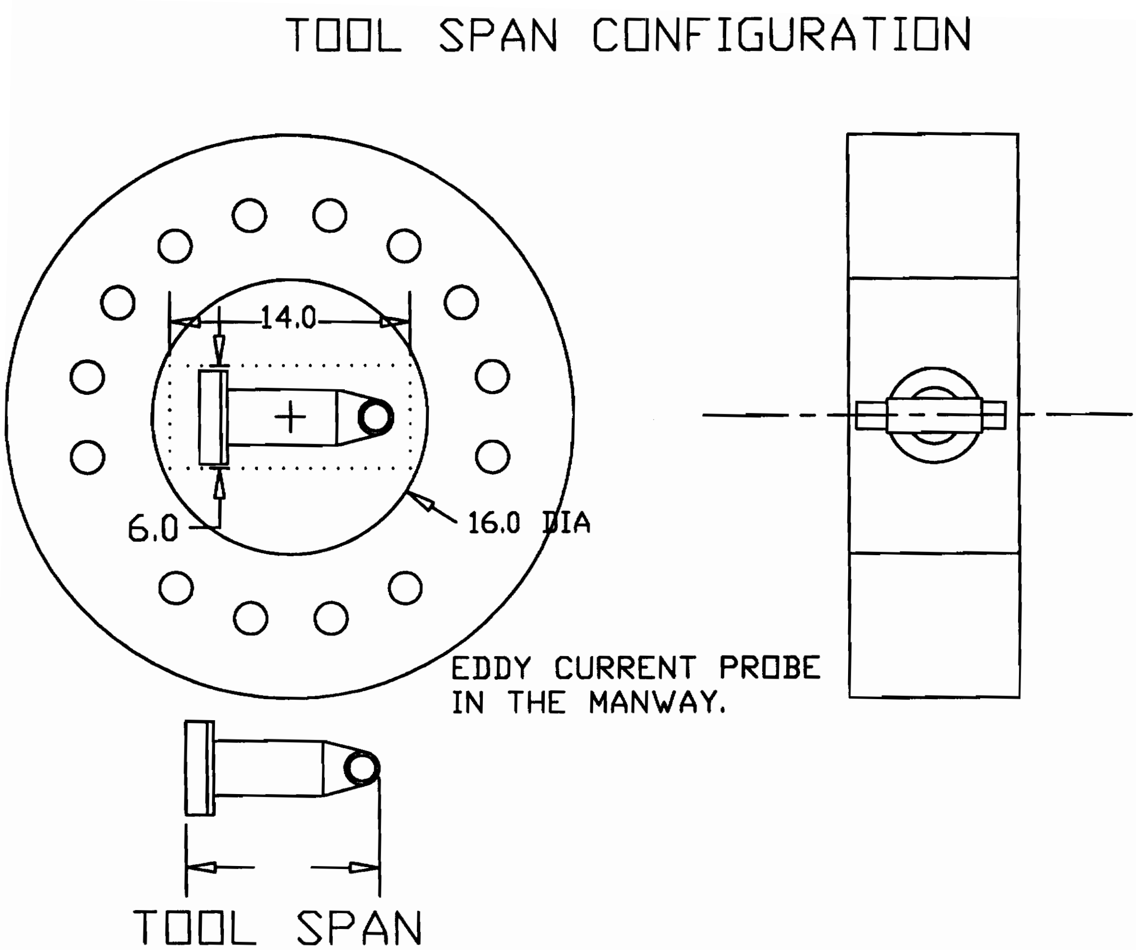

Figure 3.1 Span Entrance Configuration

Tool Racks and Hoses

Many of the toolheads have feeder hoses and cables attached which cause concern during tool handling. There are two principal concerns in dealing with the hoses. The first is getting the tool and hoses in and out through the manway,and the second is dealing with multiple toolheads and multiple lines outside the bowl. The movement of toolheads and hoses through the manway is dependent on each individual concept. The arrangement and presentation of the toolheads outside of the bowl is accomplished using a tool rack. The type of tool rack used depends upon the manipulator concept, but all the racks fall into one of three categories: linear motion, semicircular or spoked wheel.

Linear Motion Tool Rack

All of the designs generated involve the use of a tool rack. The most functional choice is a straight rack with the tools aligned parallel to the manway opening, see figure 3.2. This arrangement works well, because it limits the possibility for crossover and tangling of the hoses and cables attached to the toolheads. Linear travel perpendicular to the manway centerline would change the toolhead being presented. Some concepts require the rack to obstruct the manway when in use, but with enough linear motion, it could travel out of the way.

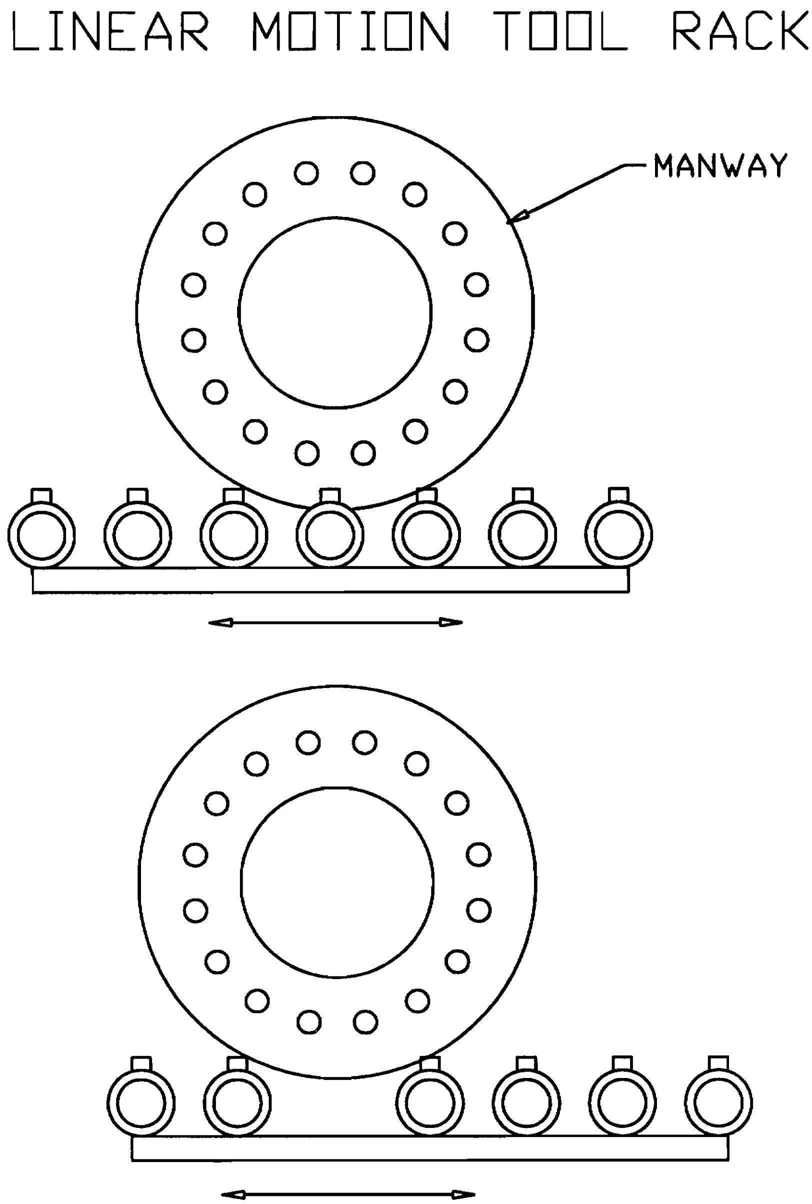

Figure 3.2 Linear Tool Rack

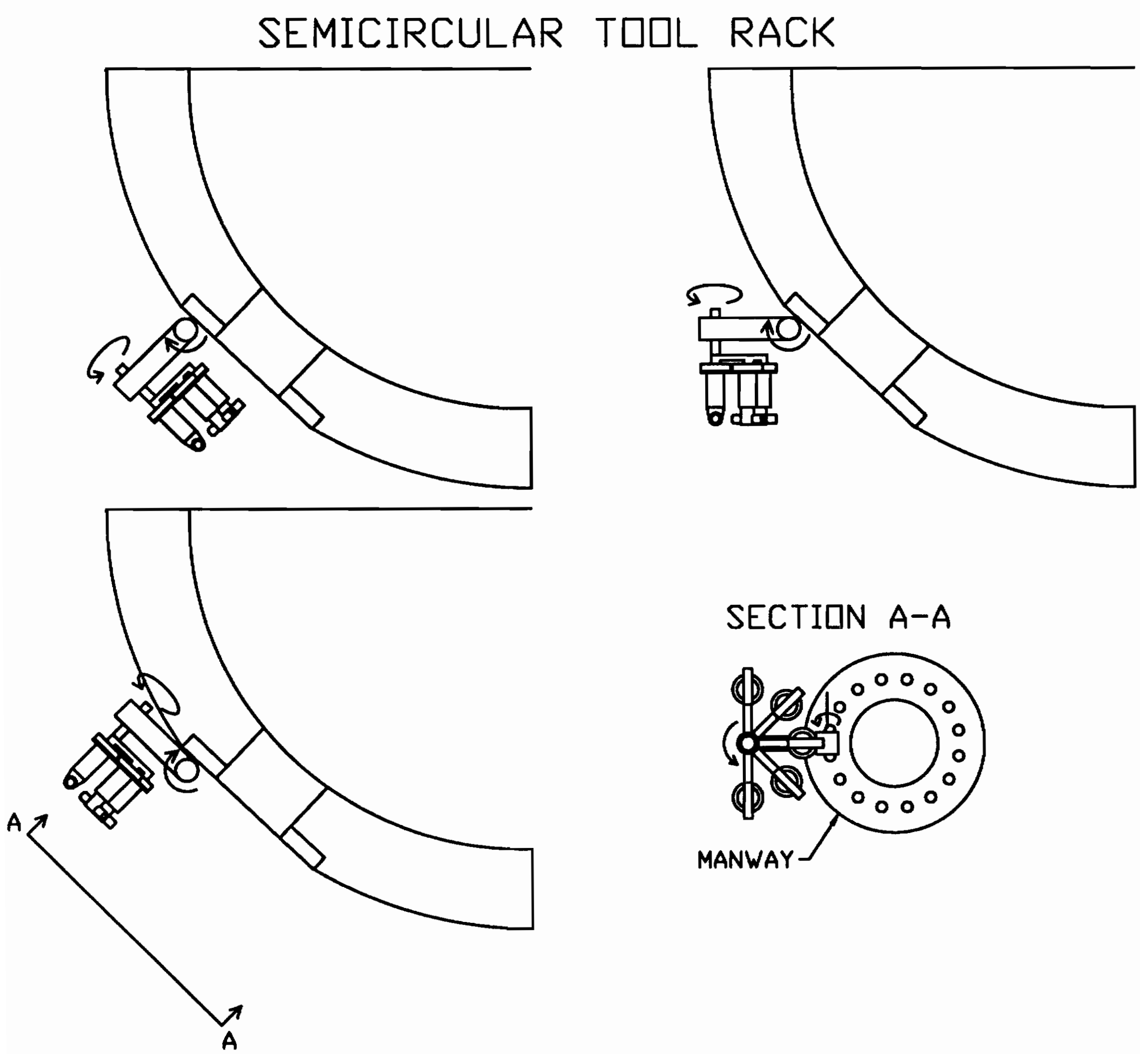

Figure 3.3 Semi-Circular Tool Rack

Semicircular Tool Rack

A half circle tool rack would allow the base of the rack to remain stationary and only rotate to present the tool, as in figure 3.3. The use of only half the circle would allow the hoses to pass through the other side without crossover. Limited rotation would keep the hoses from tangling.

Spoked Wheel Tool Rack

This is also a circular tool rack with the tools arranged like spokes of a wheel, see figure 3.4. The rack would mount on the top of the manway and rotate to present the various toolheads. Using approximately three quarters of a wheel to hold the toolheads would allow the remaining one quarter open to clear the manway of obstruction in this position.

Manipulator Concepts for the BWNS System

I. Revolute Jointed Manipulator

The first concept is a revolute jointed manipulator attached to the manway ring having high mobility and having four or five DOF, see figure 3.5. Four DOF are needed to perform the exchange and five would provide greater mobility outside of the bowl. This configuration has good characteristics to perform operations other than toolhead feeding outside the bowl. For example, the configuration would be able to pick up toolheads from outside the bowl and dock

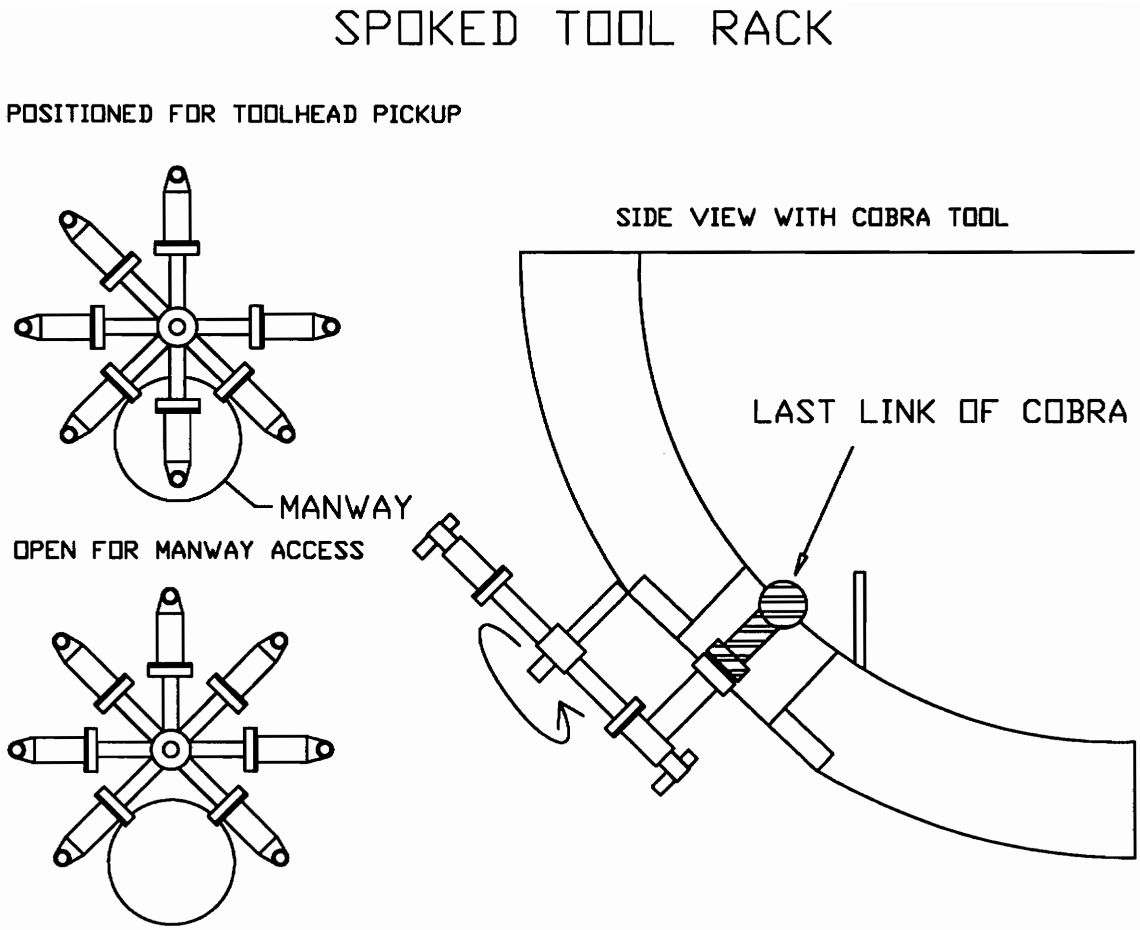

Figure 3.4 Spooked Tool Rack

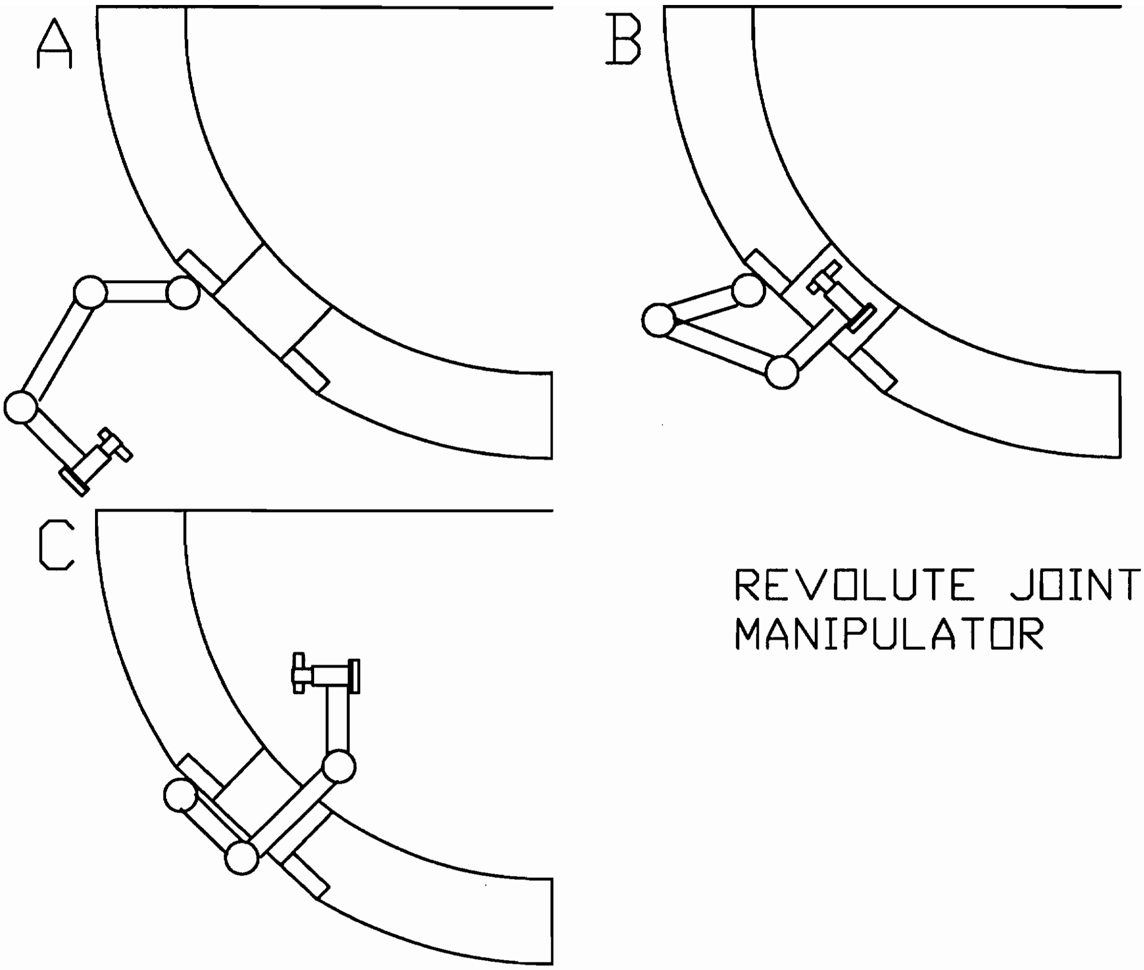

Figure 3.5 Revolute Jointed Manipulator

them with COBRA and could be fitted with attachments to perform platform duties such as managing cables.

II. COBRA Tool

This solution is to add a tool to COBRA that extends COBRA's reach outside the bowl to pick up a toolhead, as seen in figure 3.6. The toolhead would be maneuvered through the manway and placed on a mounting fixture in the bowl with the toolspan vertically aligned. The mounting fixture would rotate the toolhead into position with the bottom of the tool, typically where the hoses exit the toolhead, pointed towards COBRA's base point. COBRA would then set the gripping tool down and dock with the toolhead. For COBRA to reach out of the manway, the mezzanine must be tilted. This concept requires a tool rack to be used to change the toolhead presented to COBRA. The spoked wheel rack would be a preferable choice for this concept because it presents the tools close to the manway in a consistent position.

III. Rotary Table on Tracks

A toolhead is placed on a rotary table that travels through the manway along tracks, as in figure 3.7. This process is similar COBRA's installation procedure. Two rotations are needed to place the toolhead into a dockable position. One rotation turns the toolhead from the span entrance

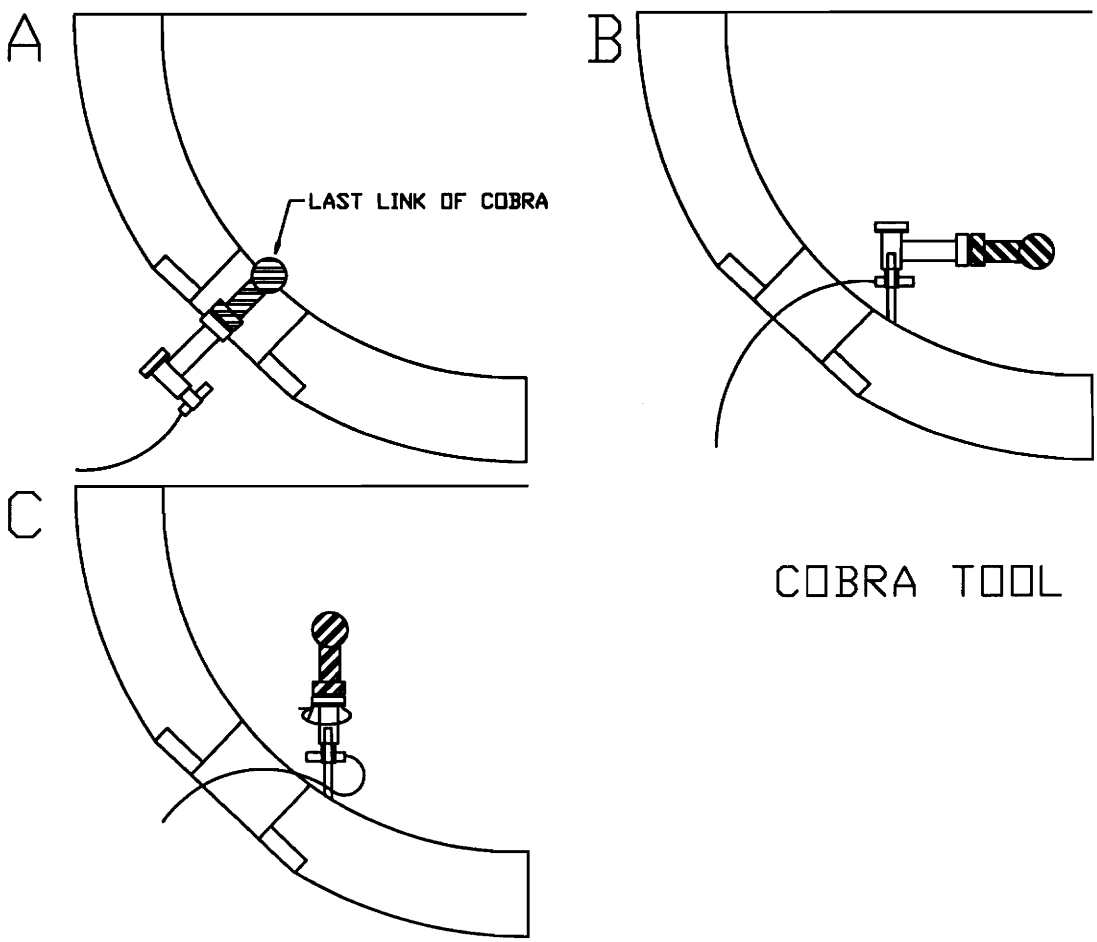

Figure 3.6 COBRA-Tool Concept

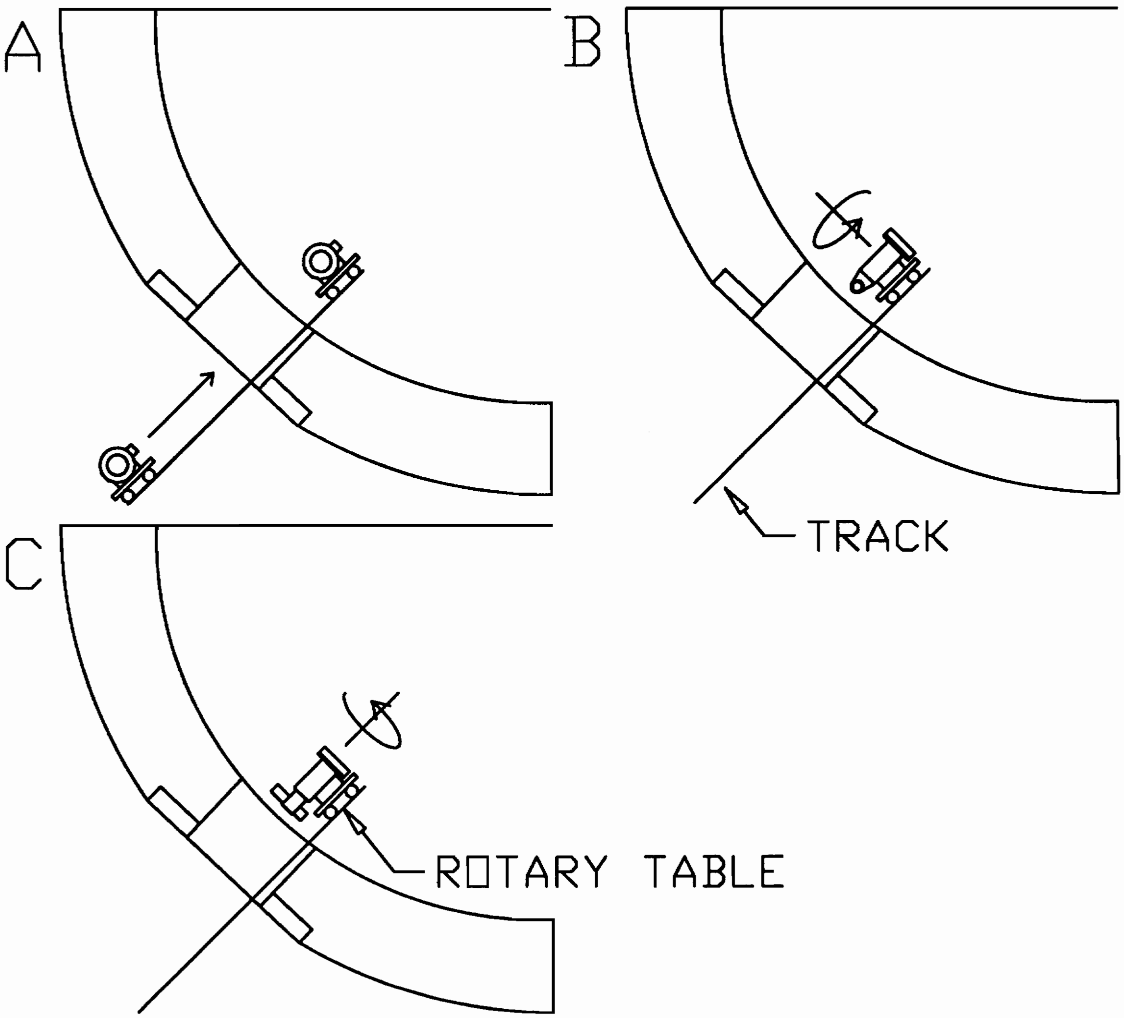

Figure 3.7 Rotary Table Mechanism

configuration and points the robocoupling toward COBRA's waist joint. The second rotation aligns the toolhead with the vertical plane. These two rotations place the toolhead into a dockable position and could be coupled to the linear travel to result in a one DOF system. The track is removable to free the manway from obstruction.

IV. Four-Bar Linkage

This approach proposes a four bar linkage attached to the manway that can swing a tool through the manway and present it to COBRA, as seen in figure 3.8. The link nearest the manway could be curved outward to allow a greater reach inside the bowl. The linkage would also have an additional prismatic joint to allow the mechanism to reach down and pick up a toolhead from a linear rack.

V. Prismatic Revolute Manipulator

This concept is based upon having a prismatic joint that travels parallel to the centerline of the manway moving the tool inside the bowl, as in figure 3.9. A revolute joint then rotates the toolhead into position for the exchange. The prismatic joint may be replaced by a scissor linkage to be collapsible and fit into the restricted workspace. A revolute joint could be mounted on the manway allowing the mechanism to move aside, thus not interfering with the manway.

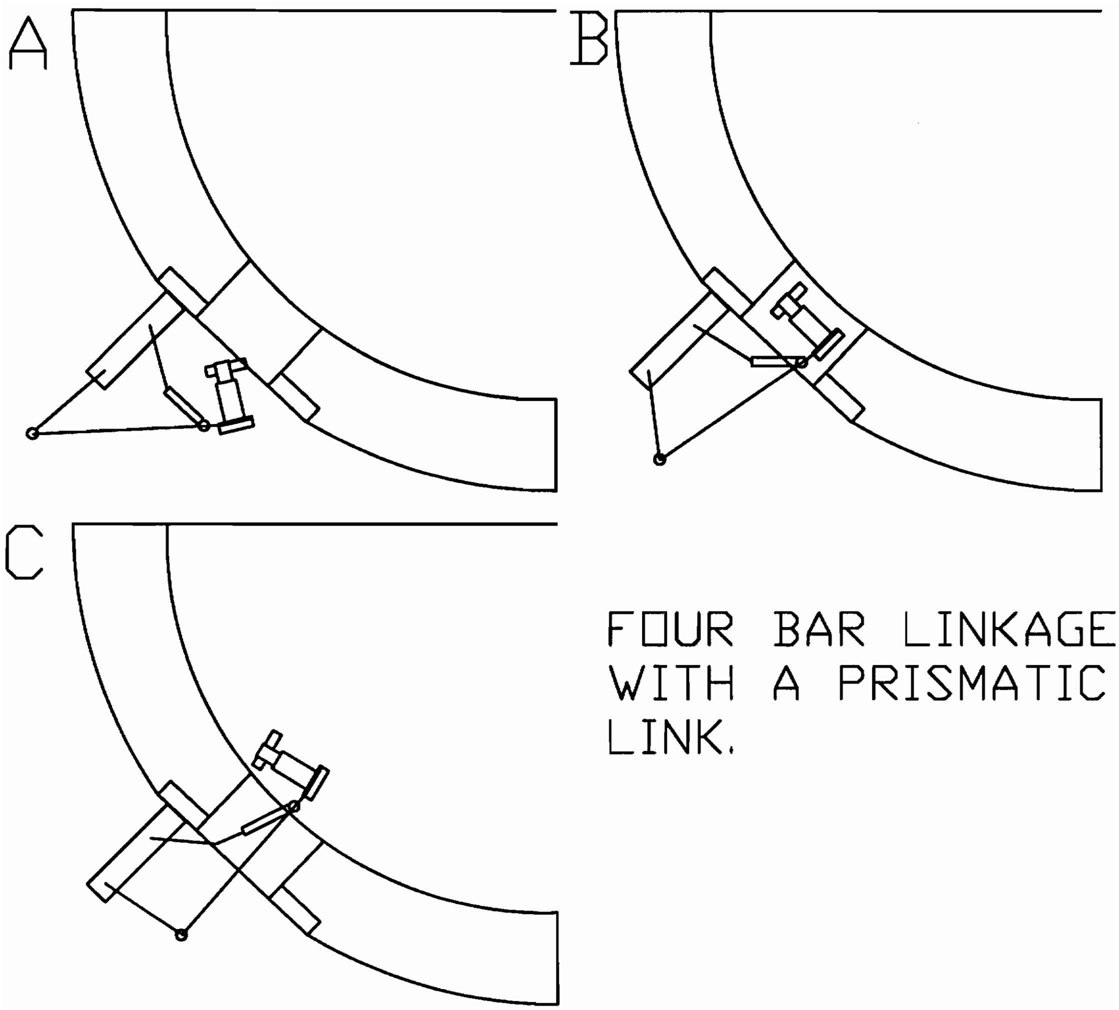

Figure 3.8 Four-Bar Linkage Mechanism

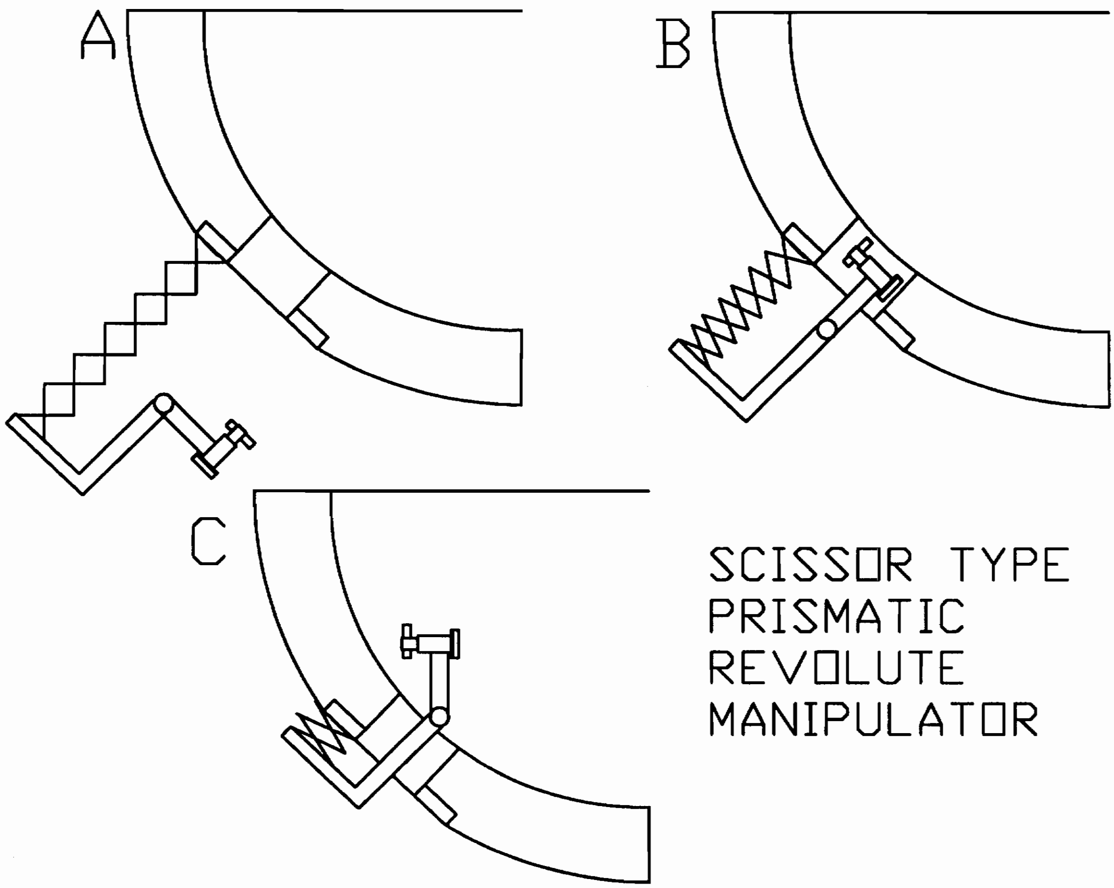

Figure 3.9 Prismatic-Revolute Mechanism

3.3 Discussion of the Concepts

The concepts can be broken down into low and high DOF systems. The rotary table has one DOF if the rotations are coupled with the linear motion. The four bar linkage with a prismatic link has two DOF. The prismatic revolute manipulator has three DOF. These represent the low DOF systems. The two high DOF systems are the serial arm and the COBRA tool, each with five DOF.

Several of the concepts have limitations. The rotary table does not fulfill the requirement of the system not obstructing the manway when not in use without manual removal of the track. No attempt was made to synthesize the four bar linkage mechanism that would work by this configuration, but it is probable one does not exist or would be awkward. The prismatic revolute manipulator needs to have several feet of linear travel along the manway centerline outside of the bowl. This workspace is unavailable at many steam generator sites due to physical obstructions. This eliminates the low DOF concepts for this particular application.

The two remaining concepts are the serial arm and the COBRA tool. Both fulfill all of the requirements given in the problem statement. During the evolution of the overall concept of toolhead feeding, however, the importance of performing platform work was found vital to reducing radiation exposure. This is an excellent example of a design requirement being clarified as the result of detailed conceptual design. The COBRA tool was eliminated due to its limited reach outside the manway and its inability to perform platform work. Due to refinements in the requirements of the system, the serial arm became the logical choice.

Chapter 4 Specific Design Selection

4.1 Refined Problem Statement

After review of the initial concepts, BWNS issued an updated list of list of platform robot requirements. The specific requirements are as follows:

- The system must mount to the top one quarter of the manway face.
- The platform arm must be capable of removing a toolhead or tube sleeve cartridge from a rack near the manway and presenting it to COBRA inside the bowl.
- When a tool is presented, it should be in vertical plane with the tool pointed at COBRA's base point.
- The arm must be able to lift 60 lbs. (27.2 kg.) at full extension.
- All motions must be monitored by video cameras.
- The platform arm need not be encoded, but should be operable in a master slave mode.
- Any hydraulic components used on the platform must be capable of operation on water-based hydraulic fluid.

With the addition of these constraints, the serial arm is the only viable choice. The serial arm will also be referred to as the platform arm. A thorough analysis of serial arms as they relate to COBRA is required.

4.2 Platform and COBRA DOF Analysis

Similar to the generic problem discussed in Section 2.1, the serial (platform) arm and COBRA system are analyzed to determine the number of DOF required. The manipulator on the right hand side of the wall in figure 2.3 becomes the COBRA, a four (five including the mezzanine) DOF robot. COBRA is a planar three DOF robot with two extra rotations at the base, as shown in figure 4.1. Starting with a minimum of three DOF in the platform robot, tools are able to be docked. Although COBRA has four DOF (one more than the previous right side manipulator examined in section 2.1) it does not reduce the number of DOF needed by the platform robot by this amount. This is because the DOF at the waist joint and mezzanine tilt have no useful component in the alignment of the toolhead into the platform arm plane as discussed in section 2.2.

In the previous case, the toolhead can easily fit through the portal. In the BWNS system, the toolheads barely fit thought the portal. Recall, most toolheads cannot fit through the manway when attached to COBRA which results in the use of the span entrance configuration. They require a linear path through the width of the portal with the toolspan across the face of the manway. To generate a linear path in a plane requires two DOF. The toolhead must be held in a set orientation during the linear move, necessitating a third DOF. The toolhead must then be held in a dockable position, which requires rotation into COBRA's plane; this is the fourth DOF. A fifth DOF could be placed at the base of the platform

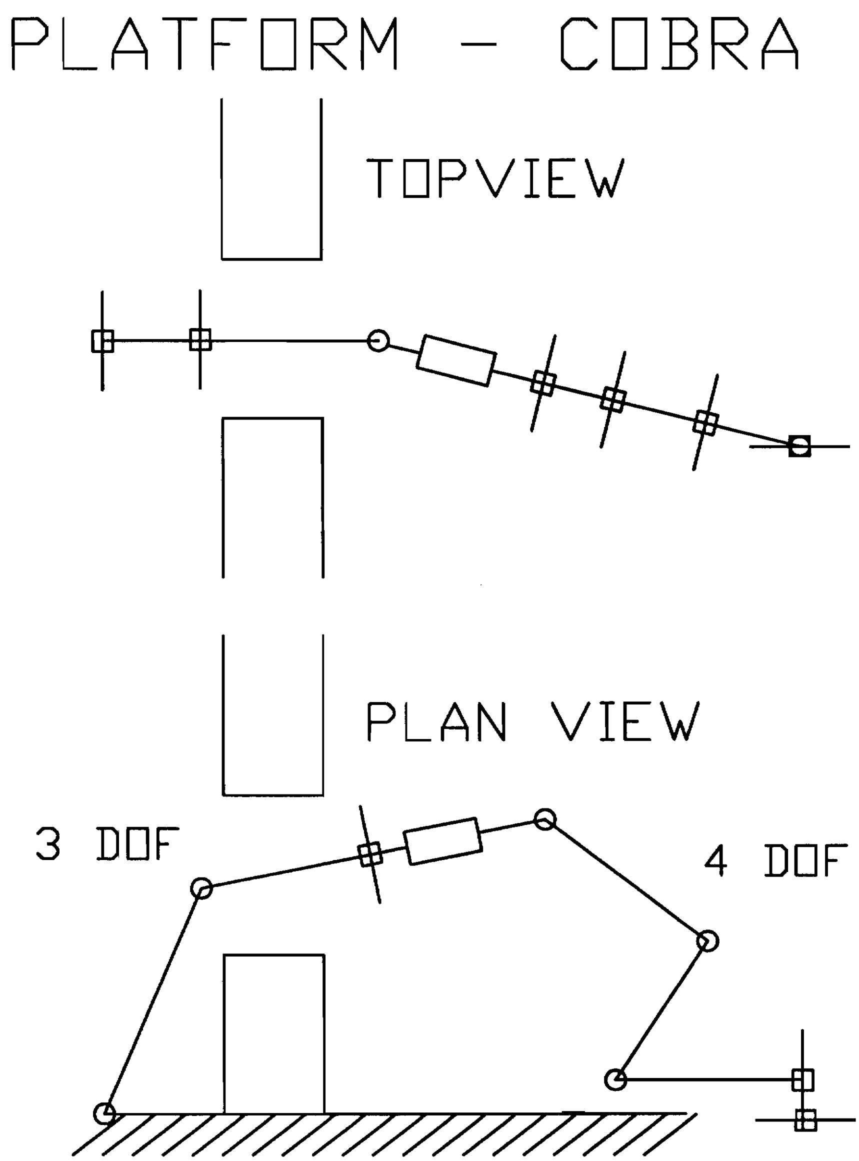

Figure 4.1 Platform - COBRA Analysis: Nonplanar

robot to enable the arm to perform platform maintenance duties. This arrangement would allow the arm to feed toolheads as well as have substantial workspace outside of the bowl. See figure 4.2

4.3 Serial Platform Manipulator Concepts

There are several possible configurations for series-type manipulator arms. Three variations are listed below. The first is the five DOF manipulator already discussed. The other two are variations that make use of special geometry to eliminate the need for a degree of freedom. An attempt is being made to operate with the minimum number of DOF to reduce the complexity and cost of the system. Each of these will need further study and examination to determine the limitations of each design.

Type-1 Arm

This arm, shown in figure 4.3, is the five DOF arm discussed in the concepts section. It would be capable of picking up toolheads on the outside the bowl, passing them through the manway in a fixed orientation on a linear path and docking them with COBRA. One DOF would be at the base for exterior bowl mobility. Two DOF are required to generate a linear path through the manway. And another two are required to orient the toolhead on its way through the manway and to dock with COBRA. This concept does not require COBRA to tilt

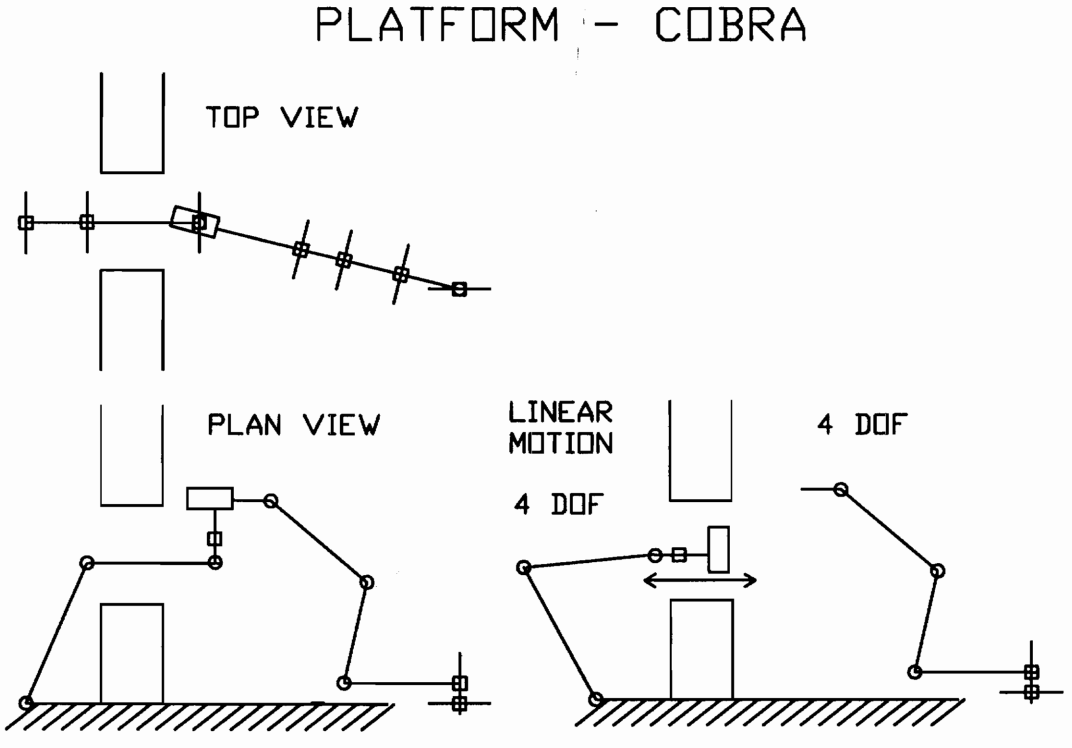

Figure 4.2 Platform - COBRA Analysis: Linear Path

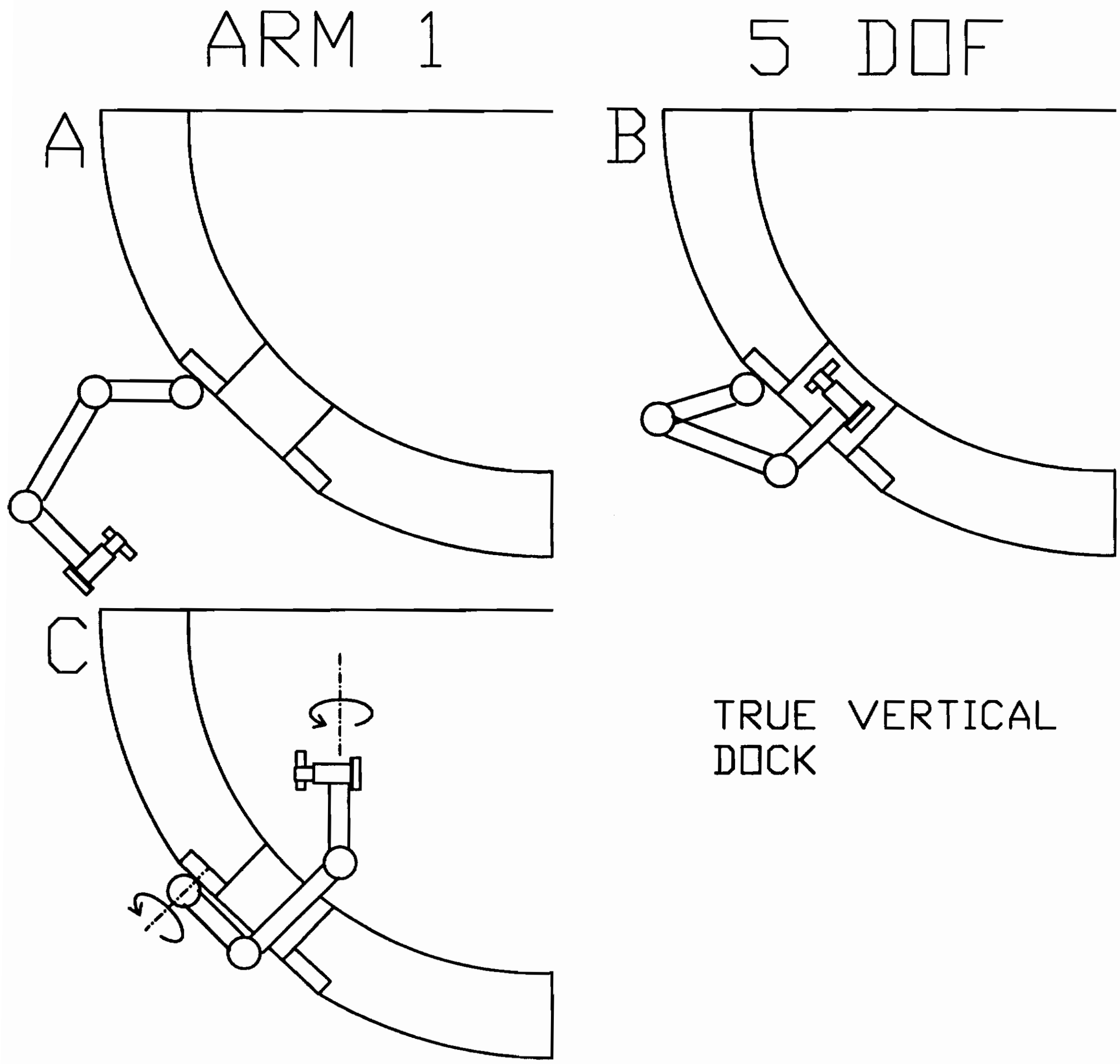

Figure 4.3 Type-1 Arm

at its mezzanine.

Type-2 Arm

This four DOF arm is shown in figure 4.4. The elimination of one DOF is accomplished by only requiring the toolhead to have its toolspan parallel to the manway during the entrance. A linear path is still made by the toolhead through the manway, however, the toolhead would be allowed to rotate about the toolspan axis during entrance. The tool vertical would vary from being parallel to the manway centerline by approximately plus or minus 30 degrees. This method does not require COBRA to tilt at the mezzanine. This concept relies on an unproven assumption that the toolheads would be capable of passing through the manway with the variation of the tool vertical. The system consists of a joint outside of the bowl for exterior mobility, a two DOF linkage for linear travel though the manway and orientation of the toolhead vertical into the true vertical, and one DOF to turn the coupling toward COBRA, presenting the toolhead in a dockable position.

Type-3 Arm

This four DOF arm is shown in figure 4.5. In this case COBRA is tilted at the mezzanine. The platform arm is mounted opposite to COBRA's mounting thus making the system planar. The system consists

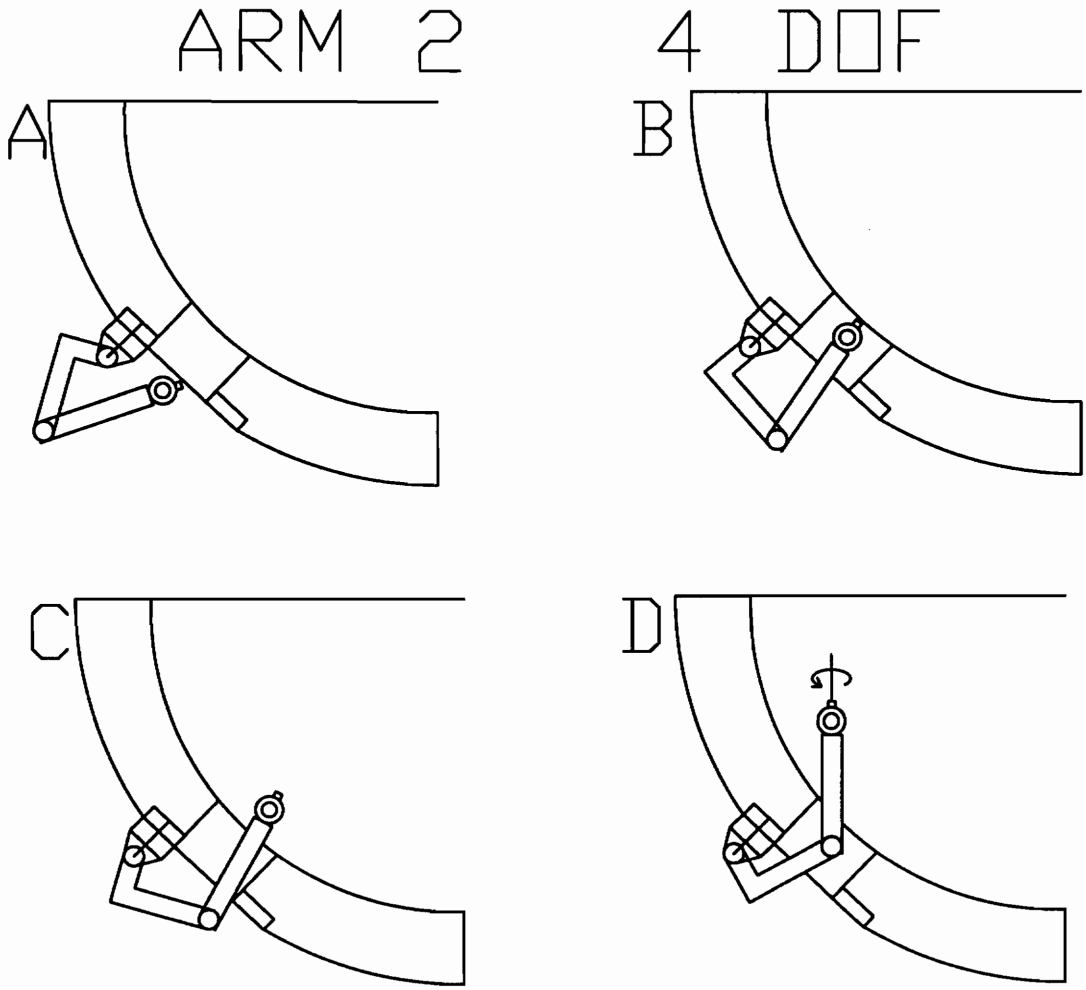

Figure 4.4 Type-2 Arm

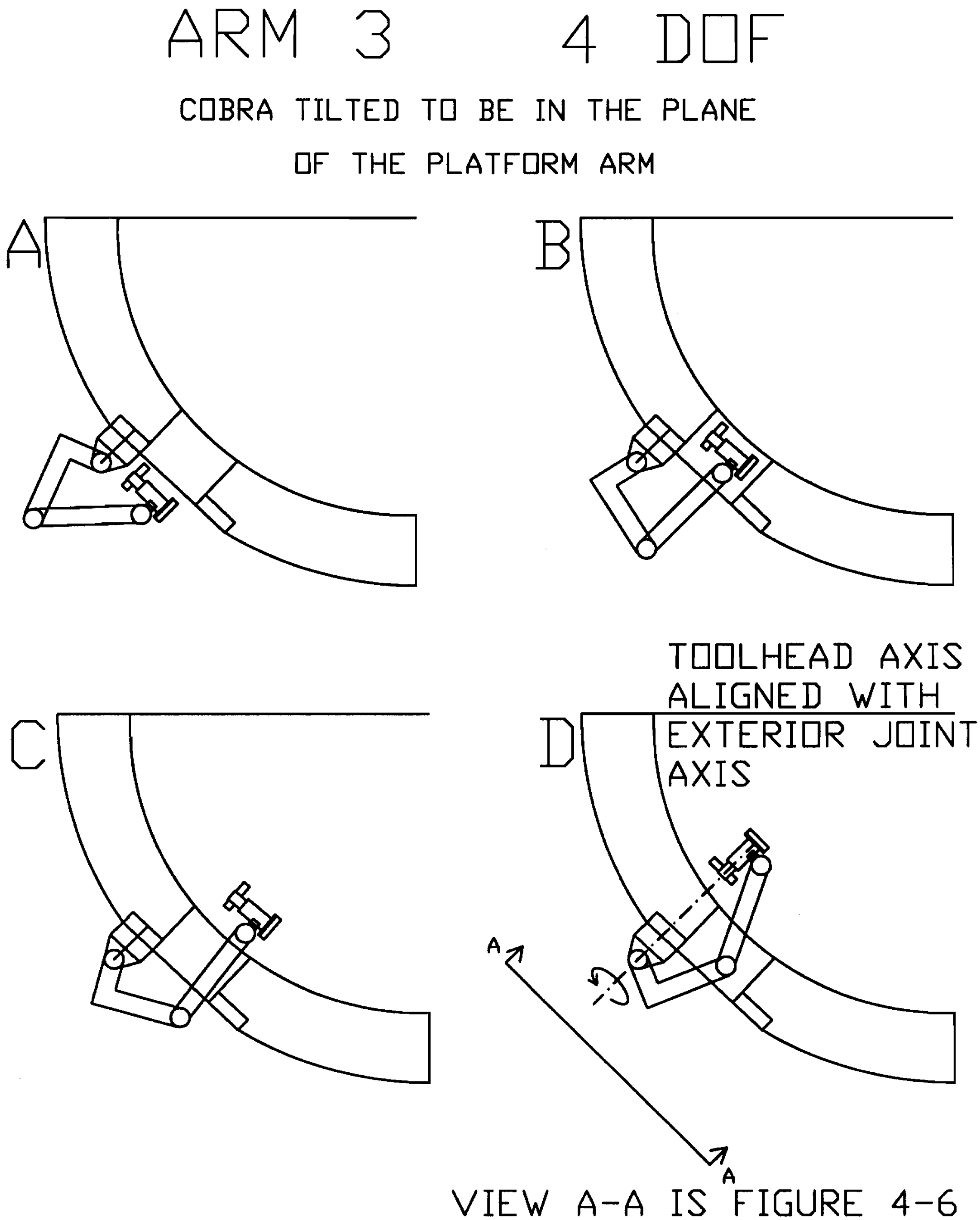

Figure 4.5 Type-3 Arm

of one joint on the bowl exterior for mobility, followed by three revolute joints with parallel axes. Two DOF trace a linear path through the manway and position the toolhead along the axis of rotation of the first exterior joint. The last joint rotates the toolhead back to align the toolspan axis with the first joint axis of rotation. This alignment provides a rotation about the toolspan axis of approximately plus or minus 40 degrees, which may be helpful in adjusting for docking. One major drawback with this system is the reduced clearance for toolheads when passing through the manway as illustrated in figure 4.6. The manipulator has no way of rotating the toolheads about the manway centerline when passing through the manway. Thus, with the platform arm mounted opposite COBRA on the manway, the space available to pass a toolhead through is reduced by COBRA's mounting obstructing some of the manway.

These concepts for four and five DOF systems are relatively complex. This level of complexity is necessary due to the multiple functions required from the system. Thus, the expected price of the systems becomes an additional consideration.

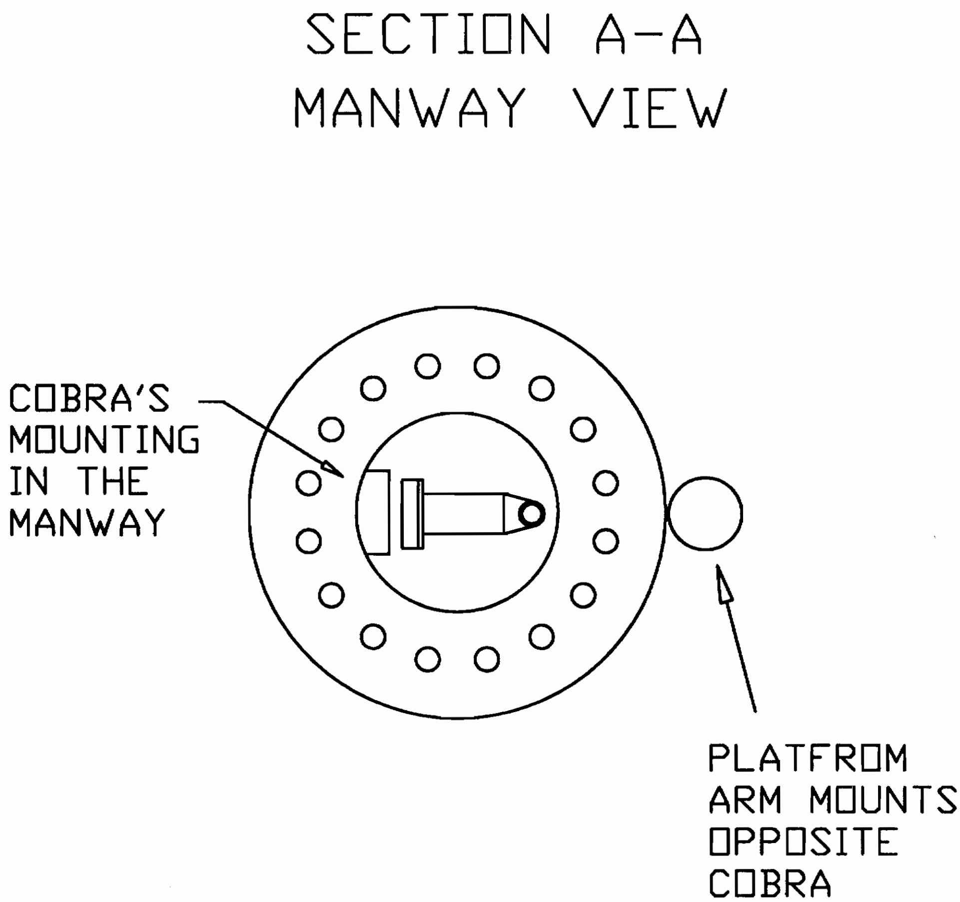

Figure 4.6 Type-3 Arm: Manway Obstruction

Chapter 5 Design Choices

5.1 Discussion of Economic Factors

A highly functional and complex robot with four or five DOF is relatively expensive. When the system is transported to a site (the steam generator at a nuclear power station) a set of spare parts is included. This is a substantial amount of equipment. If the platform manipulator and COBRA are completely independent systems, the number of parts transported to the site roughly doubles. This becomes a significant burden on the efficiency of the operation. Using identical parts eliminates the need for two sets of backup parts.

In addition to mobility, the amount of down time (time spent servicing the generator) is a critical issue in steam generator maintenance. The steam generator is usually on the critical service path, meaning that time lost in this task is additional plant shut-down time. Lost income to a utility is typically more than a half million dollars for each day the plant is shut down. If the platform robot is a second COBRA robot and a malfunction occurred in the bowl robot, it could be quickly removed and replaced with the platform arm. Platform maintenance and toolhead changes would be performed manually as they are presently. This interchangeability is of great economic benefit both in limiting the replacement parts inventory and shortening down time in the event of a failure.

5.2 Discussion of an Exterior Mounted COBRA

The concept of using a second COBRA as a platform arm is examined. Using COBRA as an exterior arm the geometry is similar to the type-1 and type-3 arms of Section 4.3. The viability of two the configurations is examined as well as the conformance to the constraints.

An attempt to use the arm in a method similar to the type-3 arm was not successful. No position of the base outside of the manway allows the toolhead to enter the bowl and align along the axis of revolution of the base revolute joint, illustrated in figure 5.1a. A rotation of the toolhead about its toolspan axis is still possible by rotating the base revolute joint, thus swinging the arm out of the plane; however this makes docking impossible. Recall, the type- 3 system relies on the two manipulators being coplanar.

Positioning the exterior COBRA as a type-1 arm was found to be feasible. This position allows the arm to pass the toolheads into the bowl, but requires the addition of a fifth DOF rotation at the end of the platform arm as shown in figure 5.1b. This is the same true-vertical-dock manipulator as the type-1 arm concept presented earlier. The exterior revolute joint, which is at an angle to the vertical, provides off-axis rotations to the toolhead inside the bowl. This allows the system to have some motion about the toolspan. A small rotation may be needed to jog the robocoupling into a mating position.

According to the constraints, the mechanism must mount on the top one

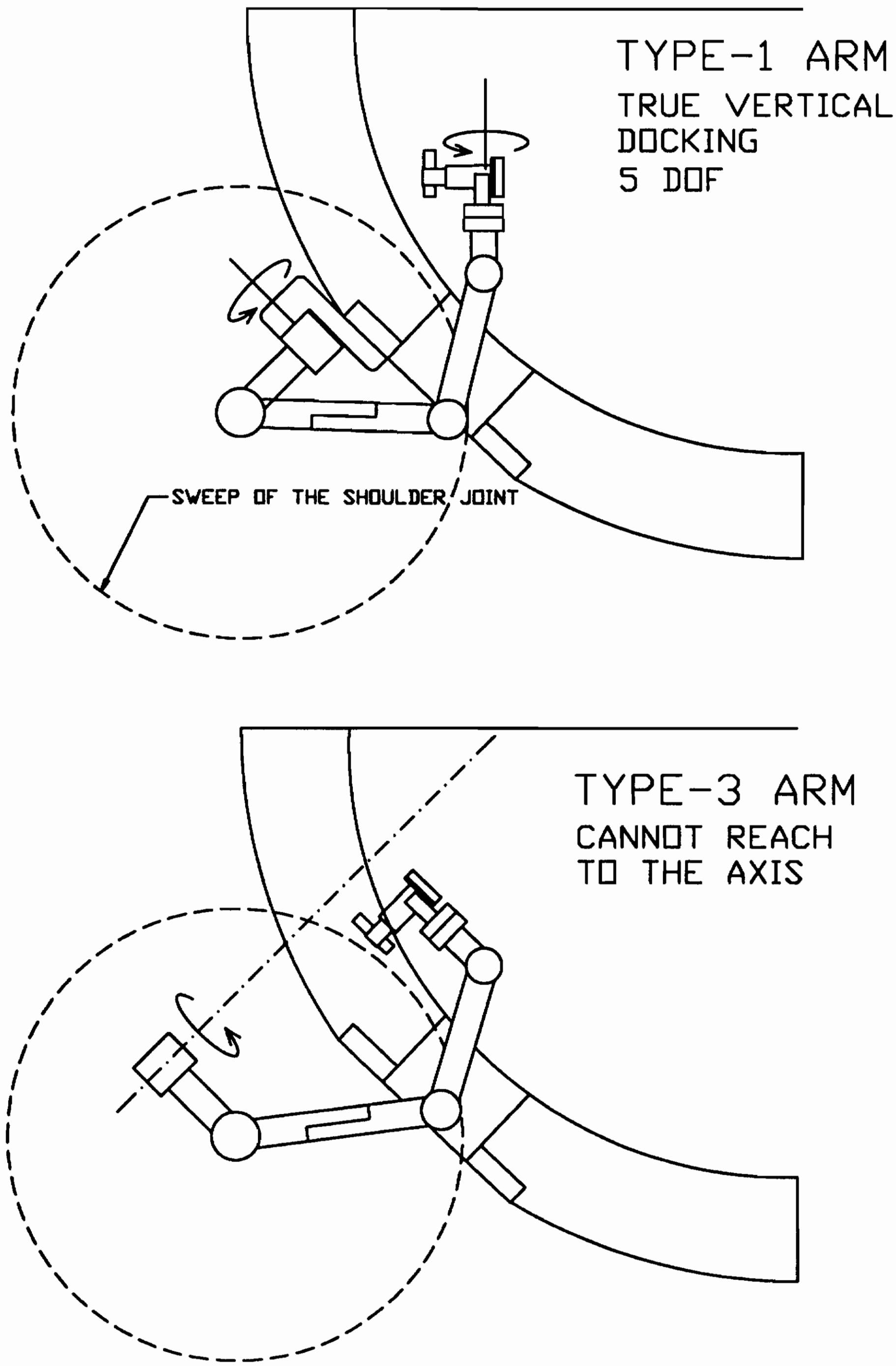

Figure 5.1 Comparison of Type-1 and Type-3: Utilizing COBRA

quarter of the manway. The platform COBRA arm will be able to fill this requirement. The bowl COBRA is mounted on a trolley that travels along a motorized track during installation. The platform COBRA does not need a complete motorized track to mount. A short section of the track, in which the base could be placed manually and securely fastened, is necessary. This section of track is held in the proper position by a bracket bolted to the face of the manway.

5.3 Description of Exterior COBRA Concepts

In the examination of the concepts, the waist joint could not provide the required torque to allow the arm its complete range of motion when the axis of rotation was tilted 45° from the vertical. In normal use, the axis of rotation of the waist joint is vertical; therefore, there is no torque load on the waist joint. The torque seen by the waist joint is a function of the absolute value of the sine of the angle between the vertical and the axes of rotation. Several options are available that would reduce or eliminate the need to produce high torques at the waist joint.

Figure 5.2 shows a comparison of the previously discussed type-1 arm over a range of the waist joints' axis angle from the vertical. At the plus and minus 45° positions the torque load on the joint is 71% of that seen at 90° (the maximum). At 0° the torque is zero.

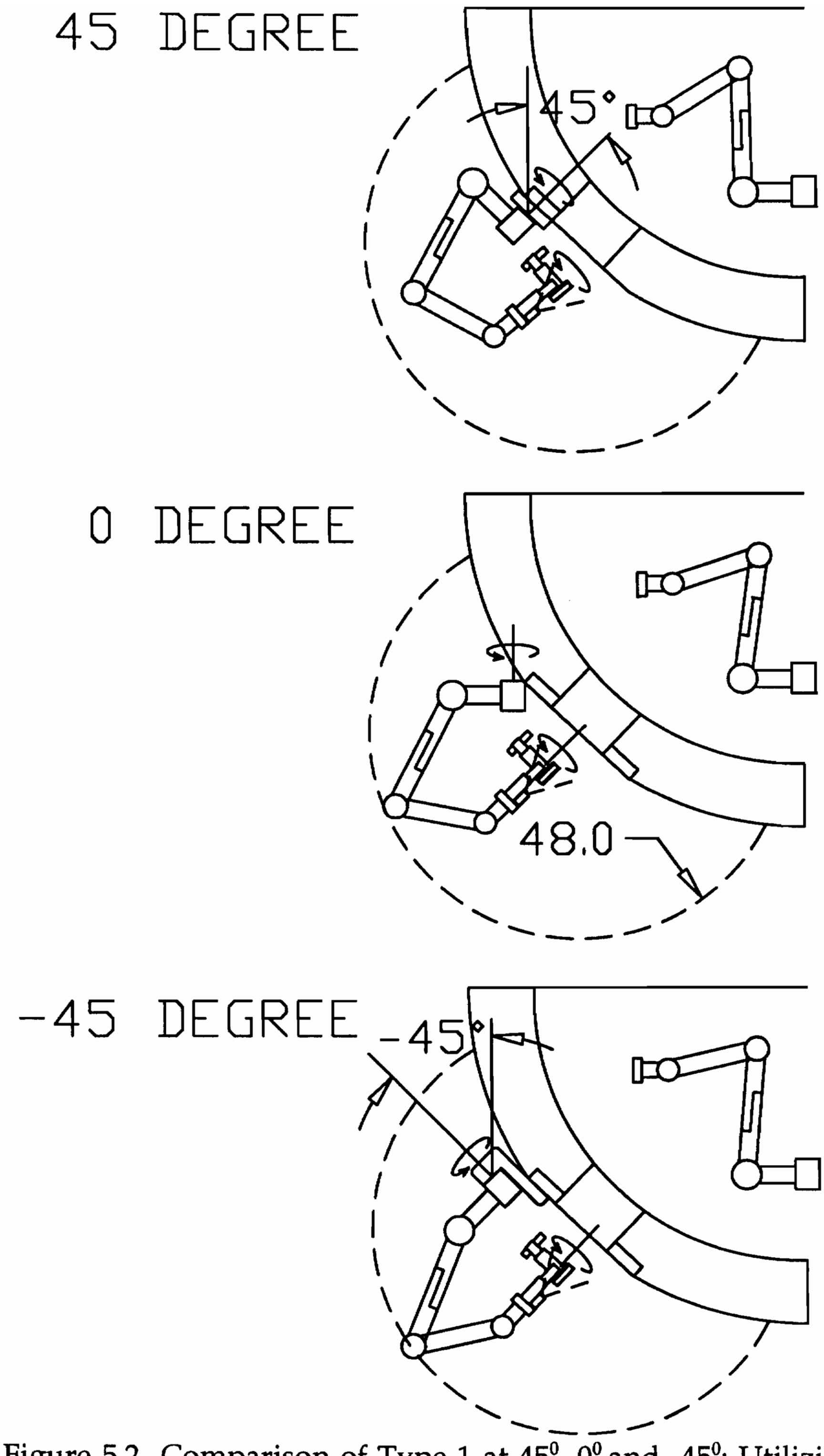

Figure 5.2 Comparison of Type-1 at 45^0, 0^0 and -45^0: Utilizing COBRA

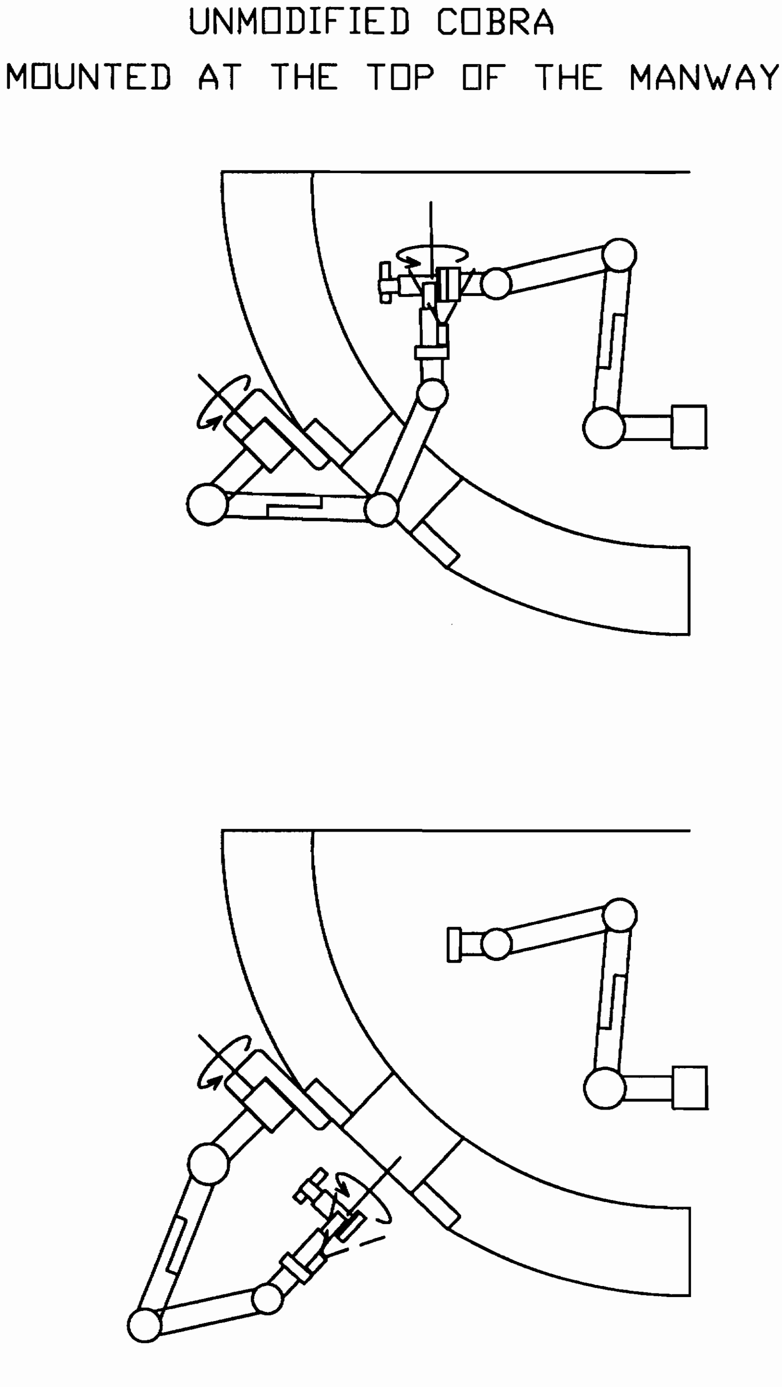

Figure 5.3 Exterior Joint Axis: -45^0 From the Vertical

The -45° position, shown in figure 5.3, discussed previously in section 5.2 requires the largest work area to operate. This is a major disadvantage in the constrictive and obstacle-filled environment of the platform. The waist joint is loaded with 71% of the maximum torque, too high for the arm to have a full range of motion on the exterior of the bowl. Interior mobility for any axis angle is limited by the manway.

In the 45° position the exterior COBRA's waist joint is parallel to the manway centerline and the links doubled back to enter the manway. This configuration is shown in figure 5.4. This position has the advantage of being able to operate in a smaller workspace. This is important for avoiding obstructions outside of the bowl. With this concept, the waist joint is incapable of producing enough torque to rotate the arm through its full range of motion. At 45° from the vertical the torque on the waist joint is 71% of the maximum. This drawback can be minimized by utilizing the trolley mounting, the same as COBRA's installation, parallel to the ground to provide more exterior mobility.

To completely avoid torque load on the waist joint, the manipulator could be mounted with the axis vertical, as shown in figure 5.5. The waist joint produces no off-axis rotations in jogging the alignment of the coupling. The end effector requires two DOF to be certain of obtaining a dockable position. This is not a major concern since the existing BWNS gripper has two DOF. The major advantage of the concept is that without a torque load on the waist joint, the

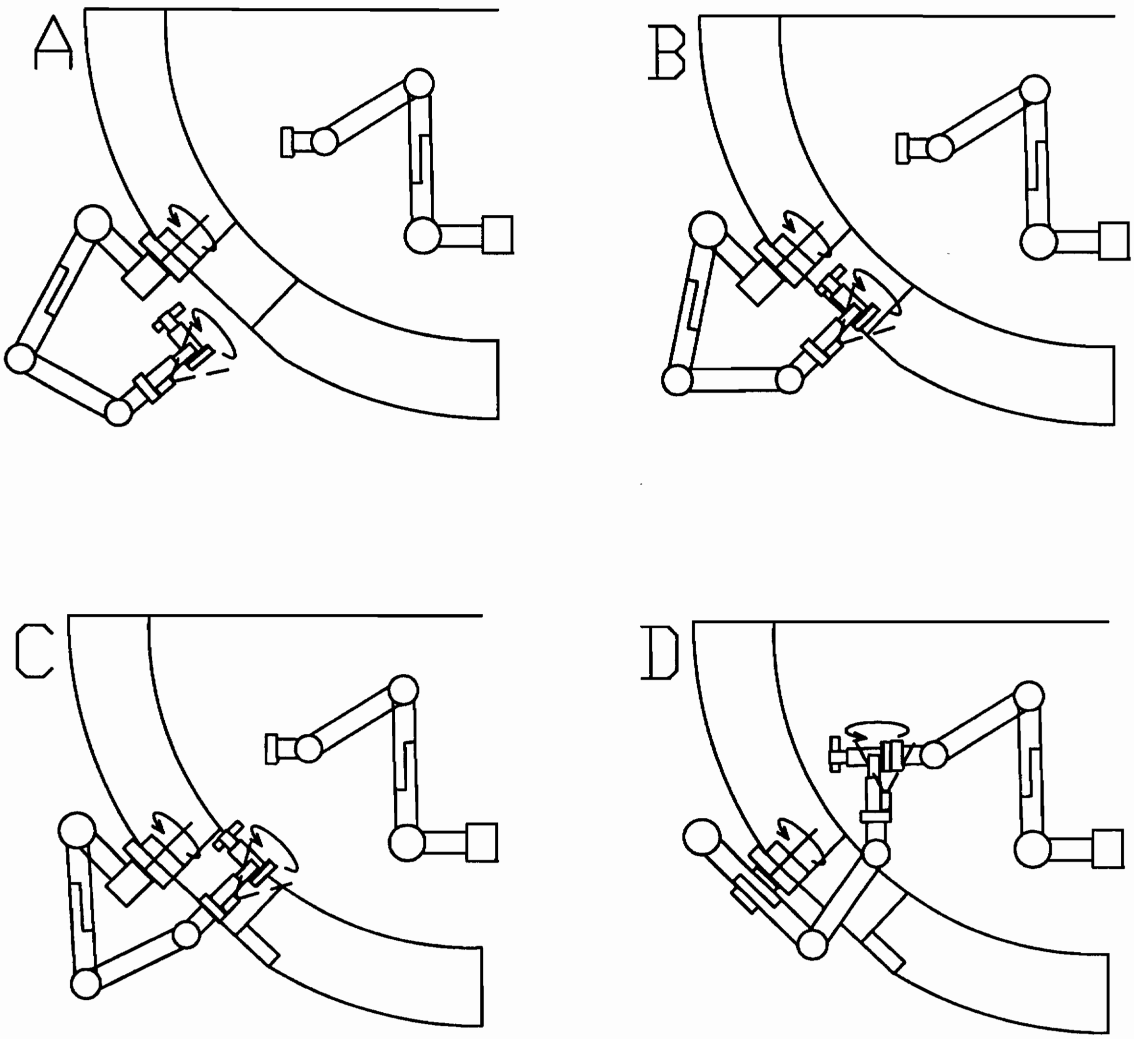

Figure 5.4 Exterior Joint Axis: 45^0 Parallel to the Manway Centerline

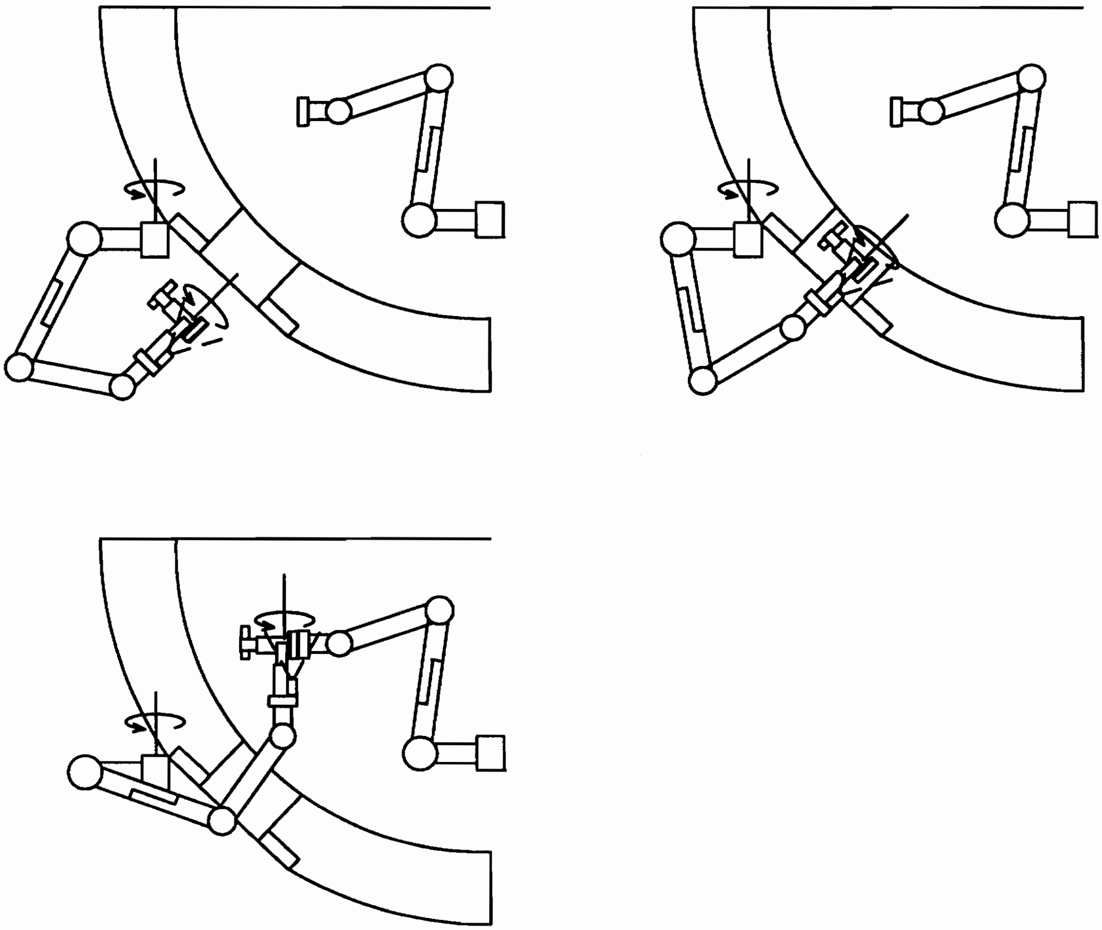

Figure 5.5 Exterior Joint Axis: 0^0 Horizontal

exterior mobility is maximized. The manipulator is able to reach any point in its workspace, points inaccessible in the other concepts due to joint torque.

Another factor in the torque at the waist joint is the amount of extension required or desired in the manipulator when operating. It is unlikely that the platform COBRA would hold a tool at full extension with the arm horizontal. The lack of joint performance, noted above, was not based on a calculation at maximum extension, but on testing done at BWNS in practical arm positions. Calculation of the maximum torque at the required positions could be compared with the strength of the waist joint and an optimal axis tilt could be determined. The reason for not eliminating axis tilt is to produce the off-axis rotations required to jog the coupling into alignment during the docking process.

5.4 Optimal Positioning of the Exterior COBRA

Since the 45 degree position has the smallest work space and the 0 degree position the lowest (zero) torque at the waist joint, it can be presumed that an optimal case exists between these two positions. Factors of this optimization are the torque at the waist joint and the work volume needed to change a toolhead.

The torque at the waist joint is a function of the joint axis angle and the operational workspace of the robot. If a robots workspace is defined as all kinematically reachable points, the operational workspace would be the subset of this volume used to perform its intended functions. For a given waist joint axis angle, at some point in the operational workspace the arm is producing a maximum torque load on the joint. This is the first factor.

The minimum work volume needed to change toolheads is also dependent on the angle of the waist joint as shown in figure 5.2. This is part of the operational workspace and can be defined as the work volume needed to perform a toolhead change.

For optimization, the relative importance of the factors involved must be rated. Thus a weight factor for the torque load W_T and a weight factor for the minimum work volume W_V must be developed. The relative magnitude, not the value of the weight factors is important. For example they could be evaluated by percentages and sum to one. If they are equally important each would be 0.5; if the first is twice as important as the second they would be 0.666 and 0.333.

In developing a simplified model, the torque load of the manipulator can be equated to the torque developed by the toolhead neglecting the weight and the torque loading of the arm. The minimum work volume can be approximated as the linear measurement of the radius from the center of the manway needed to make toolhead changes. In this model both torque due to tool weight and the minimum work volume are functions of theta. Combining these factors with their weight factors an equation optimum position and be stated as the equation:

$$X(\theta) = W_T \bullet [\, T(\theta) \,] + W_V \bullet [\, WA(\theta)]$$

This equation can then be manipulated to find the minimum and maximum values of X (θ) to determine the optimum angle of the waist joint axis. Various numerical optimization methods are available for finding the extreme values of such a function, see Haug and Arora (1979).

This concept, using COBRA as a platform arm, requires the construction of a mounting bracket, a tool rack and a toolhead gripper. The platform COBRA's toolhead gripper must be capable of feeding steam-generator service toolheads to the bowl COBRA and performing platform maintenance. This system requires few additional parts.

Chapter 6 Design Details

6.1 Common Feature Extraction for a Feature to Grasp

In manipulating non-standard toolheads, a need arises for a set method to grasp them. The only feature common to all of the toolheads is the robocopling that attaches them to the bowl COBRA. The couplings, while common to all of the toolheads, have been customization with the addition of pneumatic and electrical lines tapped into the sides. This has created enough variation to make a set method of grasping them impractical. This results in the need to add a common feature for grasping.

The feature could be mounted to the bottom of the tool under the center of gravity to help reduce the torque load produced by the toolhead. The feature and the gripper are designed to match.

6.2 Gripping Toolhead Development

The end effector of the exterior COBRA must rotate the grasped toolhead it is grasping to accomplish the dock with the bowl COBRA. Other requirements include hose and tether manipulation and the handling of sleeves. BWNS has a gripping end effector with a wrist that provides two rotations, as shown in figure 1.4b. The feature could be designed to match the gripper jaws with the pinchers fitting in a grooved block. This provides for a stable hold of the toolhead, and the torque load on the gripper is carried by the sides of the pinchers, not just the contact force of the grip.

6.3 Placement of Cameras

To assist in manipulating toolheads and performing platform maintenance it is useful for the operator to have several views of the work environment. The end effector developed for the exterior COBRA will have a camera, which will be useful in docking. Other cameras are needed for tether manipulation and obstacle avoidance outside of the bowl. Two cameras placed to provide perspective views of the any exterior obstructions should be sufficient. The present interior COBRA operates with only one camera with a perspective view, two cameras would allow for adequate viewing of the exterior environment.

Chapter 7 Conclusions

7.1 Conclusions Regarding the Generic Problem

Restricting the discussion to toolhead exchanges the solution can be a mechanism having relatively few degrees of freedom. The generic problem is dependent on several factors including:

- The number of DOF of the system requiring toolhead changes. (i.e. How dexterous is the manipulator needing a toolhead change?)
- Geometric obstacles that must be avoided.
- The orientation and path needed to deliver the toolhead.
- The coupling geometry, whether axissymetric or one specific orientation.

The toolhead changes depend not only upon the number of DOF in the robot serviced, but also on the relation between its mobility and the mobility of the feeding mechanism. Aligned axes can cause singularities where moving different joints produce the same output motion. This can result in the need for additional DOF in the feeding mechanism.

As seen in the generic problem discussion in Chapter 2, the restriction of a portal through which a toolhead must be passed requires at least an additional DOF. Other geometric restrictions, such as two portals in series, a long entrance or multiple pipes causing obstruction may necessitate additional DOF.

If the toolhead can only travel through the restriction to the interior robot's workspace in a specially predetermined orientation, this can also add to the number of DOF needed. The linear path and toolspan orientation discussed in Chapter 3 show that extra mobility is necessary to perform tool changes in the case of COBRA.

The type of coupling mechanism between the manipulator and the toolhead also effects the design. An axissymetric coupling allows for docking at any orientation in a plane. A specific orientation coupling limits the dockable positions to the tolerance of the coupling. This is a strict limit on the accuracy and dexterity of the feeding mechanism.

The generic problem can be solved with a low DOF system if the geometry is not overly restrictive and the robot undergoing the toolhead change has sufficient mobility. The required mobility can sometimes be minimized utilizing special geometry of configurations that may be present. The general problem of toolhead exchanges becomes much more complex with the addition of the extraneous requirements such as the platform work be preformed in the case of the BWNS system.

7.2 Conclusions for the Platform COBRA System

The platform manipulator system for feeding tools to COBRA is the result of the requirement to perform platform maintenance autonomously. Humans have the ability to perform relatively complex operations. In replacing the human, the system requires a highly complex exterior manipulator. Four DOF is the minimum number needed to a perform simple toolhead changes and this involves unproven concepts. The use of COBRA as the external manipulator, though requiring five DOF, is an effective choice for accomplishing the required task.

Although COBRA is a complex and expensive system its use as an exterior toolhead changing manipulator it is efficient. The use of identical systems limits the number of spare parts needed on site, and allows for immediate replacement of the bowl COBRA in the case of manipulator hardware failure, thus limiting down time.

The development costs of the new system are also minimized by using COBRA. The platform COBRA has the same control structure and mechanical part; therefore, few pieces of new equipment need to be developed. The only new parts to be developed for the platform COBRA are a tool rack, an end effector to grip the toolheads being exchanged and provide a rotation, and a manway mounting base. This use of existing and mature equipment should result in low development costs, and higher system reliability.

7.3 Suggestions for Platform COBRA Development

In the continued development of the toolhead exchange system there are some areas for further examination. The use of the RobCAD modeling system at BWNS is a valuable analysis tool for proof of the concept. RobCAD can model the manipulator/generator system in three dimensions and can be used to check for interferences and the ability to dock. It can also be used to help find the best position for the manway mounting. Additionally, a RobCad model could help determine the effectiveness of the system at different sites by analyzing the bowl exterior environment.

Analysis of the positions required of the platform COBRA would determine the optimal angle to tilt the waist joint, and thus determine the design of the manway mounting. Another more elaborate solution would be to redesign the waist joint with adequate torque capacity to operate in the 45° position. This would involve retrofitting of the existing COBRA's and could be expensive, COBRA's existing joints cost approximately $20,000 each.

Another area of ongoing research is the use of machine vision for position feedback on COBRA. A potential area of application is docking the toolhead on the platform arm with the end of COBRA. For docking, the toolhead and the end of the COBRA manipulator could be fitted with optical targets. The measurement of the position and orientation of the targets relative to each other could be used to control the docking procedure. This eliminates the need for the operator to jog the system for fine adjustment, as well as operator skill as a factor in docking.

7.4 Summary

The design of toolhead changing manipulator is highly dependent on the specific application. The geometry, mobility of the existing system, the toolhead robot interface and the toolhead size and shape all are major factors in the development of an effective solution. The addition of other functional requirements increase the complexity of the design. The platform maintenance functions required in the BWNS problem increased the complexity to a 5 DOF feeding manipulator. This solution, while complex, is an effective and efficient solution to this specific application. The result should be a significant reduction in human radiation exposure and reduced steam generator service time.

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