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PARAMETRIC DESIGN STUDIES OF LONG-REACH MANIPULATORS*

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ABSTRACT A number of different approaches have been studied for remediation of waste storage tanks at various sites. One of the most promising approaches is the use of a high-capacity, long-reach manipulation (LRM) system with a variety of end effectors for dislodging the waste. LRMs may have characteristics significantly different from those of industrial robots due to the long links needed to cover the large workspace. Because link lengths are much greater than their diameters, link flexibility, as well as joint or drive train flexibility, is likely to be significant.

LRMs will be required for a variety of applications in the Environmental Restoration and Waste Management Program. While each application will present specific functional, kinematic, and performance requirements, a design approach for determining the kinematic applicability and performance characteristics considering link flexibility is presented with a focus on waste storage tank remediation. This paper addresses key design issues for LRM-based waste retrieval systems. It discusses the effects of parameters such as payload capacity, storage tanks size, and access port diameter on manipulator structural design. The estimated weight, fundamental natural frequency, and static deflection of the manipulator have been calculated for various parameter conditions.

INTRODUCTION

Long-reach manipulators (LRMs) are currently being considered for application to the remediation of waste storage tanks but may also find application in other Environmental Restoration and Waste Management Program areas. Since the initiation of production of radioactive materials in the mid-1940s, high-level radioactive waste products have been produced at a number of U.S. Department of Energy sites. These waste by-products have been stored in large tanks with capacities of up to 1 million gal. Some waste storage tanks have diameters of up to 23 m (75 ft) and depths of up to 13 m (43 ft). The earliest versions of the tanks often utilized a single-shell design, which does not allow monitoring for leakage, and a number of the tanks are suspected of leaking. Federal Facility Compliance Agreements have been negotiated that set timetables for the remediation of the tanks at several of the sites.

A variety of approaches have been considered for the remediation of waste storage tanks. One traditional approach is the use of overhead bridges, trolleys, and vertical masts for the movement of manipulation systems required for remediation. However, this approach has the disadvantage that the tank dome would have to be removed following the construction of a large containment structure. The use of an LRM system provides one approach to avoid the need for the removal of the tank dome while minimizing the number of tank penetrations needed.

This basic approach to waste storage tank remediation involves the uses of several subsystems, including a retrieval manipulator, a variety of general and special purpose end effectors, waste removal equipment, and waste-processing equipment. A support structure for the

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remediation equipment would be constructed to span the tank, avoiding loading of the tank dome. The remediation system would be remotely operated from a control room located outside of the regulated zone.

A possible operating scenario could be described as follows. Remediation would be initiated with the insertion of viewing systems. Existing risers and other in-tank hardware would be removed, to the extent possible, prior to insertion of the retrieval manipulator. The retrieval manipulator would then be inserted into the tank, which may require cutting some of the remaining risers as the manipulator is inserted. After having been fully inserted, any remaining risers would be cut and removed using an in-tank hardware conveyance system, which consists of a container and mechanical lifting system. This process would require the retrieval manipulator to reach the full volume above the surface of the waste, including the tank dome. General purpose end effectors would be required as well as various cutting devices. Following the removal of exposed in-tank hardware, waste removal would begin. Special purpose end effectors would be utilized to dislodge and to rubblize solid waste. Other special purpose end effectors and an associated waste conveyance system are under development for use in retrieval of the waste.

The waste retrieval manipulator would be capable of being deployed through a central riser of limited diameter [some tanks have existing 107-cm-diam (42-in.) risers] and positioning and orienting a variety of end effectors throughout the tank volume to accomplish waste and in-tank hardware removal. The retrieval manipulator would consist of a high-capacity LRM for gross positioning and a short-reach manipulator (SRM) at the end for positioning and orienting end effectors in the performance of tasks within a local volume in the tank. The retrieval manipulator would be designed for telerobotic operation (i.e., teleoperation, robotic operation, and combinations of these).

The horizontal and vertical reach of the retrieval manipulator, when combined with a restricted entry port diameter and end effectors weighing up to 3560 N (800 lb), indicate that the LRM is likely to exhibit significant structural flexibility as well as joint compliance. The control of such devices is inherently different from that of typical industrial robots. Gross motion positioning of the LRM as well as relatively accurate positioning and effective teleoperation of the SRM will likely require advanced control algorithms. Static deflection compensation and path planning or command filtering in conjunction with passive and active damping will be needed to provide minimal vibration and a stable platform for operation of the SRM. The most effective damping of the LRM may be obtained by integrated control of both the SRM and LRM. Given the combination of desired characteristics for the retrieval manipulator, which includes relatively accurate robotic positioning and bilateral force-reflecting teleoperation, as well as the undesirable characteristics of structural compliance, the retrieval manipulator presents a significant technical challenge.

This paper addresses the key design issues for the LRM that will have an important role in determining the performance of the waste retrieval manipulator. In the second section, several kinematic configurations for an LRM are presented. Approaches to deployment and workspace analysis are presented. The advantages and disadvantages of the various configurations are discussed from a kinematic point of view. The third section contains a parametric study of LRM designs. Constraints and assumptions are discussed. An approach to optimal design of manipulator links and a parametric design study are presented. Finally, the paper is summarized, and several conclusions are drawn.

KINEMATIC CONFIGURATIONS

This section presents three basic kinematic configurations that provide different deployment through a constrained access hole. Advantages and disadvantages of each configuration and the necessity of each degree of freedom (DOF) are analyzed.

Kinematic Constraints

Figure 1 shows the nominal storage tank used in this study. Its diameter is 22.86 m (75 ft), the height without considering the domed roof is 9.14 m (30 ft), and the dome height is 3.66 m (12 ft). The tank is buried 2.44 m (8 ft) below the ground surface. A clearance of 0.61 m (2 ft) is provided between the ground surface and the support structure. This tank configuration requires the retrieval manipulator to cover the workspace of 15.85 m (52 ft) deep and 22.86 m (75 ft) in diameter.

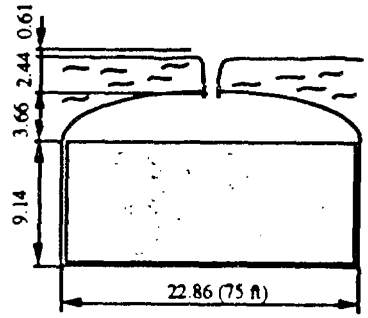

Fig. 1. Nominal waste storage tank dimensions (in meters).

The walls and dome of the tank are made of concrete, and the side wall and bottom are covered with a steel liner. The waste is assumed to be contained in the liner up to 9.15 m (30 ft). To avoid unnecessary contamination of the manipulator, only the end effector should come in contact with the waste. Therefore, the retrieval system has to be able to be deployed into the clearance of 3.66 m (12 ft) between the dome and the waste surface to begin the remediation procedure. This clearance height will limit the length of links that will be initially deployed.

Comparison of Potential Configurations and Deployment Procedures

Three similar configurations (Fig. 2) have been identified as potential candidates for an LRM for waste storage tank remediation. Each is a six-DOF positioning device. One of the most severe constraints of the LRM is its insertion through the access port, which is relatively very small compared with the workspace to be covered, and its deployment in the dome clearance over the highest possible waste level. The three configurations and their deployment characteristics are as follows:

1. The folded entry type (FET) LRM shown in Fig. 2(a) has a roll-extend-pitch-roll-pitch-extend (REPRPE) configuration. The FET manipulator can fold up the upper and lower arms inside the mast and unfold in the tank above the surface of the waste. The deployment of this type of manipulator would not be restricted by the presence of risers or other objects and would not require the removal of waste to provide clearance.

2. The telescopic sequential entry type (TSET) of Fig. 2(b) would introduce the links of the manipulator sequentially and extend the lower arm as needed. It has an REPRPE configuration. To deploy this type, preliminary planning is necessary because the links already introduced may have to be moved to avoid obstacles, the dome wall, or waste.

3. The sequential entry type (SET) shown in Fig. 2(c) with REPRPE configuration will have a different strategy for deployment. It will introduce only the last link, or the two last links, of the arm to clear a hole that will allow the rest of the manipulator to be inserted inside. This deployment procedure will depend on the ratio of dome clearance to tank diameter.

Analysis of the DOF of the Reference Kinematic Configurations

The LRMs shown have six DOFs as positioning devices of the SRMs. They include redundant three DOF for positioning. The solution of the resulting redundant inverse kinematics problem will be required for certain modes of operation of the manipulator. A number of different procedures have been suggested for the solution of the inverse kinematics problem for redundant manipulators that could be appropriate for these cases (Abdel-Rahman 1991; Dubey, 1988; and Goldenberg, Benhabib and Fenton, 1985). To explain their kinematic necessity, functions of these six DOFs are detailed in the following paragraphs.

First DOF: Rotational Joint. A rotational DOF is necessary at the base of the robot because of the radial symmetry of the waste storage tanks.

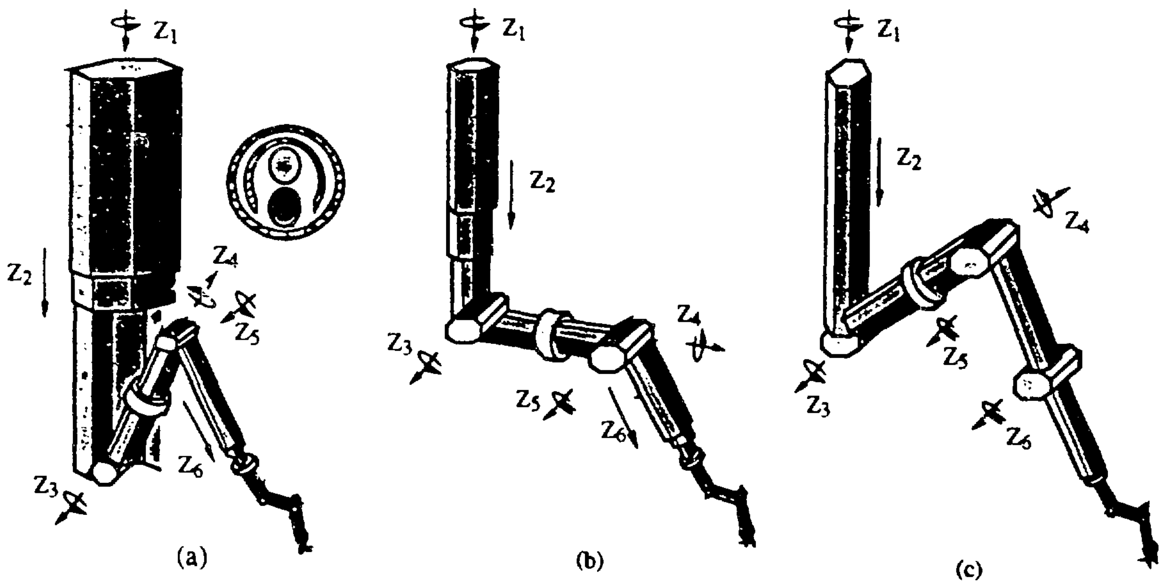

Fig. 2. Potential candidates for an LRM for waste storage tank remediation: (a) folded entry type (FET), (b) telescopic sequential entry type (TSET), and (c) sequential entry type (SET).

Second DOF: Prismatic Joint. A translation along the z axes will cover the workspace with close to minimum wasted workspace. For the SET and TSET cases a telescoping prismatic joint in the column reduces the overall length of the LRM by approximately 9 m (30 ft). In addition to minimizing transportation and installation problems, reducing the length of the column minimizes the effects of its deflection and vibration on the other links of this manipulator. The penalty will be increased lateral backlash in the link.

Third and Fifth DOFs: Rotational Joint. The two-pitch rotational joints are part of the classical configuration of a rotational manipulator. They give maximum workspace coverage for minimum overall length of the manipulator (Paden and Satstry 1988; and Jansen 1991, et al.).

Fourth DOF: Extra Rotational Joint. Even though the extra roll DOF between the two pitches of all three cases adds complexity of mechanical design, it has the following important advantages:

1. Singularity elimination. The singularity that all three cases exhibit when the end-point is aligned with the column axes is eliminated.
2. Obstacle avoidance. DOF is the one that gives the LRM obstacle avoidance capability.
3. Reduction of the second pitch motion. The range of motion of the second pitch should be at least from −140 to 140° to cover all of the workspace. The addition of the extra roll allows the same virtual range of motion (−140 to 140°) of the second pitch with just a real range of motion from −140 to 0°. This extra joint will allow the LRM to reach the top of the tank with a linear actuator instead of a rotary for this second pitch joint.
4. Workspace connectivity. A consequence of the use of this rotational DOF is an improvement of the connectivity of the workspace (Wenger and Chedmail, 1991) because the second pitch joint will not need to go through the stretch-out singular configuration to cover the workspace.
5. SCARA Configuration. Without the roll, the LRM must always work in an elbow (i.e., up or down) configuration. This joint enables the manipulator to work in a SCARA (i.e., horizontal) type or intermediate configurations.
6. Vibration Damping. The mixed configurations between elbow and SCARA will allow the LRM to be configured to better control the vibration in any direction.

Sixth DOF: Prismatic Versus Rotational Joint. As in the FET and TSET cases, if a telescopic joint is used, then it will reduce the height of the supporting tower by about 3 m (10 ft), and its compressed length by approximately 5 m (16 ft). A telescopic joint is recommendable to improve deployment and obstacle avoidance capabilities and to reduce the total length of the manipulator. In contrast, the rotational joint of the SET configuration would have less lateral backlash.

Advantages and Disadvantages of Each Configuration

Each manipulator type has its own advantages and disadvantages. The SET with a rigid, non telescopic column may have the simplest mechanism. However, the total length of all links and columns is the greatest, resulting in the highest support tower. The advantage of the FET is to reduce the tower height by folding the manipulator link inside the column. If all links are completely folded, then the tower height can be reduced to approximately 28% of the tower height required for an SET with a non telescopic column and to 40% if telescopic. These are the bounding cases with respect to the tower height of the manipulator types considered.

The TSET manipulator with a telescopic column provides one compromise between the two bounding cases discussed above. The use of a telescopic column and a telescopic final link will reduce the tower height to approximately 52% of that of the SET with a rigid column and to 75% if telescopic. Because the manipulator is not folded, the links will have larger cross-sections, which will give as small a static deflection as the SET.

A key design feature of the LRM should be the possibility of recovery from any single failure. A common way is to use double actuators with a differential gear connection for each joint. This will provide driveability by one of them even though the other has failed. In the event of a complete failure, the LRM will have to be withdrawn without having power at its joints. Because links of the TSET and SET configurations potentially could snag on the waste or in-tank hardware, additional precautions should be considered. On the other hand, the FET configuration entered folded, and it can be folded from outside with use of a simple cable that goes through the prismatic column and attached to the second pitch joint. The FET case appears to be the most appropriate for failure recovery.

PARAMETRIC STUDY OF LRM DESIGNS

To suggest appropriate structural design specifications of the LRM, a parametric design study was performed to demonstrate trends of the manipulator structural characteristics for various constraint conditions. The dimensions of a typical waste storage tank shown in Fig. 1 are used as nominal conditions. A program was developed to optimize the dimensions of each of the links for various tank diameters, entrance port diameters, payloads, and deflection design criteria. The weight, static deflection, and natural frequency are estimated based on that design. The design program optimizes the size and weight of each link to satisfy constraint conditions using discrete link thicknesses that are commonly available for fabrication.

Constraint Parameters

Structural design parameters such as link length, area size, and thickness will depend on the following constraints: the entrance hole diameter, the tank radius, the tank depth from the ground to the bottom, the dome clearance of the tank, the payload with its dynamic characteristics, a strength design criteria, a static deflection allowance, the minimum inner size of each link, and the material. Primarily, tank size, the dome clearance of the tank, and available tower height determine the kinematic design for the type, configuration, and link lengths of the manipulator. Secondly, the payload and design criteria for strength and static deflection determine the size and thickness of the beam. The entrance hole diameter limits the maximum characteristic diameters of the links. If a link's outer dimension is over the limit due to the entrance hole or is under the minimum inner size, it is adjusted by changing the link thickness parameters.

Assumptions for the Manipulator Design

Several basic assumptions were made that significantly affect the design of a LRM for waste tank remediation. These are discussed in the following paragraphs.

The waste level is assumed to be at almost 100% of the tank capacity. The manipulator has to have a working configuration in the dome clearance space following its insertion through the entrance hole. The dome clearance height, the depth of the waste, and the diameter of the tank will determine the link lengths of the manipulator.

The entrance port is assumed to be at the center of the dome. Entrance port diameters are assumed to vary between 61 and 152 cm (24 and 60 in.). The analysis performed here can be extended to different specific geometries in a straightforward manner.

The actuator weight is estimated from the required power capacity using the linearized weight and power relations that have been derived from the specifications of commercially available hydraulic actuator products.

Deflections due to bending moments are considered. If the roll DOF between two pitch DOF is employed, torsional deflections should be considered when the plane of the last links is not vertical.

Shape of the Link Structure

A circular link would have the highest inertia-to-area ratio for the circular entrance hole restriction (Jansen, et al., 1991). However, circular columns are very difficult to manufacture. Hexagonal-type structures give relatively high inertia-to-area ratios, are easy to build, and are good for telescopic extensions. When two links are folded inside the column for the FET, a square cross section of the two links gives a higher inertia-to-area ratio than a circular cross section and is also easier to build. Therefore, a hexagonal cross section was chosen for the column; a square cross section for the other links.

Optimal Design of the Manipulator Links

Link size. For an SET manipulator, the minimum size of each link is limited by the diameter of the extension cylinder, hydraulic hoses, and supply lines for end effector tools. In this analysis the minimum inner sizes of the links were assumed to be 25 cm (10 in.) for the lower link(s), 29 cm (11.5 in.) for the upper link, and 38 cm (15 in.) for the column. The maximum outer size of the column link is assumed to be limited to 80% of the entrance hole diameter to allow some clearance for the possibility of including a manipulator boot in the final design.

For an FET manipulator the minimum sizes of the links are assumed to be the same as for the SET: 25 cm (10 in.) for the lower link and 29 cm (11.5 in.) for the upper link. The minimum inner size of the column should be greater than the sum of the upper link and lower link outer sizes to be folded inside the column. Thus, the minimum diameter of the column is assumed to be 110% of the sum of the two. The maximum diameter of the column is assumed to be 80% of the entrance hole diameter. The maximum upper and lower link characteristic diameters are limited to 40% of the column characteristic diameter to allow them to be folded inside the column.

The structural strength design criteria with a safety factor of 2.5 was applied at the maximum stress point to satisfy the working cycle requirements.

The static deflection requirement is more strict than the strength design criteria in most cases. The size and thickness of a link is mainly determined by the deflection criteria. Static deflection is also closely related to natural frequency. It is well known that the maximum bandwidth of the manipulator with a joint controller will be about half of the fundamental natural frequency (Book, et al., 1975). Therefore, the specification of the static deflection can be considered as the criteria for the bandwidth of the manipulator system.

The beam thickness has been optimized with discrete values to avoid unrealistic continuous numbers for practical manufacturing.

Parametric Design Analysis Procedures

A parametric design analysis procedure was developed and implemented using MATHEMATICA (Wolfram 1988). First, assuming the range of input variables (which are the constraint parameters such as tank size, entrance hole diameter, and payload), the type of the manipulator, the number of links, the shape of the links, and the material are specified. Secondly, the parameters to be varied and those to be fixed are chosen, and the iterative procedure for the structural design is initiated. The moment distribution and reaction force of the link with payload from the end link to the column are calculated. The link size is optimized to minimize the weight while satisfying the strength design criteria, static deflection design criteria, and other constraint conditions with a discretized wall thickness (a minimum wall thickness of 1/8 in. and incremental increases in thickness of 1/16 in. were assumed). After the link dimensions are calculated, the actuator weight is estimated from the link weight and payload. The structural system characteristics such as total system weight, static deflection, and the fundamental system natural frequency are then calculated. The fundamental natural frequency is approximately proportional to $1/\sqrt{\text{static deflection}}$ as shown in Fig. 3 (Blevins 1979). We have confirmed that the natural frequency approximately estimated from the static deflection agrees reasonably well with the exact solution (errors are of the order of 10 to 20%). In this analysis the approximate natural frequency results were used. Finally, after completion of the iterative procedure for the whole range of the parameters, the output parameters are plotted along the appropriate input parameters.

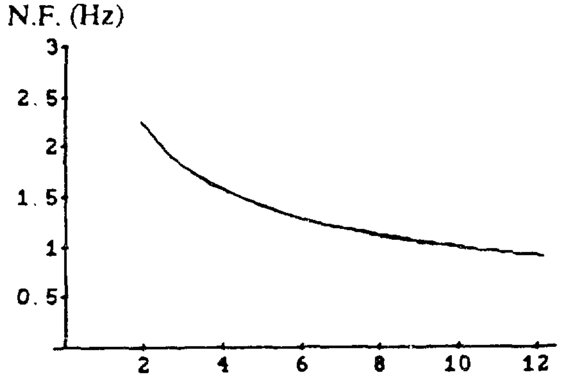

Fig. 3. Fundamental natural frequency with respect to static deflection of the (TSET) manipulator .

Analysis of Parametric Design Results

The objective of design is to obtain the stiffest structure that gives the least static deflection and the highest structural natural frequency. However, excessive weight and an excessively high tower is not desirable. The parametric design analysis will provide the structural characteristics trend for the range of interest of design constraint parameters of payload, static deflection allowance, tank size, and entrance hole diameter, and will suggest suitable design criteria of those constraint parameters, which do not result in a severe manipulator weight penalty. Manipulator weight is a general indicator of the overall trend of a design and is, therefore, used as a basis for comparison of design results. The design results are compared by varying payload, static deflection allowance, tank size, and entrance hole diameter. Other design results such as outer dimensional size of the links, thickness of the links, static deflection, and structural natural frequency have been published (Kwon, et al., 1993).

The manipulator is simplified into three parts: column, upper link, and lower link. The extensions of the column or links are assumed to be one simple column or one link to reduce calculations that would be needed for different types. Telescopic extensions were assumed to be one uniform, rigid link. Since the structural characteristics of the SET and the telescopic TSET are almost the same, only the two cases of the TSET and the FET were considered in this analysis.

<u>Case 1</u>: Varying the static deflection requirement with different payloads for the TSET manipulator.

This case considers varying the static deflection requirement with different payloads for telescopic SET manipulators. Static deflection was varied from 10 to 30 cm (4 to 12 in.) for payloads of 227, 454, and 680 kg (500, 1000, and 1500 lb). The diameter of the entrance port was fixed at 107 cm (42 in.), and the maximum column characteristic diameter size was restricted to 80% of the entrance port diameter. The size of the tank was fixed at a depth from the ground to the tank bottom (i.e., the column length) of 15 m (50 ft) and a tank radius (manipulator horizontal reach) of 12 M (38 ft).

As shown in Fig. 4, the manipulator weight changes rapidly when the static deflection allowance is less than 10 cm (4 in.). A reasonable static deflection requirement seems to be 10 to 18 cm (4 to 7 in.) at the end point of the manipulator. For the 680-kg (1500-lb) payload case, a static deflection of more than 24 cm (9.5 in.) is not allowed by the structural strength design criteria. That means that if static deflection design criteria is relatively large, the strength design criteria will determine the size and wall thickness of the manipulator.

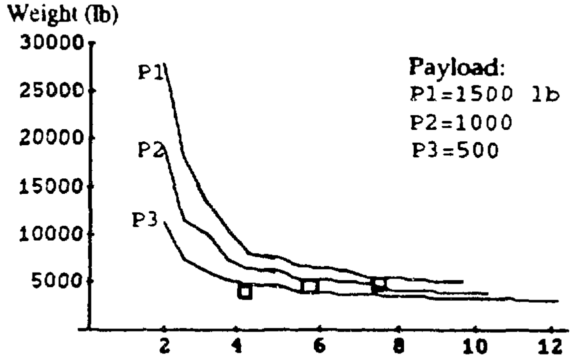

Fig. 4. TSET manipulator weight vs static deflection allowance.

Case 2: Varying the entrance hole diameter with different tank sizes for the TSET manipulator.

In this case tank radii of 7, 9, and 12 m (24, 31, and 38 ft) and port diameters from 64 to 140 cm (25 to 55 in.) were considered. Tank depth is assumed to vary proportional to tank radius change. The payload was fixed at 454 kg (1000 lbs), and the desired static deflection at the maximum payload was fixed at 15 cm (6 in.).

As shown in Fig. 5, if the tank radius is smaller, then the manipulator will be lighter, and a smaller entrance hole will be acceptable because the stress and static deflection design criteria can be satisfied by smaller size links. If the entrance hole becomes too small, the manipulator design methodology will increase the wall thickness of the links to meet the design criteria because the size of the links is very limited. A heavy manipulator will be unavoidable. If we increase the entrance hole diameter, the allowable diameter of links will be increased. Consequently, the weight of the manipulator will be decreased until the thickness has reached a minimum and the design criteria are still satisfied. If the thickness is reached at a minimum, the diameter of the links do not need to be increased, even though the entrance hole size is increased. Therefore, there is an appropriate range of entrance hole diameters for a specific capacity manipulator. For a tank radius of 12 m (38 ft), a hole diameter between 89 and 114 cm (35 and 45 in.) will be an appropriate constraint condition, assuming actuators can be embedded within the links.

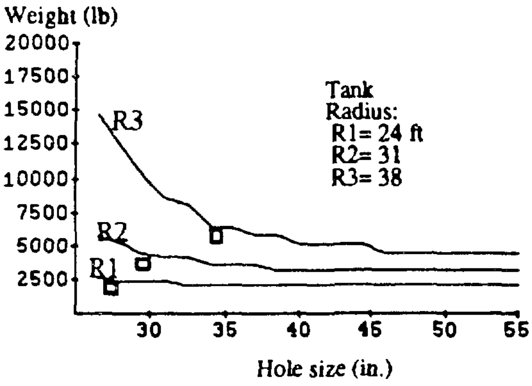

Fig. 5. TSET manipulator weight vs hole diameter.

Case 3: Varying the static deflection requirement with different payloads for the FET manipulator.

This case is the same as case 1 except that it is for an FET manipulator rather than an SET manipulator. The FET manipulator weight increases more rapidly than the TSET when the static deflection requirement decreases, as shown in Fig. 6. A reasonable static deflection requirement seems to be 15 to 20 cm (6 to 8 in.) for the FET. For the 680-kg (1500-lb) payload case, a static deflection of less than 10 cm (4 in.) is almost impossible because the outer size of the column is limited by the entrance hole diameter, the inner size is limited by the size of other links that will be folded inside, and the maximum size of the upper and lower links also have to be limited by the size of the column. Therefore, the FET is suggested only if relatively large static deflections are allowed.

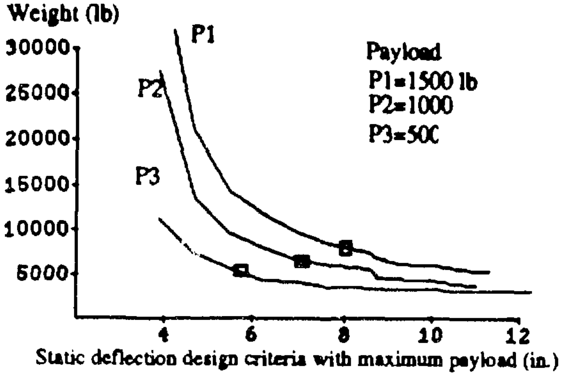

Fig. 6. FET manipulator weight vs static deflection allowance.

Case 4: Varying the entrance hole diameter with different tank sizes for the FET manipulator.

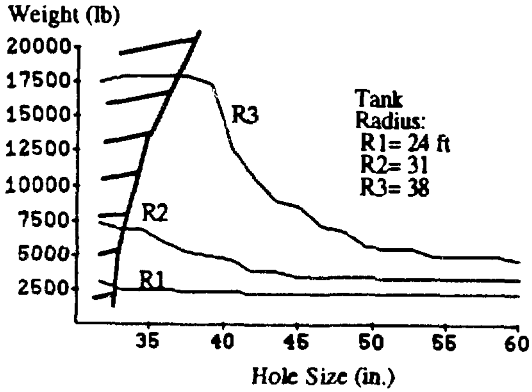

Fig. 7. FET manipulator weight versus hole diameter.

This case is the same as case 2 except that it is for an FET manipulator rather than a TSET manipulator. If the entrance hole is too small, all of the design constraint conditions cannot be satisfied for the FET.

The lined region in Fig. 7 represents conditions under which the links cannot be folded inside the column. For a 12-m (38-ft) radius tank, if the entrance hole is less than

94 cm (37 in.), the design constraint conditions should be relaxed or another type of manipulator should be considered. To have the same weight as that required for the TSET, the FET requires about a 25-cm (10-in.) larger entrance hole.

Discussion on Design Results

It is desirable to design LRMs to have characteristics such as minimum static deflection, maximum structural natural frequency, maximum actuator bandwidth, and minimum tower height without penalizing the weight excessively. The excessive weight will require larger capacity actuators and a larger external support system. That will result in an inefficient retrieval system. The parametric design study reveals quantitative suggestions of design criteria for LRMs. It gives quantitative estimations for weight, static deflection, and natural frequency of the manipulator with respect to a wide range of constraint condition parameters. It also shows the acceptable constraint condition ranges for TSET type and FET manipulators.

In general, less static deflection and higher structural natural frequencies are obtained with an SET manipulator than with an FET one because the smaller diameter of the lower links required for folded entry. The structural natural frequency of the system was not improved dramatically by designing the manipulator with smaller static deflection design criteria or changing the type. Due to dramatic changes in weight required for small static deflections, reasonable static deflections requirement will be very important for design. Generally, the static deflection requirement range of the FET manipulators will be greater than that of the SET manipulators. For the typical 12-cm (38-ft) radius tank, the static deflection of FET manipulators is likely to be 15 to 20 cm (6 to 8 in.), while for SET manipulators it will be 10 to 15 cm (4 to 6 in.). Column static deflection was a major contributor to end effector deflection. In general, as the entry port diameter was increased, the manipulator weight for the same static deflection criteria decreased until the minimum desired wall thickness was reached.

CONCLUSIONS

Several key design requirements and objectives of the LRM were identified. The tank structure cannot be loaded, and recovery from failures must be possible. Manipulator deployment must be possible in the constrained space above the waste, and the manipulator workspace must provide coverage of the entire tank. The key objective is to design a stiff manipulator that can use the existing central ports for manipulator deployment and can minimize the height of the tower required to support the manipulator. For improved dynamic performance, the structural natural frequency should be maximized, the static deflection should be minimized, and the weight should be minimized; however, improvements in vibration damping are more likely to be significant. Since excessive weight of the manipulator is not desirable, design tradeoffs between these objectives will be required.

In the kinematic study, it was shown that at least five positioning DOF are required because of the constraints involving the tank dimensions, the port through which the manipulator will be deployed, and the deployment clearance.

A comparison between a design that allows the lower links of the manipulator to be folded into the column for deployment and two designs that require sequential deployment of the manipulator was made. From the parametric study, one can conclude that the penalty of the FET manipulator is (1) heavier weight to maintain the same deflection or (2) larger deflection and lower natural frequency with the same weight. Generally, the FET requires a larger hole to have the same performance as the TSET type and the SET. The advantages of the FET manipulator are easy deployment inside the tank, the resulting reduction in compressed manipulator length and, therefore, lower tower height and greater ease in transportation and installation.

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