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On Stiffening Cables of A Long Reach Manipulator

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Abstract

A long reach manipulator will be used for waste remediation in large underground storage tanks. The manipulator's slenderness makes it flexible and difficult to control. A low-cost and effective method to enhance the manipulator's stiffness is proposed in this research by using suspension cables. These cables can also be used to accurately measure the position of the manipulator's wrist.

Keywords: flexible manipulator, nuclear waste cleanup, modal analysis, robot mechanisms.

1. Introduction

Large underground storage tanks have been used to store waste with moderate radiation levels since 1943. Three hundred and thirty-two tanks at different DOE sites contain over 100 million gallons of waste. Many of them have exceeded their design life span, and at least 67 single shell tanks at Hanford, Washington site are known or assumed to have leaked. Some of the tanks are potentially explosive.

As part of its clean up efforts, DOE wants to remove the waste from the tanks and place it in safer, permanent disposal or storage. Emptying the tanks is a technically challenging job made difficult by the hazardous nature of the tank contents. All waste has to be removed through a specially sealed pipe in the top of each tank. This waste material is chemically complex and includes physical forms ranging from thick, sticky sludge to a crystalline saltcake. The sludge has the consistency of soft mud and saltcake approximates low-grade concrete. Most of the tanks also contain small amounts of liquid.

A typical underground storage tank, as shown in Figure 1, has a radius of 75 ft and a height of 48 ft, including 12 ft of the dome's height. Access to the interior is through a 42" diameter hole at the top of the dome. In the project of Underground Storage Tank Remediation Robotics for DOE Environmental Restoration and Waste Management, a long reach manipulator (LRM) is proposed for waste recovery. The LRM is attached to a 65-foot upright mast that is mounted in a support tower and guides the arm when it is raised and lowered into the tank [1,2]. The manipulator will be equipped with sensors and cameras to help operators direct its movements. It will be fitted with tools that enable it to grasp objects and break apart the solidified wasted. Once the hard waste is broken up, other attachments will allow the manipulator apparatus to suck up the waste, not unlike a high-powered vacuum cleaner, as shown in Figure 2. The removed waste will be pumped to processing tanks for further treatment before final disposal or storage.

A short reach arm (SRM) is attached at the end of the LRM for dexterous tasks like survey, inspection, digging, scooping, cutting, etc. Therefore, the LRM is responsible for gross motion, or a positioner in Cartesian space, and the SRM is responsible for fine motion with six DOF. A Schilling Titan II robot [3] is a candidate for the SRM. The robot is hydraulic powered with a maximum reach of six feet and a lifting capacity of 240 pounds. It can be controlled by a force-reflection master arm, an ideal candidate for remote manipulation in hostile environments. Titan II robot offers a radioactive-hardened version, capable of 10^7 RAD Gamma accumulated exposure with no performance loss.

A three degrees-of-freedom (DOF) manipulator, as shown in Figure 3, is a likely candidate for the LRM [4,5,6]. The first joint J_1 is rotating about the base; J_2 and J_3 are the shoulder and elbow of the articulated arm. The LRM has a reach of 33 ft, much longer than 6 ft of a typical manipulator or industrial robot. The large aspect ratio (length to diameter) of the arm makes the LRM very flexible and difficult to control. The control of one DOF flexible arm has been extensively researched [5]. That of two DOF flexible arm is currently under investigation [7,8]. The control of three DOF flexible arm is not explored yet.

2. Suspension Cables

Using suspension cables as a low-cost and effective method to enhance the manipulator's stiffness is studied in this paper. Four cables are proposed to connect the boom to the wrist of the LRM to stiffen the manipulator, in a way similar to cables supporting flagpoles or masts. The four cables are attached to the sides of the wrist of the LRM to avoid interference between links and cables. The symmetric arrangement of these cables about the vertical radial plane is shown in Figures 4 and 5.

The attachment bar where C_1 and C_4 are fastened can be folded to go through the access hole, and be deployed once the boom is lowered and locked. Cables C_2 and C_3 are fastened to the boom at a higher elevation. Winches will be used at attachment points at the bar or the boom, and motors driving the winches can be placed outside the storage tank by routing cables through the boom.

A cable can be viewed as an extension spring that can not take compression forces. Cables C_2 and C_3 will yield a resultant tension force along the outward radial direction, as shown in Figure 5(a), and therefore these two cables will stiffen the LRM in this direction. The resultant tension force of cables C_1 and C_4 are also in the outward radial direction, as shown in Figure 5(a). These two cables also provide stiffness in the lateral (tangential) direction, as shown in Figure 5(b). Because the attachment points of C_2 and C_3 at the boom are higher than those of C_1 and C_4, the resultant of their radial forces will also provide the stiffness in any direction on the radial plane.

The four cables are controlled by motors attached to winches. With three joint motors in the LRM, the whole system has seven motors and becomes highly redundant for a three DOF positioner. These seven motors will be controlled in two categories. Joint motors are controlled according to the rigid body motion (gross motion) with consideration of static deflection caused by gravity force and tension in cables. Four cable motors will be controlled to yield constant tensions on the cables to ensure the cables will be taut all the time. Therefore, the joint motors are to control the position of the LRM, and cable motors are used to stiffen the system.

Once the LRM has reached its position, all motors in the LRM should be locked, and the SRM will perform dexterous tasks. The cable system will form a stable positioner (or platform) for the SRM since cables and the LRM assume a truss-like structure.

3. Modal Analysis

To assess the stiffness enhancement, we can compare the lowest natural frequencies of the LRM at selected configurations with and without cables. Modal analysis is a tool to find natural frequencies of a system, but it works only in a linear system. Because the cable can be considered as a one-way spring, which is a non-linear component, the stiffness estimation is not straightforward.

To understand the nonlinear behavior, consider a cantilever beam connected to a cable, as shown in Figure 6. This system is easy to analyze, and is important because the LRM may be locked as a positioner for the SRM to control the dexterous motion. A locked LRM can be treated as a cantilever beam.

Consider the free vibration of the beam when an initial displacement x_0 is applied. Because this is a free vibration, the displacement vs. time curve will be sinusoidal. When x>0, the cable is slack, and we will consider the spring constant of the beam only. When x<0, the cable is taut, and we need to consider the spring constants of the beam and the cable. The system equation can be expressed as:

$$m\ddot{x} + kx = 0$$

where m is the payload at the end of the LRM, which is the mass of SRM in a simplified model. k is the spring constant of the system. $k = k_b$ if the cable is slack (x>0), and $k = k_c + k_b$ if the cable is taut (x<0). $k_b = \frac{3EI}{l^3}$ and $k_c = \frac{AE}{l}$ are spring constant of the beam and cable respectively.

The initial condition of the system is $t = 0,\ x = x_0,\ \dot{x} = 0$, and at the transition from the slack to the taut cable, the boundary condition is the first order continuity: the velocity and position continuity. In other words, the end condition of the first phase becomes the beginning condition of the second phase, as shown in Figure 7. In the first phase, the displacement is $x = x_0 \cos \omega_1 t$, where $\omega_1 = \sqrt{\frac{k_b}{m}}$. In the second phase, the displacement is $x = -x_1 \sin \omega_2 (t - t_1)$. In this equation, $t_1 = \pi / 2\omega_1$ is the period of the first phase, $\omega_2 = \sqrt{\frac{k_b + k_c}{m}}$, and $x_1 = x_0 \omega_1 / \omega_2$ In Figure 7, the stiffness of the cable k_c and that of the beam k_b are the same, and $\omega_1 = 5\pi$ and $\omega_2 = 10\pi$.

Since the displacement function is sinusoidal, Fourier transformation can be used to find the natural frequencies of the system. Figure 8 shows the first and second modes of the system, and the magnitudes of higher order modes are negligible. Because the first mode is dominant, we can estimate the lowest natural frequency from the period of the displacement function.

When a preload is applied to a cable, the cable is extended with an elongation. If the initial displacement applied to the system does not completely cancel the elongation, the cable works as a normal two-way spring, and the system becomes linear. Then modal analysis can be used. The initial displacement is probably caused by the inertial load and acceleration or deceleration of the LRM.

I-DEAS Master Series [9], a comprehensive CAD software package including finite element analysis, was used to perform modal analysis to compare the lowest natural frequency of a beam with or without suspension cables. The worst case of lowest natural frequency of the manipulator is when the arm is extended like a cantilever beam. If the beam is 33' long with a tube cross section of 6" outside diameter and 4" inside diameter, the lowest natural frequency of the beam alone is 1.045 Hz. With all four cables, each of 1" diameter, as shown in Figure 4, the lowest natural frequency is 4.442 Hz. If only two cables are used, vertical cables C_2 and C_3, or horizontal cables C_1 and C_4, the lowest natural frequency is not much improved. The results of four different cases are summarized in Table 1.

Notice that for this geometry, the stiffness of each cable is k_c =22.43 lb/in, and that of the beam is k_b =3.123 lb/in. Although the cable has a higher stiffness, its effectiveness is reduced because only the vertical component of the spring, which is very small, is used to stiffen the beam vibration.

	Lowest Nat. Freq.
Beam alone	1.045
Beam with horizontal cables only	0.983
Beam with vertical cables only	1.017
Beam with all four cables	4.442

Table 1 Lowest Natural Frequency of a Cantilever Beam with or without Cables

The stiffness and the lowest natural frequency of the system also depend on the location of cables. Different attachment points were explored and the corresponding lowest natural frequencies are listed in Table 2. As shown in this table, if the attachment points are higher on the mast, as y value (the vertical distance) is increased, the lowest natural frequency will increase. Also, if the attachment points are farther away from the mast, as z value (the horizontal distance) is increased, the lowest natural frequency will increase. However, as cables move further away from the shoulder of the LRM, interference between cables and the obstacles inside the storage tank becomes more likely. The best case in this table happens when y=8' and z=5'. However, the improvement of this case over the case of y=6' and z=4' is less than 10%. Therefore, the optimal attachment location for stiffness enhancement is y=6' and z=4'.

	y=4'	y=6'	y=8'
z=±3'	3.563	3.772	3.771
z=±4'	3.562	4.442	4.441
z=±5'	3.561	4.493	4.858

Table 2 Lowest Natural Frequencies with Cables at Different Locations

5. Discussion

As shown in Table 1, with suspension cables, the lowest natural frequency of the LRM is increased by 425%. Therefore, using suspension cables is a low-cost and effective method to enhance the LRM's stiffness. A lot of solid waste like risers are above the sludge inside the tank, and they become obstacles to the suspension cables. Therefore, in the beginning of the clean-up process when obstacles are not clear yet, do not deploy cables. Once these obstacles are cut using large hydraulic shears, cables can be deployed to enhance the throughput.

Suspension cables proposed in this research will enhance the stiffness of the LRM by changing the LRM from a serial manipulator to a semi-parallel manipulator. A fully parallel manipulator with suspension cables, as the one developed at NIST [10], will provide the best stiffness, but it can not go through the access hole and can not render obstacle avoidance because of its bulky structure.

Since cables are always taut, they can be used as position sensors to detect the position at the wrist of the LRM. Using position sensors at the joint motors will not yield accurate wrist position because of the link deflection.

Acknowledgments

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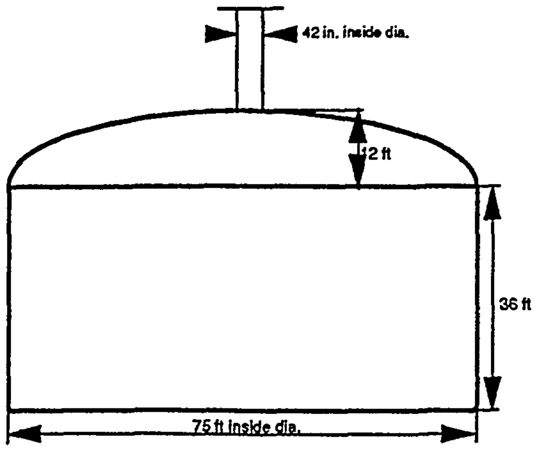

Fig. 1 A Typical Underground Storage Tank

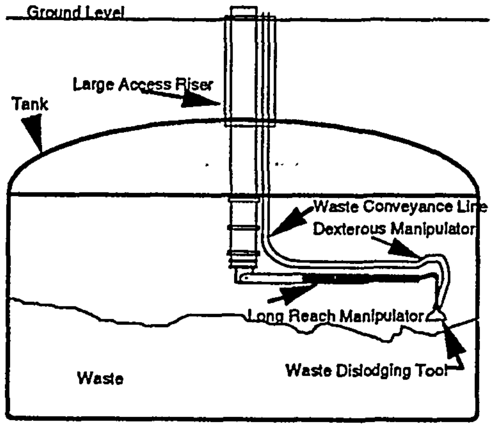

Fig. 2 A Long Reach Manipulator in a Storage Tank

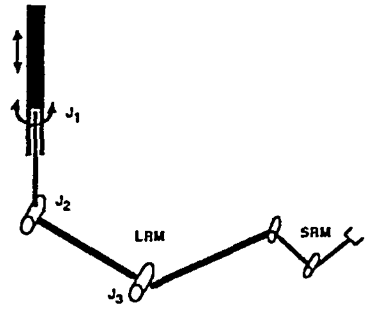

Fig. 3 A Long Reach Manipulator with a Short Reach Manipulator

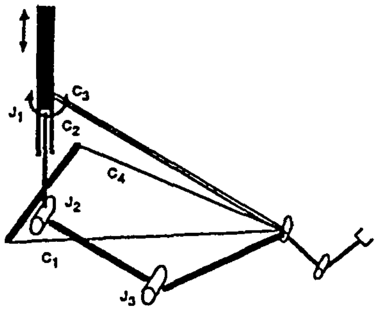

Fig. 4 A Long Reach Manipulator with Suspension Cables

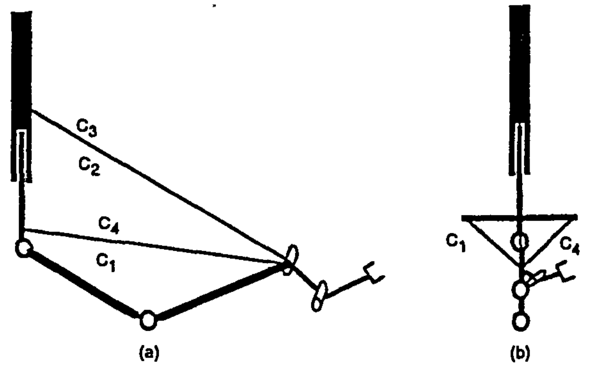

Fig. 5 Side and Front Views of a Long Reach Manipulator with Cables

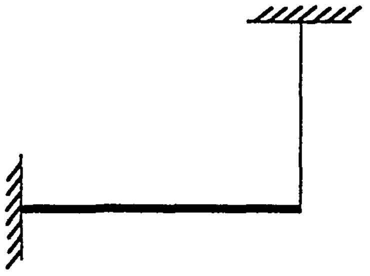

Fig. 6 A Cantilever Beam with a Cable

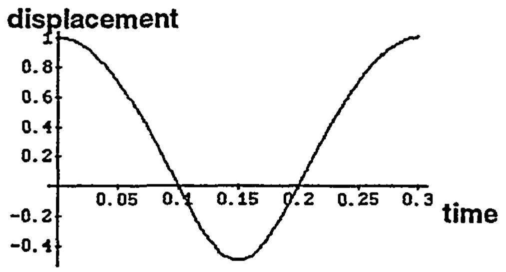

Fig. 7 Vibration of A Cantilever Beam with a Cable

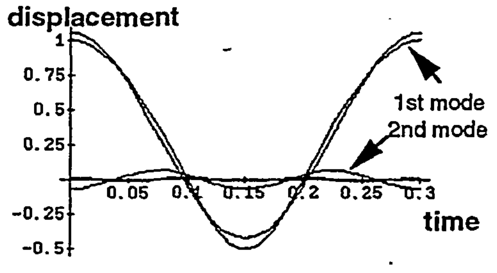

Fig. 8 Fourier Transform with the 1st and 2nd Modes