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SIMULATION TOOLS FOR HAZARDOUS WASTE REMOVAL*

K. C. Bills
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6426
(423) 576-5884

L. J. Love
Oak Ridge Institute for Science and Education
P. O. Box 2008
Oak Ridge, Tennessee 37831-6426
(423) 576-4630

ABSTRACT

The primary mission of Oak Ridge National Laboratory (ORNL) during World War II was the processing of pure plutonium metal in support of the Manhattan Project. By-products of this process include radioactive cesium-137 and strontium-90. Between 1943 and 1951, the Gunite and Associated Tanks (GAAT) at ORNL were built to collect, neutralize, and store these by-products. Currently, twelve gunite tanks and four stainless steel tanks are located on the ORNL complex. These tanks hold approximately 75,000 gal of radioactive sludge and solids and over 350,000 gal of liquid. Characterization studies of these tanks in 1994 indicated that the structural integrity of some of the tanks is questionable. Consequently, there is a potential threat to human health through possible contamination of soil and groundwater. These risks provided the motivation for remediation and relocation of waste stored in the ORNL tanks.

A number of factors complicate the remediation process. The material stored in these tanks ranges from liquid to sludge and solid and is composed of organic materials, heavy metals, and radionuclides. Furthermore, the tanks, which range from 12 to 50 ft in diameter, are located below ground and in the middle of the ORNL complex. The only access to these tanks is through one of three access ports that are either 12 or 24 in. in diameter.[1] These characteristics provide a daunting challenge: How can material be safely removed from such a confined structure? This paper describes the existing strategy and hardware projected for use in the remediation process. This is followed by a description of an integrated hardware system model. This investigation has isolated a few key areas where further work may be needed.

I. INTRODUCTION

As part of a Comprehensive Environmental Response, Compensation, and Liability Act Treatability Study funded by the Department of Energy (DOE), ORNL is preparing to demonstrate and evaluate two approaches for the remote retrieval of waste in underground storage tanks. This work is being performed to identify the most cost-effective and efficient method of waste removal before full-scale remediation efforts begin in 1998. One of the strategies focuses on the use of multiple long-reach manipulators for waste retrieval. With this approach, two robots operate cooperatively to guide a Confined Sluicing End-Effector (CSEE) through the waste. The first robot, the Hose Management Arm (HMA), carries the CSEE, which breaks up and sucks out a host of materials from the tank. The second robot, the Modified Light Duty Utility Arm (MLDUA), grasps the CSEE and moves it over the waste surface. This process can be executed either autonomously or via teleoperation command.[2]

A. Modified Light Duty Utility Arm

The large volume and small access ports in the tanks require a robot that is both long and slender. In addition, the manipulator will interact with the environment and carry a host of tools. Subsequently, the robot will need a relatively high payload capacity. Spar Aerospace is

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program. The system model includes a detailed model of the MLDUA (complete with Spar's inverse kinematics algorithm) and a dynamic model of the HMA and flexible exhaust hose connecting the two arms. The goal of the system model is threefold:

- The model shall provide a tool for operator training. The system can simulate teleoperation input commands through the same interface available on the hardware. Lighting and camera views may be adjusted to identify optimal viewing ports for operation.
- The model shall provide a benchmark for identifying potential mining strategies. A working model of the CSEE and waste provides a visual cue simulating waste removal. As the operator moves the CSEE through the waste, the texture of the waste surface varies with the amount of material remaining. It is also possible to record the net amount of material removed during a mining process.
- The model shall provide an interface capable of investigating alternative control strategies for the HMA. Alternative control strategies are easily imbedded in the simulation and can be run during robotic and/or teleoperation tasks.

A. Stand-Alone Model of the MLDUA

In the fall of 1995, Spar Aerospace provided a stand-alone TeleGrip model of the MLDUA to the Idaho National Engineering Laboratory. This model has since been made available to ORNL. This TeleGrip model features many novel characteristics, including accurate modeling of the MLDUA's kinematics, teleoperation or robotic input commands, and realistic response to these commands. Furthermore, the algorithm for the inverse kinematics used to resolve the joint angles from Cartesian commands is the same algorithm that will be used on the real hardware. The master input device, a pair of 3-D.O.F. joysticks, can be used to provide desired translational and rotational velocity input commands to the model by an operator.

B. Dynamic Modeling of the HMA and Hose

To better understand the coordinated motion of MLDUA and HMA, a comprehensive modeling effort was focused on integrating a dynamic model of the HMA and hose with the stand-alone MLDUA model. During operation, the total system is quite complex. The MLDUA grasps the CSEE, which is coupled to the HMA by a long, flexible hose. Thus, during operation, the entire system consists of a closed kinematic chain with a flexible hose acting as one of the links in the chain. One of the challenges during the modeling process was the solution of the kinematics of the hose and HMA. The strategy for dynamic simulation consists of treating the tip position of the MLDUA as an input into a dynamic model of the hose and HMA. Movement of the MLDUA, and subsequently one end of the hose, produces a deformation of the hose from its equilibrium. A joint torque on the hose model is computed by the product of the hose stiffness, K_h, and joint deformation. This deformation provides a resultant reaction force at the tip of the HMA and MLDUA. This reaction force drives a dynamic model of the HMA that will subsequently provide an updated tip position of the HMA (and subsequently, a new hose position for the next iteration of the algorithm).

1. Energy Model of the HMA. The HMA is modeled as a 2-D.O.F. planar manipulator operating in the horizontal plane. The dynamic model includes inertial effects, $D(q_{hma})$, and nonlinear coupling and friction terms, $C(q_{hma}, \dot{q}_{hma})$. The model also includes external inputs to the robot from tip and joint forces. The tip force, F_{hose}, currently used in the integrated system model is provided by the deformation of the hose. The computation of this force is described shortly. Joint forces may be generated by the motors under some form of joint level control, $\tau_{control}$. In the current planar model of the hose, an additional joint torque is produced by the deformation of the hose yaw joint, q_e.

$$D(q_{hma})\,\ddot{q}_{hma} + C(q_{hma}, \dot{q}_{hma})\,\dot{q}_{hma} = J^{t}{}_{hma}(q_{hma})\,F_{hose} + \tau_{control} + K_h\,q_e \tag{1}$$

Subsequently, the dynamic model consists of computing the joint motion, q_{hma}, due to external forces applied at the tip and joints of the robot. The joint motion can then be transformed to motion at the tip of the HMA. This provides the location of the second end of the hose, where the first end is located at the tip of the MLDUA.

2. Hose Boundary Conditions. As stated earlier, the hose and HMA model have a few novel boundary conditions. First, one end of the hose must terminate at the CSEE, held by the MLDUA. The second end of the hose terminates at the end of the HMA. However, when the HMA is not under control (passive), only the vertical position is fixed, and the robot is free to move in the horizontal plane. The combined motion of the MLDUA and HMA is resolved by combining the dynamics of the HMA with the boundary condition of the hose. The HMA has an initial configuration that minimizes the horizontal distance between the tips of the two robots. In

$$x = \sum_{j=1}^{N} \frac{L}{N} \cos\left(\sum_{k=1}^{j} q_k\right) \tag{8}$$

$$y = \sum_{j=1}^{N} \frac{L}{N} \sin\left(\sum_{k=1}^{j} q_k\right) \tag{9}$$

First, substitute Eq. (10) into Eqs. (8) and (9) to provide a localized linear expression of the trigonometric functions. Then Eqs. (7) to (9) can be combined and rearranged to provide the relationship in Eq. (11). The index k represents the iteration of the algorithm.

$$\begin{aligned} \sin(q_i[k]) &\cong \sin(q_i[k-1]) - q_i[k-1]\cos(q_i[k-1]) + q_i[k]\cos(q_i[k-1]) \\ \cos(q_i[k]) &\cong \cos(q_i[k-1]) + q_i[k-1]\sin(q_i[k-1]) - q_i[k]\sin(q_i[k-1]) \end{aligned} \tag{10}$$

$$\begin{bmatrix} \ddots & & \vdots & \vdots \\ K_h & & v_x^t & -v_y^t \\ & \ddots & \vdots & \vdots \\ \cdots & -v_x \cdots & 0 & 0 \\ \cdots & v_y \cdots & 0 & 0 \end{bmatrix} \begin{Bmatrix} \vdots \\ q_r[k+1] \\ \vdots \\ \lambda_1 \\ \lambda_2 \end{Bmatrix} = \begin{Bmatrix} \vdots \\ \sum_{i=r}^{N} m\, g\, \frac{L}{N} \sum_{j=1}^{i} \sin\left(\sum_{l=1}^{j} q_l[k]\right) \\ \vdots \\ x - \sum_{i=1}^{N} \frac{L}{N} \left\{\cos\left(\sum_{j=1}^{i} q_j[k]\right) + \left(\sum_{j=1}^{i} q_j[k]\right) \sin\left(\sum_{j=1}^{i} q_j[k]\right)\right\} \\ y - \sum_{i=1}^{N} \frac{L}{N} \left\{\sin\left(\sum_{j=1}^{i} q_j[k]\right) - \left(\sum_{j=1}^{i} q_j[k]\right) \cos\left(\sum_{j=1}^{i} q_j[k]\right)\right\} \end{Bmatrix} \tag{11}$$

with

$$\begin{aligned} v_x(r) &= \frac{L}{N} \sum_{j=r}^{N} \sin\left(\sum_{l=1}^{j} q_l[k]\right) \\ v_y(r) &= \frac{L}{N} \sum_{j=r}^{N} \cos\left(\sum_{l=1}^{j} q_l[k]\right) \end{aligned} \tag{12}$$

The above equation can then be put into a simple linear format.

$$\left[\, A(\bar{q}[k]) \right] \begin{Bmatrix} \bar{q}[k+1] \\ \lambda_1 \\ \lambda_2 \end{Bmatrix} = \left\{ B(\bar{q}[k]) \right\} \tag{13}$$

The solution to the hose joint angles now falls to the solution of N + 2 linear equations. Furthermore, the solution can take the form of a recursive algorithm that, as the hose tip position varies, the algorithm will solve for the hose configuration accordingly. For the work described in this paper, the Newton-Gauss Elimination proved to be robust and computationally efficient.

5. Hose Interaction Force. The next issue related to the hose model is the resultant force applied to the HMA from the hose. The strategy adopted in this modeling effort is to compute the effective torque at each joint and define a Jacobian from the hose joint space to the coordinates on the tip of the HMA. The joint torque is the product of the joint stiffness and the deviation of the joint position from its equilibrium configuration. First, an estimation of the static configuration of the hose is necessary. An iterative solution to the static generalized coordinates is sought which satisfies Eq. (14).

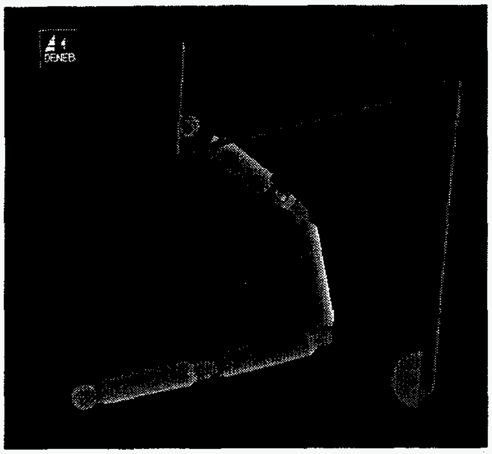

Figure 5: Collision with tank

V. CONCLUSIONS

A comprehensive integrated system model of the gunite tanks and waste remediation hardware has been successfully modeled under the TeleGrip simulation platform. The model permits simulation of remediation tasks under either robotic or teleoperated commands. Presently, the system is being used to develop mining strategies and to understand the physical constraints of the hardware. The model is flexible in that it will permit future studies of alternative kinematic resolution and cooperative control strategies of the dual-arm system.

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