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STRATEGIES FOR REDUNDANCY RESOLUTION OF DUAL-ARM SYSTEMS WITH PASSIVE ELEMENTS FOR TANK WASTE REMOVAL*

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ABSTRACT

The work described in this paper focuses on the coordination and control of two manipulators coupled by passive elements operating in a confined space. An example of one such system is the hardware used for the environmental response treatability study funded by the Department of Energy at Oak Ridge National Laboratory (ORNL). The motivation for this project is to establish the methodology necessary to extract large volumes of hazardous waste from underground storage facilities. The hardware used at ORNL consists of two long-reach manipulators. The first robot, the Modified Light Duty Utility Arm (MLDUA), is an 8-degree-of-freedom long-reach manipulator. The second arm, the Hose Management Arm (HMA), has two active degrees-of-freedom and provides hardware to break up and extract materials from the tank. Current strategies call for the MLDUA to grasp a combined sluicing end-effector attached, by a long flexible hose, to the HMA. The MLDUA will then move the combined system through the waste, extracting material. This paper describes many of the issues related to redundancy resolution and the coordinated control of these two robots. First, we provide a brief outline of the project and the existing hardware. This is followed by a description of existing redundancy resolution techniques and the impact redundancy has on the success of the project. Finally, preliminary simulation results show the effect cooperative control has on the level of forces generated between the dual-arm systems when coupled by an elastic exhaust hose. These results show a significant reduction in forces when both arms are active and have a combined manipulation strategy.

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I. INTRODUCTION

A. ORNL's Waste Remediation Program

Currently, an aggressive program at ORNL is directed toward the remote retrieval of hazardous waste stored in underground tanks. One of the strategies focuses on the use of multiple long-reach manipulators. 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 either be executed autonomously or via teleoperation command.

B. Roles for Redundancy

Presently, the redundant joint MLDUA will act as a leader while the planar HMA will be operated in a follower, or passive, mode. Preliminary simulation studies suggest that the performance of the hardware during remediation tasks may be enhanced through a combination of alternative redundancy resolution and control strategies. The primary focus of our research is the redundancy resolution and cooperative control of two robots operating in the constrained space of an underground waste storage facility. Our investigation is focusing on the following issues:

1. Optimize inverse kinematics: Our investigation is focusing on the development of a theoretical framework for resolving the inverse kinematics of the redundant joint MLDUA so as to maximize the distance between the robot and waste surface, avoid joint limits, minimize the oscillations of the arm, and avoid collisions between the arms and the tank walls.
2. Increase redundancy: Preliminary simulation studies show that during some operations, only five or fewer of the robot's Cartesian Degrees of Freedom (D.O.F.) may need to be controlled. Control of all six cartesian degrees, under certain conditions, drives the system into singularities.
3. Cooperative control: Develop new active control strategies for a dual-arm system and compare them with the currently existing strategies with HMA being passive.

Successful accomplishment of these goals will first show the need for proper utilization of redundant degrees-of-freedom of MLDUA for operation in confined spaces such as underground waste storage facilities. Secondly, this work will demonstrate the potential benefit of active dual-arm control over the existing active/passive strategy adopted for the tank waste retrieval program.

II. SIMULATION TOOLS

The Robotics and Process Systems Division (RPSD) at ORNL has developed a number of simulation tools to aid in investigating any potential problems that may arise during the remediation process.[1] An integrated system model of the hardware, illustrated in Fig. 1, is presently operational under the TeleGrip[a] simulation 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.

A. Modified Light Duty Utility Arm

The large volume and small access ports in the tanks requires 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 providing ORNL a robot that achieves each of these requirements. The MLDUA is an 8-D.O.F. manipulator that has a 15 ft. reach and 200 lb payload capacity. Furthermore, the robot has a maximum cross-section diameter of 9 in., ensuring easy access into any of the ORNL tanks.[9]

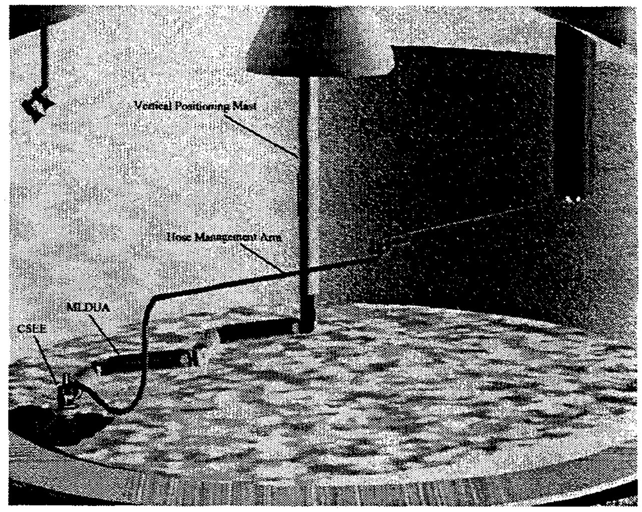


Figure 1: Gunite tank and associated remediation hardware

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 MLDUA

The second robot deployed during the remediation process is called the HMA. This arm has 4-D.O.F. and is used to carry a hose and CSEE. The CSEE has a vacuum pump as well as a rotating head with high-pressure water jets. The combination of water jets and vacuum enable the CSEE to break up a wide range of solids and transport the waste from the tank, through a companion hose, through the HMA, and into a safer, secondary storage facility.

[a] TeleGrip is a versatile graphical and dynamic robotic simulation package produced by Deneb, Inc.

To better understand the coordinated motion of the MLDUA and HMA, a comprehensive modeling effort 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 ability to solve for the kinematics of the hose and HMA without having a dynamic model of the MLDUA. The strategy for dynamic simulation consists of treating the tip position of the MLDUA as an input device to 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 and HMA from an equilibrium. The dynamic model of the HMA and hose are used in the computation of the hose and HMA response to motion of the MLDUA. The simulation system reported in Ref. 1, serves as the test environment for our strategies.

III. REDUNDANCY RESOLUTION

One of the primary issues related to the hardware is redundancy resolution. Several performance criteria[3-5] are available for optimal redundancy resolution of manipulators with redundant degrees-of-freedom. Issues related to simultaneous optimization of multiple performance criteria, optimization of multiple degrees of redundancy, design of redundant joints, variable task space, joint and actuator velocity and torque limits, joint limit avoidance, obstacle and singularity avoidance, etc., have been addressed in several publications.[6-8, 11,12] The following section describes a few approaches and their potential relevance to the waste removal program at ORNL.

A. Historical Perspective

Only six joints are necessary in general for a manipulator to arbitrarily position and orient its end-effector in its workspace. In that case, as shown in Fig. 2, motion of the manipulator's elbow is possible without corresponding motion of the end-effector position, allowing avoidance of joint limits, obstacles, and singularities. Redundancy can also be used to improve mechanical advantage, increase manipulator stiffness, etc.

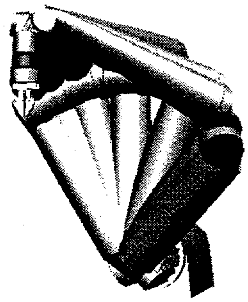


Figure 2: Redundancy in the RRC joint limit avoidance

One approach for avoidance of joint limits is with a variable-weighted least-norm solution.[2] This approach avoids the problems encountered with the traditionally used gradient projection and standard-weighted least-norm methods. In gradient projection methods, the gradient of a performance criterion based on joint limits is projected onto the null space of the Jacobian to obtain the necessary elbow motion. A weighted least-norm solution was originally implemented by Whitney,[10] who used it for redundancy resolution, while Hollerbach and Suh used a similar technique for joint limit avoidance. The variably weighted least-norm solution that was developed and implemented in our laboratory penalizes the motion of an individual joint more heavily based on its distance to a joint limit. This method has several distinct advantages over traditional methods.

Comparison of joint motions for traditional redundancy resolution schemes [i.e., least-norm solution (LN) and gradient-projection method (GPM)] are made with variable-weighted least-norm (WLN) are made in Fig. 3. The trajectory was selected such that both joints 2 and 3 were close to their limits, thus making the task of optimization relatively difficult. As shown in Fig. 3, the trajectory has to go through a narrow valley created by the cost function to avoid both joint limits. This is not achievable by LN solution, and GPM results in large oscillations unlike WLN, which avoids joint limits with a smooth trajectory. There are several clear advantages of WLN over LN- and GPM-based schemes. It uses self-motion only when necessary, thus resulting in lower joint motion cost. It guarantees joint limit and obstacle avoidance. The variable WLN-based method adjusts the magnitude of the self-motion automatically based on the need. It is well suited for teleoperation since it eliminates the elbow or self-motion of the slave manipulator when there is no master motion.

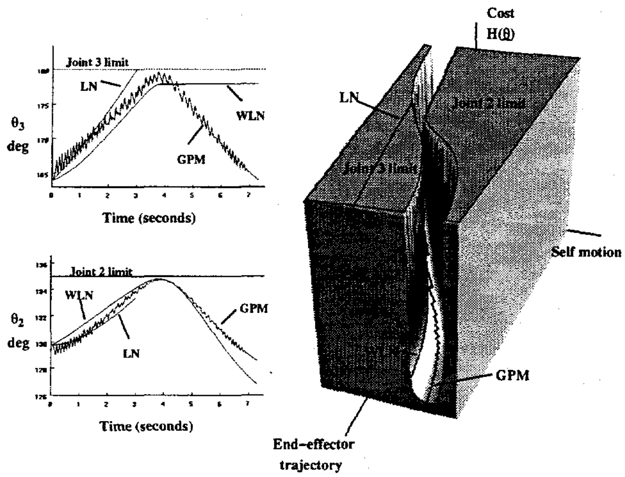


Figure 3: Comparison of WLN with LN and GPM

B. Variable-Dimension Task Space for Collision Avoidance

In general, robot manipulators are programmed to control the position and orientation of the end-effector. For a general purpose robot, this requires controlling six coordinates. However, several tasks do not require controlling all six coordinates. For example, in the case of MLDUA, the wrist yaw could be neglected, thus requiring only five coordinates to be controlled. Figure 4 shows one scenario where command of the MLDUA's wrist yaw is not necessary and can cause the robot to reach joint limits.

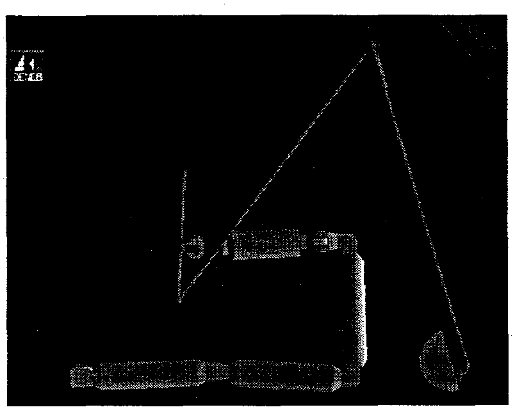
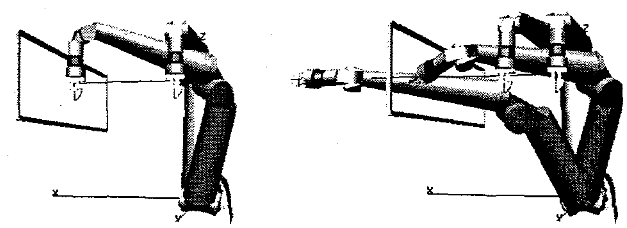


Fig. 4: Joint limits with 6 cartesian D.O.F.

Similarly, for a robot holding a symmetrical tool, the wrist roll could be ignored. This provides an additional degree-of-freedom to be used for other objectives such as obstacle avoidance and joint limit avoidance. As shown in the left simulation of Fig. 5, if both position and orientation of the RRC manipulator are controlled while following a given straight-line trajectory going through a window, the manipulator hits an edge of the window before reaching the desired end point. On the other hand, if only the hand position is controlled and orientation is ignored, three additional degrees of redundancy are available for obstacle avoidance. This lets the manipulator reach the desired end point without hitting the edge of the window. We have developed a scheme that smoothly switches between different task spaces such as from six-dimensional task space to the three-dimensional task space in this example.



position and orientation control (6x7 Jacobian)   position control only (3x7 Jacobian)

Figure 5: Obstacle avoidance with variable-dimension task space

C. Obstacle Avoidance Using Ultrasonic

1. Sensors

We have implemented a redundancy optimization scheme in teleoperator mode for obstacle avoidance using ultrasonic sensors on the fourth joint (the elbow) of the RRC manipulator as shown in Fig. 6. Whenever the sensor indicates that an obstacle is near, the elbow is rotated away from it, without disturbing the operator-commanded motion of the end-effector. Thus the burden of obstacle avoidance is partially lifted from the operator.

There are two potential scenarios where this has an impact on waste removal, collision between the arms and collision between either of the arms and the tank wall.

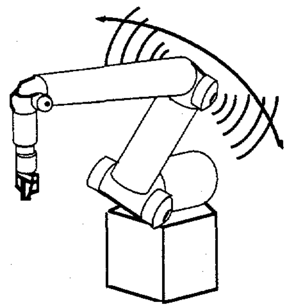


Figure 6: Obstacle avoidance using ultrasonic sensor

D. Arm and Tank Collision Avoidance

Performance criteria can be developed to avoid collision of MLDUA and HMA with each other and tank walls. These criteria will be determined based on the dimensions of the tank and MLDUA and HMA kinematics. These criteria are likely to be complex because of changing kinematic configurations of the MLDUA and HMA; therefore, they will have to be simplified so they can be optimized in real time. Redundancy will be utilized for the optimization of these criteria. Figure 7 shows a likely scenario where the hose management arm can collide with the tank walls.

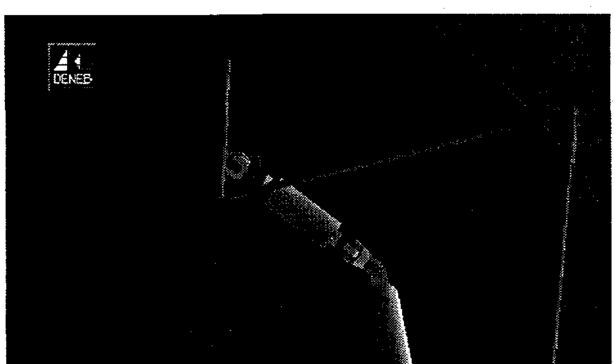


Figure 7: Collision with tank

The existing Spar redundancy resolution calls for the arm to take a Scara configuration. Figure 8 illustrates an example configuration when the arm moves near the waste surface. It is evident from this picture that a large portion of the robot's arm will always be close to the surface of the waste. This may not be desirable. There is a potential for collision with in-tank hardware, solid waste, and other debris that may be located near the surface of the waste. Alternative inverse kinematics solutions are sought that could adopt different criteria. One example could be identifying the joint configuration that maximizes the distance between the waste surface and the links of the robot.

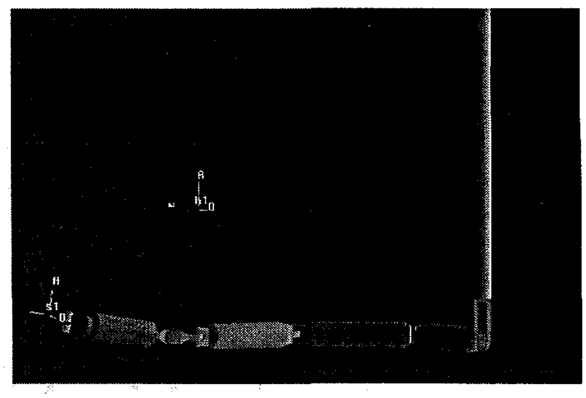


Figure 8: SCARA configuration near waste

E. Simultaneous Optimization of Multiple Criteria

1. Performance Criteria

In a "real-world" application of a robot manipulator with redundant degree-of-freedom, it is important to utilize the redundancy to simultaneously avoid obstacles, joint position and velocity limits, torque limits, singularities etc., while following a desired end-effector trajectory. If the manipulator is not near any of the above hardware limits or obstacles, the redundancy may be utilized to follow a desired end-effector trajectory in an efficient manner, for example, with least movement of joints or with higher mechanical advantage. In order for a manipulator to utilize the redundancy in this manner, several performance criteria need to be optimized simultaneously.

We have defined performance criteria corresponding to joint position limit, joint velocity limit, etc., in such a way that their weights automatically go up when the corresponding limits are approached. A simple example of such a function would be the inverse of the square of the joint position distance from its limit. It is also important to assign different weights to the performance criteria according to how critical some performance criteria may be compared to others. For example, avoiding obstacles could be considered more critical compared to joint velocity or torque limits. While hitting an obstacle could damage the manipulator, reaching a joint velocity limit would merely produce an end-effector trajectory error, since such a velocity is not physically realizable. On the other hand, higher efficiency and mechanical advantage may not be critical to the manipulator's operation but are desirable for improved performance.

Because of numerical values of means, maximum values, and ranges of performance criteria being equal to infinity most of the time, normalization with respect to these variables becomes impossible. We have developed a new scheme[7,8] in which the performance criteria are normalized such that the probability functions of the gradients projected onto the null space have the same distribution.

IV. COOPERATIVE CONTROL

Presently, it is planned to control the MLDUA and HMA such that the MLDUA acts as a leader and HMA follows it passively. However, there is a potential problem with the integrated hardware because of the dynamics of the combined MLDUA/HMA. Figure 7 illustrates a potential collision between the HMA and the tank's walls. Cooperative control strategies can ensure a number of critical criteria. First, it is desirable to reduce the interaction forces between the HMA and MLDUA. Furthermore, some hose configurations can possibly submerge portions of the hose in the waste, increasing the potential for binding the hose on submerged hardware. Preliminary simulation studies show that a simple control strategy based upon the tip position of the MLDUA and an optimal horizontal displacement of the hose can ensure low bias forces as well as reduced hose motion. Figure 9 illustrates the motion of the combined system during a straight-line motion when the system is operated in passive mode. Furthermore, Fig. 10 shows the interaction force between the HMA and hose during operation. Since the HMA is passive, the horizontal distance between the tip of the HMA and MLDUA will vary, thus stretching the hose and increasing interaction forces. Next, we execute the same maneuver with an active control scheme that not only tracks the tip position of the MLDUA but tries to maintain a constant standoff distance between the MLDUA and HMA. By controlling the standoff distance, and thus the contour of the hose, we are able to not only minimize the interaction forces but variations in the forces as well. Figures 11 and 12 illustrate the resultant motion and force profile of the actively controlled system respectively.

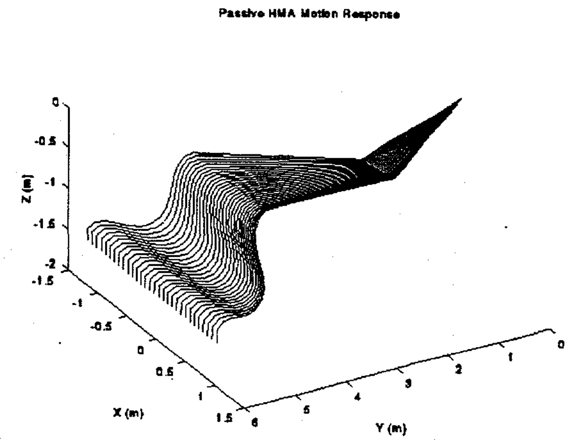


Figure 9: Motion of HMA and hose during passive operation

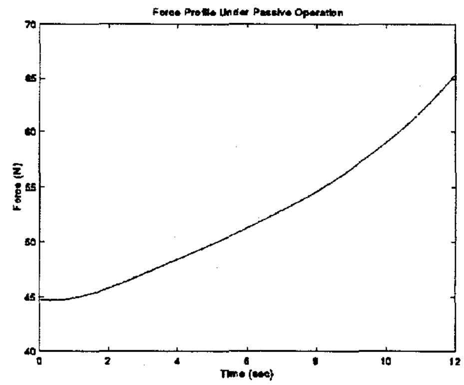


Figure 10: Force on HMA during passive operation

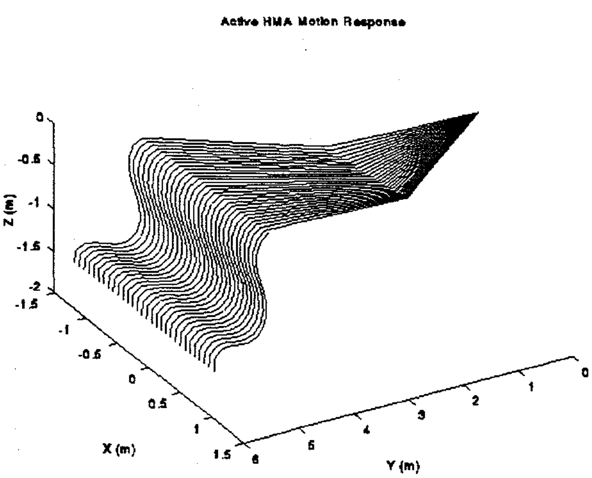


Figure 11: Motion of HMA and Hose during Active Operation

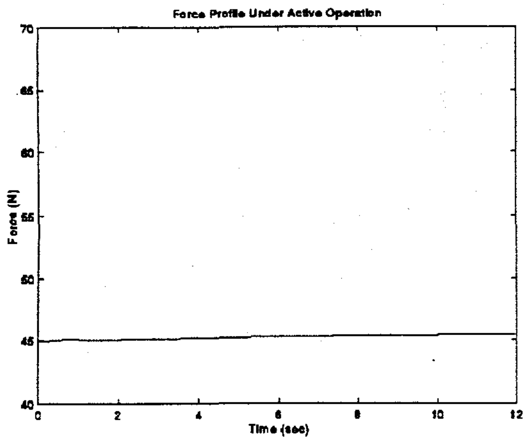


Figure 12: Force on HMA during active operation

CONCLUSIONS

This manuscript describes the basic components of a relatively complex manipulation system used for the remote remediation of hazardous waste. We have tried to describe a number of novel research issues and some of the research currently conducted jointly between ORNL and The University of Tennessee. In particular, we focused on design and control issues related to redundancy resolution and cooperative control. The constraints of an underground storage tank force novel approaches to redundancy resolution in order to avoid collisions with other hardware and the tank, maximize mechanical stiffness during operations, as well as avoid mechanical limits and singularities. Furthermore, we have presented preliminary simulation studies cooperative control of the dual-arm system and the expected advantages.

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