PROPOSED USE OF A VARIABLE GEOMETRY TRUSS MANIPULATOR FOR RADIOACTIVE WASTE REMOVAL FROM UNDERGROUND STORAGE TANKS

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ABSTRACT

The U.S. Department of Energy's Hanford Site's single-shell tank waste problem and some proposed requirements for a waste retrieval manipulator are described. A proposed variable geometry truss (VGT) manipulator is described. The kinematic configuration of the VGT joint and the kinematics of the manipulator are discussed. The developmental needs to field a working manipulator are described.

INTRODUCTION

The cleanup of the single-shell radioactive waste tanks at the Hanford Site will require a rugged, reliable retrieval system that is sufficiently adaptive to handle the many types of waste materials and equipment in the tanks. This paper proposes using a novel type of long-reach manipulator as the primary delivery system for waste removal operations. The proposed manipulator would be capable of positioning a number of different end-effectors, or, perhaps, a secondary, dexterous manipulator, for waste retrieval.

The demanding physical requirements for accomplishing the waste removal task mandate that the manipulator be constructed to provide for a very long-reach (approximately 40 ft), while maintaining the positioning accuracy of a substantial payload (perhaps as large as 1000 lb). Clearly, the critical design components for such a manipulator are the joints, which must withstand tremendous forces and torques. One possible solution to the need for very strong joints is to use variable geometry trusses (VGT's) as the active joints. A VGT is a truss in which some struts are capable of changing length; these extensible struts enable the truss to alter its shape in a precise, controllable manner. Figure 1 shows the extensible struts on a VGT at the National Aeronautics and Space Administration (NASA) Langley Research Center. Like an ordinary static truss, the struts of a properly designed VGT will be loaded only in pure tension or compression, a condition which results in the most efficient (least weight) structure to carry a given load. Figure 2 represents a conceptual schematic of the proposed waste removal manipulator in a storage tank.

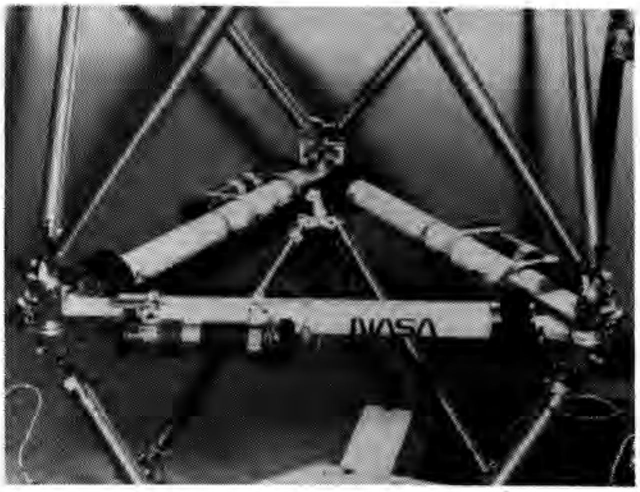

Fig. 1. Extensible struts on a VGT at NASA Langley Research Center.

Simple VGT's are actually quite common and have been employed in engineering applications for decades. Many common configurations of draw bridges and construction cranes can be classified as VGT's. However, most of these applications utilize a VGT element only as a single degree-of-freedom mechanism. This trend remained unbroken until 1965 when Stewart (1) proposed a six degree-of-freedom (DOF) "platform type" manipulator. Although Stewart's specific geometry was technically not a VGT, this initial proposal illustrated that it was possible to construct a parallel (more than one load path to ground) manipulator capable of positioning and orienting a platform in 3-D space.

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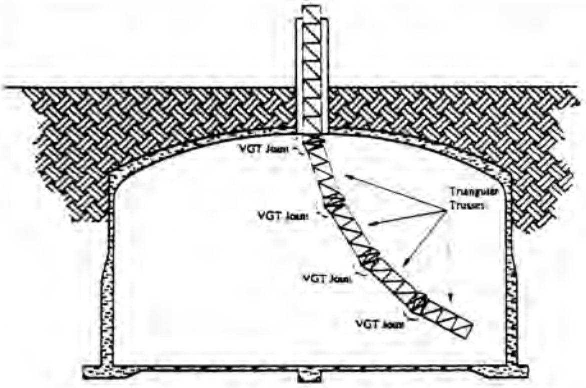


Fig. 2. Schematic of a VGT manipulator in a waste tank.

Recent developments concerning VGT manipulators have received much attention from NASA (2). NASA's primary interest involves the use of VGT segments that could be used to damp spacecraft vibrations (3,4,5,6,7). Also, researchers have investigated the possibility of constructing long-chain robotic manipulators for automated assembly and other robotic applications (8-13).

BACKGROUND

Hanford Waste Tanks

The Hanford Site contains 149 single-shell, carbon-steel-lined, concrete underground radioactive waste storage tanks built between 1943 and 1964. Twenty-five of the tanks are of about 1,000,000 gal capacities; 48 tanks, about 750,000 gal; 60 tanks, about 500,000 gal; and 16 tanks, about 55,000 gal. The 55,000 gal tanks have a diameter of 20 ft and a height of 25 ft; the 500,000, 750,000, and 1,000,000 gal tanks have diameters of 75 ft and wall heights of about 18, 24, and 32 ft, respectively. The tanks are buried 5 to 12 ft underground to provide radiation shielding.

The waste consists primarily of chemicals from the chemical separation of reactor fuel during the production of plutonium for the nation's nuclear weapons program. The bulk waste is in physical forms ranging from thick, sticky sludge described as being like peanut butter to saltcake described as being as hard as concrete. There is a small amount of supernatant liquid as well as some liquids in pockets in the saltcake. In addition to this chemical waste, the tanks contain hardware of various sorts. For example, most tanks contain numerous vertical pipes, called risers, that penetrate from the dome into the tank to various depths; common diameters are 4, 12, and 42 in., with other diameters occurring less frequently. Others contain air circulators from past cooling operations, as well as pumps and pump shafts. In addition, many tanks contain numerous long, steel tapes, level instruments and other contaminated scrap. Some tanks contain unusual items, such as tank 101-U which contains a small amount of experimental reactor fuel and slugs with kilocurie amounts of Co-60. It is believed that other articles were discarded in the tanks and never recorded.

In addition, a number of the tanks contain materials that present special hazards. Twenty-four of the tanks contain ferrocyanide material that is believed to be potentially explosive at elevated temperatures. Twenty-three tanks have the potential for hydrogen accumulation above the lower flammability limit, and 11 tanks generate enough heat from radioactive decay to require forced-air cooling.

Tri-Party Agreement

The Tri-Party Agreement (formally the *Hanford Federal Facility Agreement and Consent Order*) is an agreement among the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the Washington State Department of Ecology that has as its ultimate objective the cleanup of the Hanford Site. Attachment 2 to this Agreement defines the procedures to be followed in pursuit of this objective and delineates specific, enforceable milestones. Three of the major milestones directly effecting the development of the single-shell tank waste retrieval system are M-06-00, which requires the development of single-shell tank waste retrieval technology by June 1994; M-07-00, which requires the initiation of full-scale waste retrieval technology by October 1997; and M-08-00, which requires the initiation of the full-scale tank farm closure demonstration by June 2004.

MANIPULATOR REQUIREMENTS

The requirements for the waste retrieval system for the single-shell storage tanks have not yet been determined. However, the requirements listed below are believed to be sufficiently comprehensive and stringent to assess whether a VGT manipulator can reasonably be used for that purpose.

- ACCESS TO THE TANKS. The manipulator must enter through a 42-in. hole in the top center of the tank. For the purpose of this requirement, all obstacles presently in the worse-case tank will be assumed to be present, and the tank will be assumed to be full to within 1 ft of the top of the liner.
- END-EFFECTOR POSITIONING. The manipulator must be capable of positioning an end-effector at any point within the tank and at any point up to 0.61 m (2 ft) beyond the tank liner.
- CAPACITY AT FULL EXTENSION. The manipulator must be capable of supporting 1000 lb at full extension.
- STABILITY AND CONTROLLABILITY. The manipulator must remain stable and controllable under all conditions expected to occur in the tank.
- DEXTERITY. The manipulator must be sufficiently dexterous to accomplish these tasks: to smoothly cut a 12-in. riser pipe with an abrasive water jet at full manipulator extension; to load and unload an abrasive water jet jig onto a 42-in. riser; to cut irregularly shaped equipment in the tank with an abrasive water jet; and to apply a CO_2 pellet stream to all points on the tank liner.
- CORROSION RESISTANCE. The manipulator must be constructed of materials which are resistant to corrosion in the tank environment.
- RADIATION RESISTANCE. The materials subject to radiation damage must function normally after receiving an absorbed dose of 10^5 Gy (10^7 rad). The manipulator will function normally in a radiation field of 1.67 Gy/s (10^4 rad/h).
- WITHDRAWAL AFTER A SINGLE FAILURE. The manipulator must be capable of being withdrawn

from the tank after the failure of any single component.

- REPLACEMENT OF FAILED COMPONENTS IN THE TANK. To the extent practical, failed components should be replaceable in the tank without withdrawing the manipulator.
- CLEANING AND GROSS DECONTAMINATION. The manipulator must be designed and constructed to enhance cleaning and decontamination, and will be capable of being cleaned and grossly decontaminated in the tank prior to removal.
- NON-INFLAMMABLE HYDRAULIC FLUID. The manipulator, if hydraulically powered, must use non-inflammable hydraulic fluid.
- EXPLOSION SAFETY. The design of the manipulator must be compatible with an explosive environment.
- VIBRATION CONTROL. The manipulator should be capable of efficiently attenuating vibrations resulting from manipulator movements and, also, of attenuating vibrations resulting from the waste removal operations.

THE PROPOSED VARIABLE GEOMETRY TRUSS MANIPULATOR

The proposed manipulator consists of alternating sections of static truss links and active, 3-DOF, hydraulically driven, VGT joints. The static sections are in the shape of triangular prisms nominally 7 ft in length and approximately 30 in. or less across each prism face. This specific geometry for the static section is presented in Figs. 2 and 3; however, it must be noted that other geometries are possible for the static sections. The VGT joint is composed of two octahedral cells joined together so as to share a common face, which is defined by the three extensible struts; this specific geometric configuration is termed a "double-octahedral" truss. Together, one active joint and one static link constitute a manipulator module, Fig. 3.

The modular structure of the manipulator presents advantages for waste tank retrieval. With this configuration, it is possible to change the geometry of the manipulator by substituting different length static elements or even changing the total number of modules present in the chain. Thus, the manipulator geometry can be altered onsite to adapt to unforeseen obstacles or other complications. Further, the modular structure also ensures that damaged or worn components can be exchanged to avoid a prolonged maintenance downtime.

The truss structure itself is advantageous, because, unlike conventional manipulators, it has an open framework that can be used for materials delivery or cabling for instrumentation and control. The exterior of the manipulator structure and the covering to control contamination would shield the more vulnerable components from abrasion and other hazards. Additionally, the parallel nature inherent in truss design ensures that the manipulator can be recovered in the event of a single structural or actuator failure.

In addition to their advantages, there are some disadvantages associated with the use of VGT manipulators. The positional control strategies, which are relatively simple for conventional manipulators, become much more complicated. As a result, any type of manual control of the manipulator must either be computer assisted or accomplished very slowly. In addition, the design and manufacturing of the mechanical joints for the VGT modules are also more difficult than conventional designs; these joints must be both strong and compact to function properly.

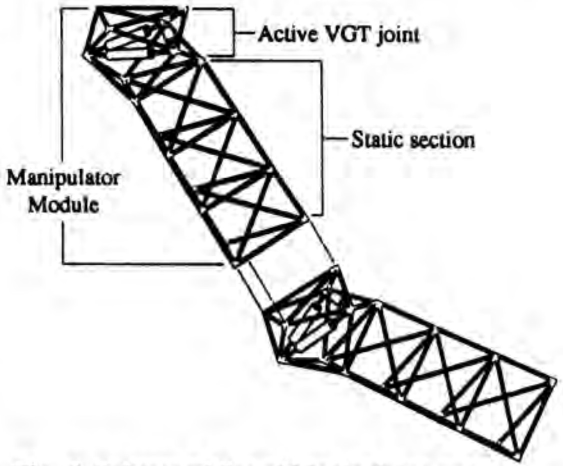


Fig. 3. Subassemblies of Manipulator system.

The following sections introduce the specific geometry proposed for the VGT joints and provide a basic description of the manipulator's kinematic properties.

Kinematic Configuration for the VGT Joint

Figure 4a presents a schematic illustration of a hydraulically actuated, double-octahedral, VGT joint. If the three members shared between the two octahedra are varied in length, a 3-DOF VGT results. With this VGT it is possible to independently control any three parameters of the position and orientation of the top face relative to the bottom face. Thus, for example, the x, y, z position of point P can be varied relative to a fixed coordinate frame $\{R\}$. Another possibility, useful for this particular application, for the three independent parameters is to specify the direction of a normal to the top face, $\hat{n}$ (as given by the two angles α & β) and a third scalar quantity representing the length of the joint, d. This parameter specification set (the normal and the length of the joint) exactly emulates the motion of a simple Hooke's coupling universal joint (14); however, the VGT possesses far superior structural properties to the Hooke's coupling. Figure 4b illustrates the parameters used in defining the Hooke's coupling model. It is possible to calculate, in closed form, the values of α, β and r that result from a specified set of strut lengths. Furthermore, it is also possible to determine, again in closed form, the set of strut lengths that will result in a desired set of α, β and r (14).

This particular geometry, a double-octahedral cell, was selected because it is believed, based on the authors' experience with similar applications, to be one of the best geometries for this type of application. However, a thorough evaluation of all possible geometries is necessary to ensure that this assumed geometry is the best for the intended task. Also, the optimum lengths for the unactuated members within the VGT joint must also be identified.

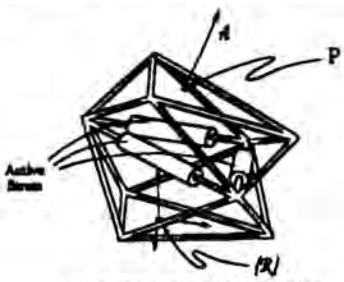
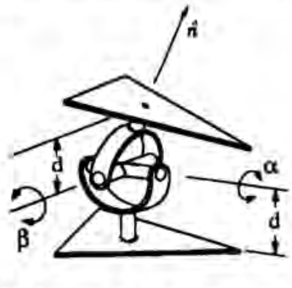


Fig. 4a. Schematic of a VGT joint.



b) Activated Hooke's Coupling model of VGT joint.

Fig. 4b. Actuating Hooke's Coupling Model of a VGT joint.

Manipulator Kinematics

The kinematic analysis of this manipulator can be viewed as two distinct problems: the forward kinematic analysis (used for position verification) and the inverse kinematic analysis (used for positional control).

The forward kinematic solution, for this manipulator, consists of finding the position and orientation of every member given the length of each extensible strut. The problem may be solved by considering the entire manipulator to be a chain of subcomponents. In this particular case, the geometry of every subcomponent is known. Therefore, it is possible to start at the grounded end of the manipulator and, progressing along the chain, calculate the position and orientation for every member of the chain.

The inverse kinematic solution consists of finding a set of variable strut lengths that will position and orient the last link in a specified manner. This is a much more difficult task than the forward kinematic problem. The manipulator described is kinematically redundant; it contains twelve degrees-of-freedom while the task specification requires only five degrees-of-freedom (three for position and two for orientation of the axis-symmetric tool). This specific manipulator is, therefore, said to have seven redundant degrees-of-freedom. In terms of the inverse kinematics, this means that there are seven implicit unknowns that must be somehow specified. The implicit unknowns could be specified by evaluating many values and selecting the one solution that results in an optimum configuration. This optimum configuration could be selected on the basis of strength, dynamic characteristics, or some other objective function. This approach requires vast computational resources and would probably slow the operation of the manipulator.

Another, more desirable, approach is to automatically specify the implicit unknowns in a manner that is known to produce practical solutions. For this particular manipulator, it is possible to adopt as a constraint that each active VGT operates like the Hooke's coupling model introduced above. If the length parameter, d, is set to a fixed value, a 2-DOF joint results. By artificially constraining each joint to behave like a 2-DOF joint, the number of implicit unknowns has been reduced to three.

With only three remaining unknowns, optimal solutions become more practical. However, they are still time consuming in comparison to closed-form unique solutions. Unique solutions, although computationally efficient, eliminate the ability of the manipulator to achieve alternative solutions for a given goal position. One attractive possibility is to actively control the number of unknowns while the manipulator is in operation. This is accomplished simply by adding or removing constraints from the system. For relatively uncluttered workspaces, computationally efficient unique solutions could be generated; for more congested workspaces, alternative solutions would be generated, evaluated, and presented to an operator for approval. Approaches of this type have been developed and stimulated successfully for positional control of very high degree-of-freedom manipulators (11).

In summary, it is possible, through the selection of artificial constraints to reduce the number of unknowns, thus easing the computational burden of positioning the manipulator. In critical situations, precise control of a large numbers of degrees-of-freedom will enable the manipulator to avoid multiple obstacles and reach a specified goal. For most general motions of the manipulator, when obstacles do not present a problem, a fast, efficient position control algorithm can be implemented. In a sense, the positional control algorithms are adapting to specific conditions to obtain practical solutions.

Active Vibration Suppression

The VGT joints that are proposed for the manipulator have been studied both analytically and experimentally for their ability to damp vibrations. These studies were directed toward solving the vibration control problem for flexible space structures. The VGT, with an appropriate control algorithm, has been shown to be a much more effective actuator for vibration control than the conventional reaction masses used for space applications (6). Experiments, both at Virginia Polytechnic Institute and State University and NASA Langley Research Center, have demonstrated the vibration control potential of octahedral VGT's in a gravity environment (4,5). Additionally, Warrington et al. (1991)(5) have shown that vibration control algorithms can be placed in parallel with motion control strategies to produce large motions with controllable amounts of added vibration suppression. These vibration control strategies can be extended to controlling persistent disturbances that will result from the waste removal process.

Developmental Issues

The next step in the development of the manipulator concept will involve work along three fronts: geometrical optimization of the manipulator; mechanical design of the manipulator systems; and detailed studies of the control design, including dynamic simulations of the manipulator operation. The geometrical optimization will involve choosing the sizes (both lengths and cross sections) for the longerons, cross longerons, and active battens to balance considerations for the range of motion (workspace) of the manipulator, the strength of links and joints over the workspace, and the dynamic properties of the manipulator. The mechanical design of the manipulator will involve detailed design and selection of the components for the links and the VGT joints. Components to receive particular attention will be active battens, joints in the VGT, and instruments. Detailed control algorithm design will also be carried out to provide both motion control and vibration suppression during the movements of the manipulator and during waste removal operations. Numerical simulations of these processes will be performed to predict the manipulator performance.

CONCLUSIONS

A variable geometry truss (VGT) manipulator is a valid candidate for a manipulator to retrieve waste from Hanford's single-shell tanks. Its strengths are its strength and stiffness per unit weight, its modularity, and its open frame for routing hoses and cables. Its major weakness is the complexity of the control algorithm. Additional work in the areas of manipulator configuration, mechanical design and control design will be necessary to determine if it is a truly valid manipulator for tank waste removal.

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