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A VARIABLE GEOMETRY TRUSS MANIPULATOR FOR POSITIONING LARGE PAYLOADS

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ABSTRACT

A major thrust within the Department of Energy's (DOE) Decontamination and Dismantling (D&D) Robotics program is the development of a Selective Equipment Removal System (SERS). SERS will consist of a mobile vehicle, a Dual-Arm Work Module (DAWM), and a deployment manipulator capable of extending the DAWM up to 6.096m (20') from the vehicle. The DAWM, built by RedZone Robotics, includes two Schilling Titan II manipulators, a unique five degree-of-freedom (DOF) module for positioning/orienting the two Schilling arms, and a massive steel backplane to maintain structural rigidity. Together with its payload, the DAWM weighs about 975 kg (2150 pounds).

In order to accurately position the DAWM, the Pacific Northwest Laboratory (PNL) together with the National Aeronautics and Space Administration's Langley Research Center (NASA LaRC) are developing a deployment manipulator, which includes two double-octahedral Variable Geometry Truss (VGT) modules connected with a static truss section. The entire SERS system (Figure 1) will include the mobile vehicle, a 2-DOF base actuation system (waist rotate and pitch) with an output link approximately 2.134m (7') in length, the VGT system and the DAWM. The VGT system (Figure 2) consists of a 1.067m (42") diameter (~1.346m (53") long) base VGT, which mounts to the end of the output link of the base actuation system, a 1.524m (60") long static truss section which tapers from 1.067m (42") diameter at its base to 0.8128m (32") diameter at the end, and a 0.8128m (32") diameter (~1.0922m (43") long) tip VGT to which the DAWM is mounted. The stiffness of the VGT system is such that with the base VGT mounted to a rigid base and the VGT system oriented horizontally (worst case), the static deflection of the DAWM together with full payload will be less than 0.0254m (1").

INTRODUCTION

The double-octahedral VGT (hereafter referred to simply as VGT) is a truss module in which three central cross struts, or battens, are replaced with hydraulic cylinders. Each VGT thus possesses three DOFs. The VGT is kinematically equivalent to an extensible universal (Hooke) joint; that is, it can extend/contract along its main axis, and pitch and yaw about any axis perpendicular to its main axis. The VGT also includes two sets of six struts (longerons). One set of longerons connects the actuated battens to the base of the VGT, while the second set connects the actuated battens to the distal end of the VGT.

The VGT-based manipulator structure offers several advantages over conventional serial manipulator structures for long-reach, large load-carrying applications. As with static trusses, all links of the VGT are essentially in tension or compression only. This allows the truss-based structure to realize the strength and stiffness requirements for accurately positioning heavy payloads at much lower weight than that required for a serial structure, in which links are loaded in combined tension/compression, bending, torsion, and shear. Also, the parallel structure of the VGT allows multiple links and actuators to share the supported load. In a conventional serial structure, each link and actuator must support the entire load, plus the load of the distal part of the manipulator, by itself. Thus, the VGT actuators can be smaller, and operate at a higher bandwidth because of the reduced inertial load.

Another advantage of the truss structure is that the open center of the truss structure provides an unobstructed, protected, central passageway for cabling and utilities required for special-purpose end effectors or tooling. This simplifies the cable-handling problem, and greatly increases the overall reliability of the system.

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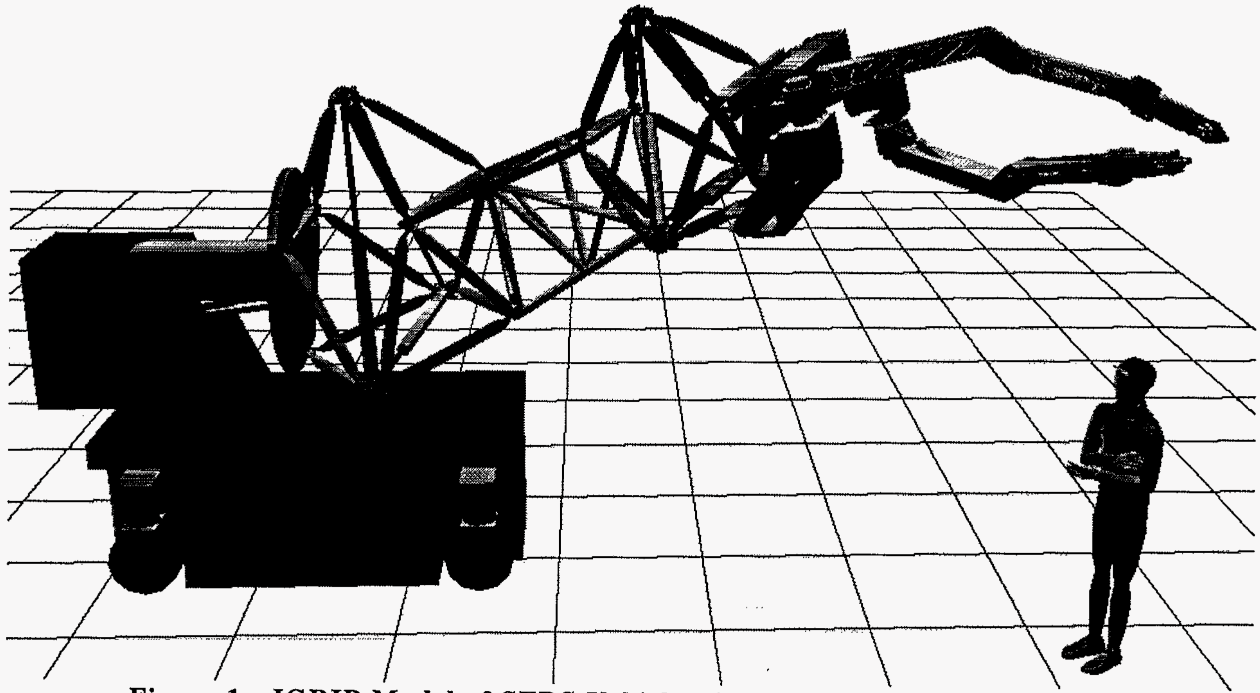

Figure 1 - IGRIP Model of SERS Vehicle with VGT Positioner and DAWM

BACKGROUND

Simple VGTs are actually quite common and have been employed in engineering applications for decades. Many common configurations of construction cranes, draw-bridges, and similar devices can be classified as VGTs. However, most of these common applications utilize a VGT element as a single DOF mechanism. Stewart's early work, although technically not a truss structure, illustrated that it was possible to construct a fully parallel manipulator capable of positioning and orienting a platform in six-dimensional space [1].

In the early eighties, NASA became interested in developing deployable space structures [2]. NASA had many applications in space that required very large, stiff structures. A natural choice for such structures is a static truss. However, because of transport problems, these large structures must either be assembled in space or be transported in a compact form for later automatic deployment. Typically, these deployable structures become static once locked into their extended position.

While investigating possible geometries for these deployable structures, Rhodes and Mikulas [3] discovered that one certain geometry of deployable truss (the double-octahedral) had properties that made it suitable to act as a three DOF spatial manipulator. This was the first true VGT manipulator concept. Refinements were later made by Rhodes and Mikulas, in conjunction with Sincarsin [4], that led to the development of a working proof-of-concept model. This model not only solved many of the complex joint geometry problems, but also successfully demonstrated the potential usefulness of these devices. This insight made possible the work of Miura and Furuya [5], and Miura et al. [6], who analyzed the kinematics of a double-octahedral VGT. This early analysis work was later extended by Gokhale and Reinholtz [7], and Padmanabhan et al. [8]. The research of Padmanabhan is particularly interesting in that it identified several tasks for which a symmetric double-octahedral truss was well suited. This work then presented closed-form solutions to these tasks. Further refinements of the physical manipulator design were achieved by Tidwell et al. [9,10]. This work included the development of design curves that enabled quick evaluation of the potential motion of a double-octahedral VGT.

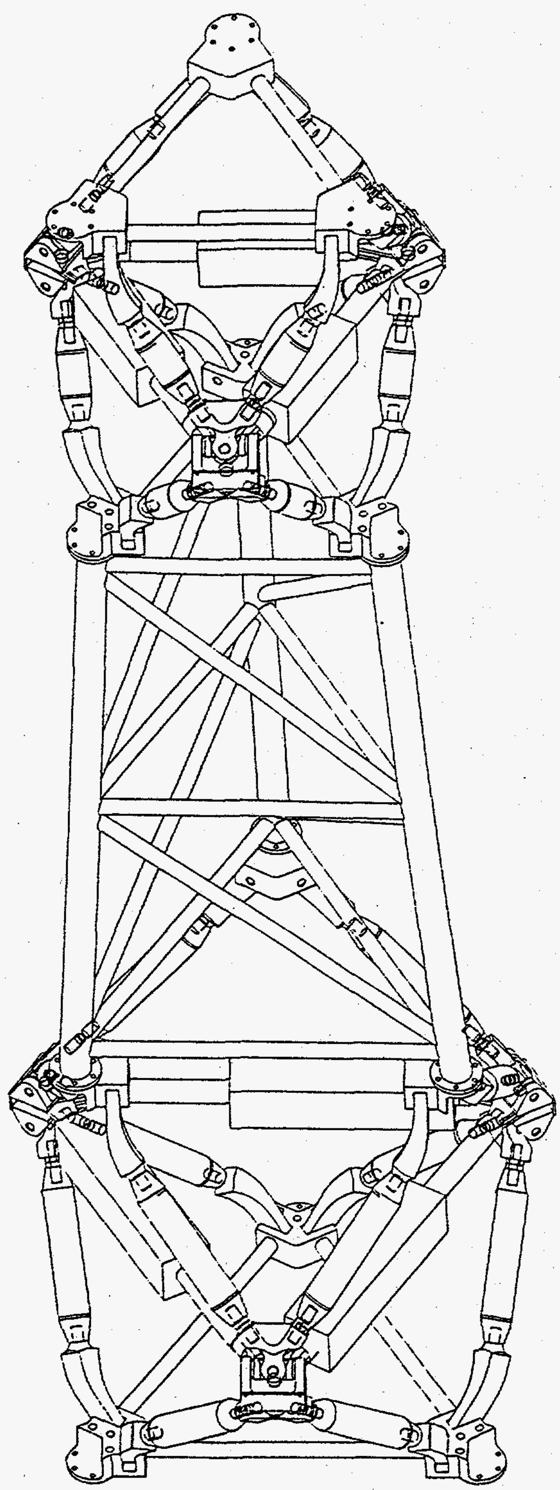

Figure 2 - NASA LaRC's Pro-Engineer Model of VGT Portion of Heavy Manipulator

Simultaneous with the development of the double-octahedral truss model, Sincarsin and Hughes [11] also explored the characteristics of four other candidate geometries. Their evaluations concluded that the double-octahedral geometry was indeed the most favorable geometry. Of primary interest in this study was the issue of collapsibility. Therefore, it should not be assumed that this is the best geometry for all applications. Jain and Kramer [12] also investigated another possible geometry and completed the design of a tetrahedral/tetrahedral VGT.

Other research concerning the use of a VGT cell as a replacement for more conventional devices has been conducted by Nayfeh [13], Clark and Robertshaw [14], and Wynn and Robertshaw [15]. Nayfeh investigated the kinematics of a foldable, revolute jointed space crane composed of several essentially planar VGT cells. The analysis undertaken was limited to only one of the proposed cells. Clark investigated the use of these VGT modules for actively damping vibration in large-truss structures. This study dramatically illustrates the superiority of VGT actuators over conventional proof-mass-type actuators for vibration control. This work was extended to the control of vibrations in spatial structures by Wynn in 1990. This last work included an impressive experimental demonstration of vibrations being actively controlled by a spatial VGT manipulator.

VGT KINEMATICS

The geometry of an individual VGT unit is shown in Figure 3. A minimal set of parameters, which completely describe the kinematics of the VGT unit, is the following:

B = fixed batten length,
L = (fixed) cross longeron length, and
l_1, l_2, l_3 = length of actuated battens.

These five parameters serve as input for the forward kinematics problem, which is to find the positions of all of the nodes of the VGT, given the actuated batten lengths (l_1, l_2, l_3). In the inverse kinematics problem, the extension and articulation angles of the truss are given, and the corresponding actuated batten lengths are found. Both the forward and inverse kinematic problems have been addressed in detail in the works described above. The inverse problem is readily solvable in closed form, while the forward problem, in general, required the simultaneous solution of three nonlinear equations.

In order to determine the motion range, or workspace, of the VGT, the actuator motion range must be specified, typically as the minimum actuated batten length (l_{min}), and the

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stroke length (S). It is convenient to express the geometric parameters B and L in terms of:

$$D = \frac{2\sqrt{3}}{3} B$$

= base diameter, and

L/B = longeron to fixed batten length ratio.

The base diameter D then becomes a scale factor, and the critical parameters for describing the workspace (in terms of angular motion range) are the ratios L/B, and the actuator stroke to length ration S/l_{min}. Given an actuated batten stroke to length ratio of 0.75, the achievable angular motion ranges in terms of L/B are given in Table 1.

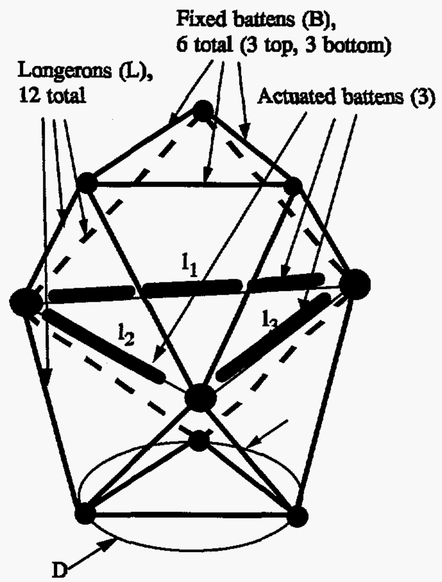

Figure 3 - Basic Geometry of the VGT

Table 1 - Angular Range of Motion vs. L/B ratio

Maximum Articulation Angles (degrees)[1]

L/B	Max	Min	Avg
0.95	82.9	65.0	71.2
1.00	72.8	55.9	61.6
1.05	65.6	49.8	55.0
1.10	60.1	45.2	50.1
1.15	55.7	41.6	46.2
1.20	52.0	38.7	43.0
1.25	48.9	36.2	40.3
1.30	46.1	34.0	38.0
1.35	43.7	32.2	35.9
1.40	41.6	30.6	34.1
1.45	39.7	29.1	32.5
1.50	38.0	27.8	31.1

[1]Assumes 75% elongation of actuated battens

MANIPULATOR ANALYSIS AND DESIGN

The conceptual design of the complete SERS system, including mobile vehicle, VGT-based heavy manipulator, and DAWM is shown in Figure 1. A ProEngineer 3-D drawing of the VGT portion of the heavy manipulator alone is shown in Figure 2. The VGT portion of the heavy manipulator consists of two VGTs separated with a static truss section. The average length of this VGT portion is approximately 3.962m (13'), with the capability of extending about 0.3048m (1'). All structural components will be made of 300 series stainless steel. The approximate weight of the system, broken down by components, is given in Table 2.

Table 2 - Estimated Mass of the VGT Portion of the SERS Heavy Manipulator

ASSEMBLY / PART(S)	MASS, KG (LBS) ITEM	TOTAL
Root VGT		
Root VGT Interface	124 (273)	
Cross longerons (12)	91 (201)	
6 Element joints (3)	35 (76)	
Actuators(3), est.	148 (325)	
Root VGT Total		398 (875)
Static Truss		
Longerons	66 (146)	
Battens	35 (77)	
Diagonals	35 (78)	
Static Truss Total		137 (301)
Tip VGT		
Tip VGT Interface	124 (273)	
Cross longerons (12)	65 (143)	
6 Element joints (3)	35 (77)	
Actuators (3), est.	147 (324)	
Root VGT Total		371 (817)
Total System Weight		906 (1993)

The overall dimensions are presented in Table 3. Because of the high loads on the actuators and mechanical interference between the actuated battens and the cross longerons, actuator elongation of 75% was not achievable. The actual actuator stroke, along with the resulting extreme bend angles and member loads, are presented in Table 3.

Table 3 - VGT Manipulator Performance Specifications

	Base VGT	Tip VGT
Diameter (D)	1.067m	0.813m
Fixed Batten Length (B)	0.924m	0.704m
Longeron length (L)	0.879m	0.668m
Min actuated batten length	0.991m	0.747m
Actuator stroke (S)	0.419m	0.249m
Max longeron load	66300 N	25800 N
Maximum actuator load	105900 N	32900 N
Minimum bend angle	33°	24°
Maximum bend angle	40°	28°

Finite Element (FE) analysis was performed in order to better understand the relationships between the fixed and actuated static member loads and geometric parameters, degree of articulation, and loading conditions. Some qualitative observations from generic analysis of individual VGT units include the following:

* All member forces resulting from applied shear or axial loads are independent of the truss diameter (D)

* An applied torque will load the longerons only - no resulting actuator loads

* Both longeron and actuator loads from an applied bending moment vary roughly with 1/D

* Actuator loads increase rapidly as L/B decreases below 0.95

* Articulating the VGT up to 45° increases actuator loads only about 15%.

A detailed FE model of the actual VGT system was developed. Six different configurations, representing worst-case scenarios, were analyzed. The DAWM was included as a 975 kg (2150 lb) point mass centered 0.9144m (3') beyond the end of the tip VGT. The resulting design loads are presented in Table 3.

VGT+SP STRUCTURE

Because of interference restrictions, the angular motion range of the tip VGT is rather limited. A novel manipulator structure, which is an offshoot of the VGT, can be readily incorporated to greatly increase the achievable workspace. Each octahedron of the VGT actually incorporates a Stewart Platform structure. Replacing the distal set of six fixed links with six prismatic actuators results in a combined VGT+SP structure (Figure 4). Combining the two structures results in a new mechanical structure with a much larger workspace (both translational and orientational) than is achievable with a simple summation of the two structures. This unique structure possesses a much larger workspace than is generally achievable with parallel manipulator structures.

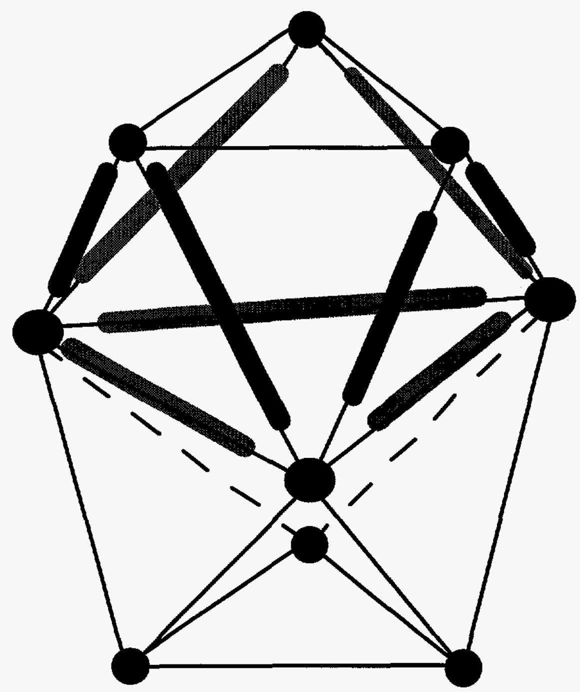

Figure 4 - VGT - Stewart's platform

The redundancy of the VGT+SP mechanism can also be used to advantage. The VGT portion of the structure allows the configuration of the Stewart Platform to be changed "on the fly" from one with a large workspace to one with high dexterity. The kinematics of the VGT+SP structure have been presented elsewhere [16], and are the subject of on-going research at PNL.

CONCLUSION

A novel design for a VGT-based manipulator was presented. The manipulator is capable of positioning the DAWM together with its maximum payload (a combined total of 975 kg (2150 lbs)) anywhere within its workspace. The VGT system will be incorporated into the DOE SERS vehicle to demonstrate remote technology for D&D of contaminated facilities.

Because of the large payload requirements and consequent large-sized actuators, links, and joints, mechanical interference restricts the motion range of the system to about ±40° at the base and ±26° at the tip. This limitation can be overcome by including a Stewart Platform mechanism in the tip VGT.

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