Proceedings of
The 1996 ASME Design Engineering Technical Conferences and
Computers in Engineering Conference
August 18-22, 1996, Irvine, California

96-DETC/MECH-1169

CONTROL OF TRUSS-BASED MANIPULATORS USING VIRTUAL SERIAL MODELS

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ABSTRACT

This paper introduces a novel method for Cartesian trajectory and performance optimization control of kinematically-redundant truss-based manipulators (TBMs), The Virtual Serial Manipulator Approach. The approach is to model complex in-parallel-actuated TBMs as simpler kinematically-equivalent virtual serial manipulators. Standard control methods for kinematically-redundant serial manipulators can then be adapted to the real-time control of TBMs. The forward kinematics transformation can be calculated more efficiently using the equivalent virtual parameters, compared to the computationally intensive in-parallel-actuated forward kinematics transformation. The method is applicable to any TBM whose modules can be modeled as a virtual serial chain. It also handles TBMs constructed of dissimilar modules, and compound manipulators with serial and in-parallel-actuated joints. The method is applicable for any level of kinematic redundancy.

1. INTRODUCTION

Truss-Based Manipulators (TBMs, also referred to as Variable Geometry Truss Manipulators, VGTMs) are statically determinate trusses where some of the members are linear actuators, enabling the truss to articulate. Such devices have been proposed for a variety of tasks, including remote nuclear waste remediation (Salerno and Reinholtz, 1994, and Stoughton, et.al., 1995) and space cranes (Chen and Wada, 1990). The following are characteristics of TBMs that represent potential improvements over the state-of-the-art in large serial manipulators. When properly designed, all TBM members are loaded axially, thus increasing stiffness and load bearing capability with a lightweight structure. They are modular, with kinematically redundant degrees-of-freedom (dof). The redundancy can be used to optimize performance, including snake-like motion to avoid obstacles. A TBM has an open structure allowing routing of cables hoses, and other utilities.

Other authors have worked in the area of Cartesian control of kinematically-redundant TBMs. Several groups of researchers have proposed use of a “backbone curve” to resolve the redundancy of these manipulators. Salerno (1989) uses parametric curves to place the intermediate links of VGTMs, and the solution is achieved by closed-form relationships. Chirikjian and Burdick (1991) use the backbone curve for the inverse kinematics of modular extensible hyper-redundant manipulators. They formulate the algorithm in a manner suitable for parallel computation. Naccarato and Hughes (1991) compare the backbone curve method to a more “traditional” approach to resolving the inverse kinematics for VGTMs. They find reduced real-time computations using the backbone curve method. The backbone curve method is attractive due to low computation and obstacle avoidance, but the method does not admit optimization of other performance criteria such as joint limit avoidance and singularity avoidance.

Salerno (1993) solved the inverse kinematics problem for hyper-redundant VGTMs using the pseudoinverse of the Jacobian matrix and projection of objective function gradients into the Jacobian null-space to achieve performance optimization. Due to the in-parallel-actuated complexity of VGTMs, the Jacobian matrix was derived by numerical differentiation at each control step. Generally, numerical differentiation is to be avoided in digital control applications. However, this work demonstrated that it is possible to control a hyper-redundant manipulator (thirty-dof) via the pseudoinverse in real-time, using a PC-compatible computer. Previous authors have stated that the pseudoinverse is too slow for real-time control; improvements in computer technology are reversing this.

Two groups of researchers have viewed non-kinematically-redundant VGTMs as equivalent serial manipulators. Subramaniam and Kramer (1992) have solved the inverse position kinematics problem for a six degree-of-freedom tetrahedron VGTM analytically by modeling the device as an equivalent manipulator of six revolute joints. Padmanabhan, et. al., (1992) have analytically solved the inverse position kinematics problem for the quadruple-octahedral VGTM by modeling it as a series of two extensible gimbals.

The current paper introduces a novel method for simultaneous trajectory and performance optimization control of kinematically-redundant TBMs. The approach is to model complex in-parallel-actuated TBMs as kinematically-equivalent virtual serial manipulators. A virtual-to-real manipulator inverse mapping is required, but this is accomplished module by module rather than for the entire manipulator. With this paradigm, standard control methods for kinematically-redundant serial manipulators can be adapted to the real-time control of TBMs. The pseudoinverse of the virtual serial manipulator Jacobian matrix (derived analytically) is used, with objective function gradient projection into the null-space for performance optimization.

The method is applicable to any TBM whose modules have a virtual serial model. A survey of active truss modules and their virtual serial models is given in (Williams, 1995). The method is also applicable for any level of kinematic redundancy, from overconstrained (here not all Cartesian dof can be controlled), to non-redundant, to kinematically-redundant, to hyper-redundant.

This paper is organized as follows. The next section presents the general theory for the novel idea. The following section applies the general theory to simulation of a specific 12-dof planar TBM to illustrate the concepts. The conclusion then summarizes the concept and outlines future work.

2. TBM COORDINATION CONCEPT

2.1 Background

Simultaneous trajectory following and performance optimization is obtained for kinematically-redundant serial manipulators via the resolved-rate algorithm, Eq. 1, well-known from the literature (Whitney, 1969, and Liegeois, 1977).

$$\dot{\Theta} = J^{+}\dot{X} + \left(I - J^{+}J\right)z \tag{1}$$

$\dot{\Theta}$ is the required vector of joint rates; $J^{+} = J^{T}\left(JJ^{T}\right)^{-1}$ is the Moore-Penrose pseudoinverse of the manipulator Jacobian matrix; $\dot{X}$ is the commanded Cartesian trajectory, leading to the primary solution for joint rates; and $\left(I - J^{+}J\right)$ is the matrix projecting an arbitrary vector z into the null-space of the Jacobian matrix, known as the secondary solution. If the arbitrary vector is defined as $z = k\nabla H(\theta)$, a user-defined objective function (or combination of functions) $H(\theta)$ can be optimized, where k is an appropriate gain.

The above discussion relates to serial kinematically redundant manipulators. Figure 1 (taken from Salerno and Reinholtz, 1994) shows a candidate TBM. This device has been proposed to remove radioactive waste from buried storage tanks at the Hanford, WA site. The TBM shown has four three-dof modules, for a total of twelve-dof. Each module is of double octahedral configuration, as shown in the kinematic diagram of Fig. 2a. There are three active battens L_1, L_2, L_3 on the mid-plane. The remaining struts L (twelve total) and L_0 (six total) are rigid members.

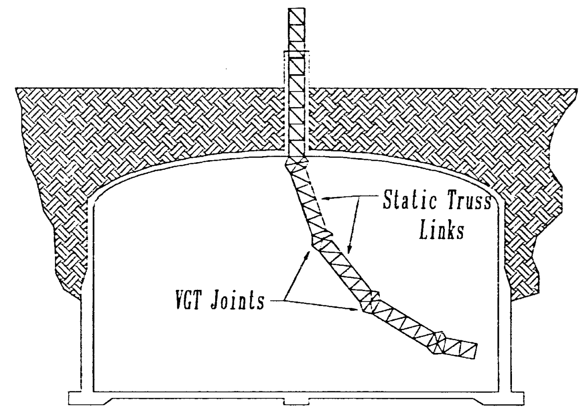
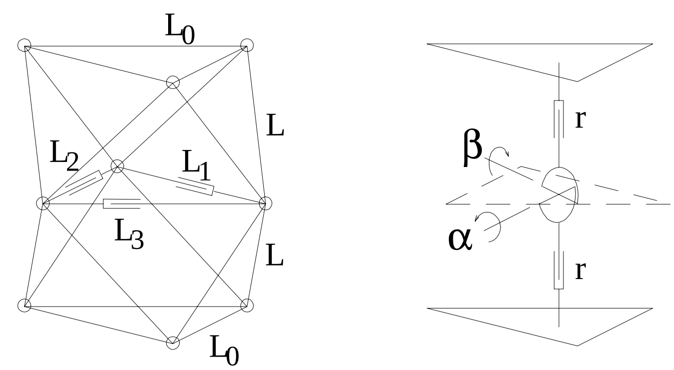


Figure 1. Underground Nuclear Waste Tank TBM



a. Actual *b. Virtual Serial Model*

Figure 2. Double Octahedral VGT Module

A possible Cartesian coordination algorithm for the manipulator of Fig. 1 adapted from Eq. 1 is given below:

$$\dot{L} = J^{+}\dot{X} + \left(I - J^{+}J\right)z \tag{2}$$

where $\dot{L}$ is the vector of twelve linear actuator rates, and J is the Jacobian matrix mapping the linear actuator rates to the Cartesian rates of the end-effector, $\dot{X}$. A possible implementation of this controller is shown in Fig. 3. The total actuator rates from Eq. 2 are integrated to commanded actuator lengths (assuming the actuators have position and not rate feedback). The feedback signal for the servo controller is measured linear actuator length (twelve total).

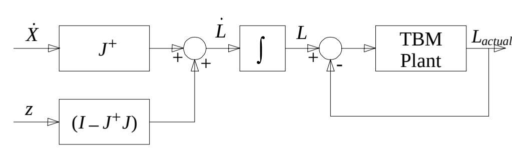


Figure 3. "Traditional" Controller

The problem with the control concept of Eq. 2 and Fig. 3 is that the Jacobian matrix J is difficult to determine symbolically, due to the complexity of in-parallel-actuated modules compared to serial manipulator chains. For the planar case, the problem is tractable, but the complexity significantly increases for manipulators constructed from spatial modules. For example, Salerno (1993) simulates Eq. 2 for control of a hyper-redundant manipulator constructed of the spatial active truss modules of Fig. 2a. To determine the Jacobian matrix J at each control step, numerical differentiation is used, considering the changes in Cartesian variables vs. the changes in linear actuator lengths about the current configuration neighborhood. In general, numerical differentiation is not robust for digital control applications.

2.2 The Virtual Serial Manipulator Approach

The current paper introduces a novel but conceptually simple control algorithm for simultaneous Cartesian trajectory control and performance optimization of TBMs. The crux of the idea is to replace the complexity of the in-parallel-actuated modules with relatively simpler, kinematically-equivalent, virtual serial manipulator chains. This concept is termed the Virtual Serial Manipulator Approach.

To illustrate the approach, again consider the proposed TBM in Fig. 1, constructed of the active module of Fig. 2a. Figure 2b presents the kinematically-equivalent virtual serial module for the parallel module of Fig. 2a. One way to represent the motion of the parallel module is as a virtual gimbal, controlling the orientation of the normal to the top plane with α,β rotations about mutually perpendicular axes, plus symmetric, accordion-like extension r of the top plane with respect to the base. This model was first proposed by Padmanabhan, et. al. (1992).

The Virtual Serial Manipulator Approach models a modular, parallel, TBM as a virtual serial manipulator *which provides kinematically-equivalent motion*. The basic equation for trajectory following and performance optimization is adapted from Eq. 1:

$$\dot{\Phi} = J_V^+ \dot{X} + \left(I - J_V^+ J_V\right) z \ . \tag{3}$$

The virtual serial manipulator Jacobian matrix J_V in Eq. 3 is generally easier to determine symbolically than the TBM Jacobian matrix J in Eq. 2, but provides the same motion for the end-effector.

Figure 4 presents the block diagram for controlling a TBM using a virtual serial manipulator model. The control flow is similar to Fig. 3. The difference is that the resolved rate algorithm (both primary and secondary solutions) is calculated for the virtual serial manipulator, not the real parallel TBM. The resulting virtual joint rates $\dot{\Phi}$ are integrated to virtual joint positions Φ. The vector Φ cannot be commanded to the real manipulator, so a transformation from virtual serial joint positions Φ to real in-parallel actuator lengths is required. This Module Inverse Kinematics is performed independently for each module i. These transformations could be accomplished simultaneously on i processors for improved real-time control throughput. The in-parallel-actuated complexity is isolated module by module, which is significantly easier (conceptually and computationally) than treating the entire manipulator in a parallel sense. For the module of Fig. 2, the module inverse kinematics solution is presented in (Williams, 1994a). This solution was implemented in real-time on a single module hardware at NASA Langley Research Center (Williams, et.al., 1995).

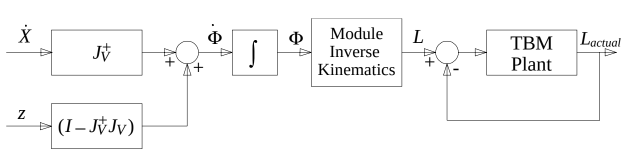


Figure 4. Virtual Serial Approach Controller

The method is applicable to any planar or spatial TBM whose modules have a virtual serial model. A survey of active truss modules and their virtual serial models is given in (Williams, 1995). The method is also applicable for any level of kinematic redundancy, from overconstrained (here not all Cartesian dof can be controlled), to non-redundant, to kinematically-redundant, to hyper-redundant. The Virtual Serial Manipulator Approach also handles TBMs constructed of dissimilar modules, and compound manipulators consisting of serial and in-parallel-actuated joints.

A major advantage of the proposed method is that existing standard methods for the control of kinematically-redundant serial manipulators (e.g. Williams, 1994b) can be adapted for the control of truss-based manipulators with in-parallel-actuated complexity. With improvements in computer power, these techniques are implementable in real-time, even for high degrees of kinematic redundancy.

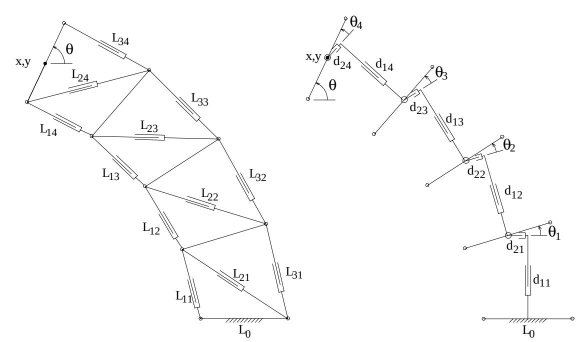
Another major advantage of the proposed method is that the forward kinematics transformation for a TBM may be achieved solely with the virtual serial joint positions Φ, and not the real actuator lengths L. The implicit assumption here is that TBMs are stiff enough to use the virtual parameters (for which there is no feedback) as opposed to the actual feedback L. For sensor-based control and position control via the resolved-rate algorithm, the forward kinematics transformation must be calculated at the real-time update rate. It is known from the literature that the forward kinematics transformation is generally straight-forward for a serial manipulator, and generally difficult and computationally intensive for in-parallel-actuated manipulators.

3. PLANAR TBM SIMULATION

In order to illustrate the Virtual Serial Manipulator Approach to Cartesian coordination of TBMs, this section presents simulation of a specific planar TBM.

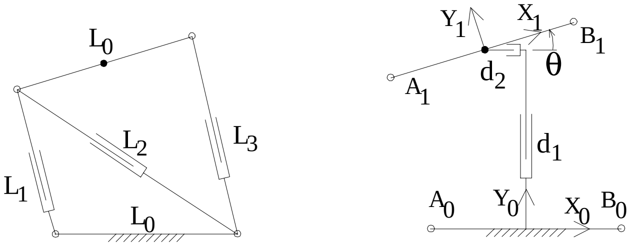
3.1 Algorithm Derivation

The planar TBM is shown in Fig. 5a. It is a twelve-dof manipulator used to position and orient the end member. This TBM is constructed of the three-dof module shown in Fig. 6a, where L_0 are the rigid members and L_1, L_2, L_3 are actuators. Figure 6b presents the kinematically-equivalent virtual serial module. In the parallel module, the three actuators work together to position the center of the moving bar, and to orient the moving bar, with respect to the base. The virtual model for this module is two linear actuators d_1, d_2 to control the translation and a revolute joint θ to orient the moving bar with respect to the base. Table I gives the DH parameters (Craig, 1988) for the virtual serial module of Fig. 6b.



a. Actual *b. Virtual Serial Model*

Figure 5. Twelve-dof Planar TBM



a. Actual *b. Virtual Serial Model*

Figure 6. Three-dof Planar Module

Table I Virtual Serial Module D-H Parameters

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	-90°	0	d_1	0
2	0	d_2	0	0
3	90°	0	0	θ

In order to model the TBM of Fig. 5a as a virtual serial manipulator, the model of Fig. 6b is used to replace each of the in-parallel-actuated modules, as shown in Fig. 5b. The fixed ground link becomes the moving rigid member for ensuing modules. The DH parameters from Table I are repeated for each module.

The control equation is Eq. 3. Figure 4 shows the block diagram for the algorithm. The virtual Jacobian matrix J_V is derived using any standard serial manipulator method. The specific parameters for Eq. 3 and Fig. 4 are given below.

$$\dot{\Phi} = \left\{ \dot{d}_{11} \quad \dot{d}_{21} \quad \dot{\theta}_1 \quad \dot{d}_{12} \quad \dot{d}_{22} \quad \dot{\theta}_2 \quad \dot{d}_{13} \quad \dot{d}_{23} \quad \dot{\theta}_3 \quad \dot{d}_{14} \quad \dot{d}_{24} \quad \dot{\theta}_4 \right\}^T \qquad (4)$$

$$\dot{X} = \left\{ \dot{x} \quad \dot{y} \quad \omega \right\}^T, \text{ where } \omega = \dot{\theta} \qquad (5)$$

$$\Phi = \left\{ d_{11} \quad d_{21} \quad \theta_1 \quad d_{12} \quad d_{22} \quad \theta_2 \quad d_{13} \quad d_{23} \quad \theta_3 \quad d_{14} \quad d_{24} \quad \theta_4 \right\}^T \qquad (6)$$

$$L = \left\{ L_{11} \quad L_{21} \quad L_{31} \quad L_{12} \quad L_{22} \quad L_{32} \quad L_{13} \quad L_{23} \quad L_{33} \quad L_{14} \quad L_{24} \quad L_{34} \right\}^T \qquad (7)$$

$$J_V = \begin{bmatrix} 0 & 1 & j_{13} & -s_1 & c_1 & j_{16} & -s_{12} & c_{12} & j_{19} & -s_{123} & c_{123} & 0 \\ 1 & 0 & j_{23} & c_1 & s_1 & j_{26} & c_{12} & s_{12} & j_{29} & c_{123} & s_{123} & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \qquad (8)$$

where:

$$j_{13} = -d_{24}s_{123} - d_{23}s_{12} - d_{22}s_1 - d_{14}c_{123} - d_{13}c_{12} - d_{12}c_1$$
$$j_{16} = -d_{24}s_{123} - d_{23}s_{12} - d_{14}c_{123} - d_{13}c_{12}$$
$$j_{19} = -d_{24}s_{123} - d_{14}c_{123}$$
$$j_{23} = -d_{14}s_{123} - d_{13}s_{12} - d_{12}s_1 + d_{24}c_{123} + d_{23}c_{12} + d_{22}c_1$$
$$j_{26} = -d_{14}s_{123} - d_{13}s_{12} + d_{24}c_{123} + d_{23}c_{12}$$
$$j_{29} = -d_{14}s_{123} + d_{24}c_{123}$$

Note: $s_{123} = \sin(\theta_1 + \theta_2 + \theta_3)$ and so on.

For the planar module of Figs. 6a and 6b, the Module Inverse Kinematics solution in Fig. 4 is straight-forward. The coordinates of points A_0, A_1 and B_0, B_1 are expressed in terms of the virtual parameters d_1, d_2, θ for each module. (Note the virtual parameter d_2 can be $\pm$ and θ can be $\pm$, measured with the right hand rule.)

$$A_0 = \begin{Bmatrix} -\frac{L_0}{2} \\ 0 \end{Bmatrix} \qquad B_0 = \begin{Bmatrix} \frac{L_0}{2} \\ 0 \end{Bmatrix} \qquad (9)$$

$$A_1 = \begin{Bmatrix} d_2 - \frac{L_0}{2}\cos\theta \\ d_1 - \frac{L_0}{2}\sin\theta \end{Bmatrix} \qquad B_1 = \begin{Bmatrix} d_2 + \frac{L_0}{2}\cos\theta \\ d_1 + \frac{L_0}{2}\sin\theta \end{Bmatrix} \qquad (10)$$

The commanded in-parallel actuator lengths are then calculated using the Euclidean norm.

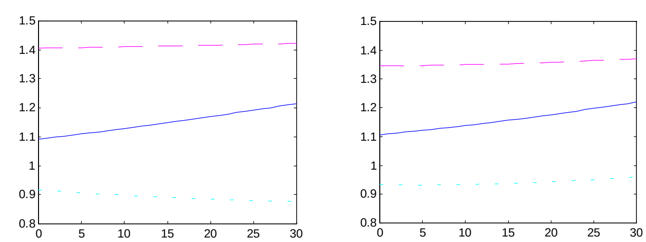
$$\begin{aligned} L_1 &= \sqrt{(A_1 - A_0)\bullet(A_1 - A_0)} \\ L_2 &= \sqrt{(A_1 - B_0)\bullet(A_1 - B_0)} \\ L_3 &= \sqrt{(B_1 - B_0)\bullet(B_1 - B_0)} \end{aligned} \qquad (11)$$

This inverse kinematics solution is applied for each module independently, given the virtual serial manipulator parameters Φ.

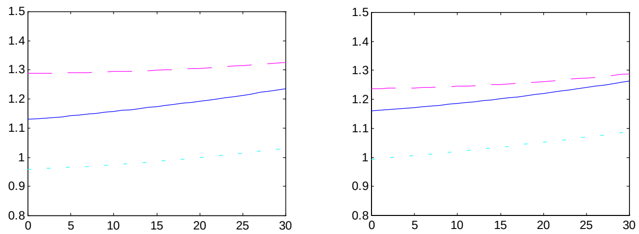
3.2 Simulation

A computer simulation with animation was developed (with MATLAB) to test the Virtual Serial Manipulator Approach for control of the planar TBM in Fig. 5. This section presents results from one simulation, for the particular solution $\dot{\Phi} = J_V^{+}\dot{X}$ only. Secondary solutions $\dot{\Phi} = \left(I - J_V^{+}J_V\right)z$ in the null-space of the virtual manipulator Jacobian matrix have been tested to verify self-motion of the TBM; performance optimization will be pursued in the future.

With $L_0 = 1$, starting from initial actuator leg lengths $L = \{1.09 \quad 1.41 \quad 0.92 \quad 1.11 \quad 1.34 \quad 0.93 \quad 1.13 \quad 1.29 \quad 0.96 \quad 1.16 \quad 1.24 \quad 0.99\}^T$ (corresponding to the virtual joint position $\Phi = \{1 \quad 0.1 \quad -10^\circ \quad 1 \quad 0.2 \quad -10^\circ \quad 1 \quad 0.3 \quad -10^\circ \quad 1 \quad 0.4 \quad -10^\circ\}^T$), a Cartesian rate trajectory $\dot{X} = \{0.03 \quad -0.015 \quad -0.01\}^T$ was commanded for 30 seconds. The units are *m*, *m/s* and *rad/s* for length and translational and rotational velocity, respectively. Figure 7 presents the in-parallel actuator commanded length histories. Figures 8a and 9a show the initial and final TBM configurations, respectively. Figures 8b and 9b show the same configurations, where the TBM is modeled by the virtual serial manipulator.

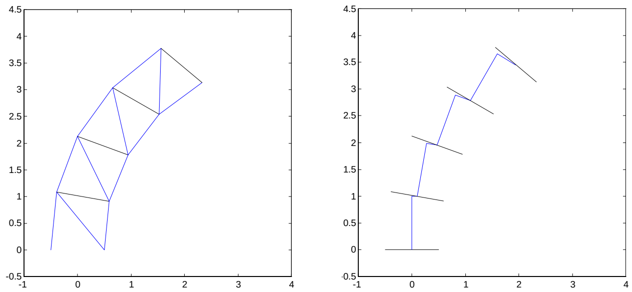


a. Module 1 *b. Module 2*



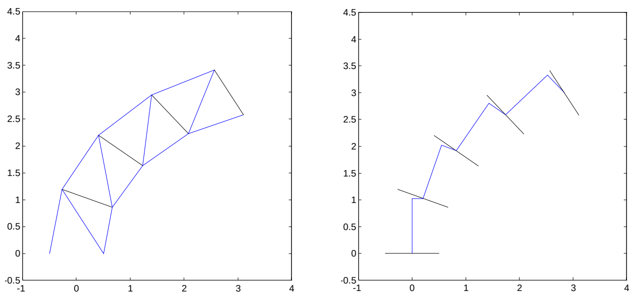
c. Module 3 *d. Module 4*

Figure 7. TBM Actuator Length Commands
L_{1i} solid, L_{2i} dashed, L_{3i} dotted



a. TBM *b. Virtual Serial Model*

Figure 8. Initial Configuration



a. TBM *b. Virtual Serial Model*

Figure 9. Final Configuration

4. CONCLUSION

A novel concept, The Virtual Serial Manipulator Approach, is presented for simultaneous Cartesian trajectory following and performance optimization of truss-based manipulators (TBMs). The approach models complex in-parallel-actuated TBMs as kinematically-equivalent virtual serial manipulators. A virtual-to-real manipulator inverse mapping is required, but this is accomplished module by module rather than for the entire manipulator. Standard control methods for kinematically-redundant serial manipulators can then be adapted to the real-time control of TBMs. The pseudoinverse of the virtual serial manipulator Jacobian matrix is used, with objective function gradient projection into the null-space for performance optimization. A benefit of the method is that the forward kinematics transformation can be calculated more efficiently using the equivalent virtual parameters, compared to the formidable in-parallel-actuated forward kinematics transformation.

The method is applicable to any TBM whose modules can be modeled as a virtual serial chain. The Virtual Serial Manipulator Approach also handles TBMs constructed of dissimilar modules, and compound manipulators consisting of serial and in-parallel-actuated joints. The method is applicable for any level of kinematic redundancy.

The method was applied to a specific planar TBM with twelve degrees-of-freedom. The algorithm was developed and a simulation was presented for this case. In the future, the researchers intend to develop the Virtual Serial Manipulator Approach for spatial TBMs. It is expected that the benefits of this method will be more clear for spatial compared to planar TBMs. A goal is to compare this novel method with "conventional" approaches.

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