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# Controlling deformations of electro-active truss structures with nonlinear history-dependent response

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ABSTRACT

This study presents simulations of shape changing in active truss structures that undergo non-linear and time dependent response. The truss structure comprises of slender members with electro-active (piezoelectric) components joined by pins, allowing for large deformations due to rotations at the pins. A nonlinear time-dependent electro-mechanical constitutive model is considered for the piezoelectric components in the truss systems. In order to find the actuation inputs to achieve a desired shape, the required shape is defined with respect to reference configuration for a equivalent 3 dimensional continuum. The mapping between reference and current configuration is used to calculate the macroscopic strains in the continuum. The corresponding strains along the longitudinal axes of the truss members whose ends coincide with certain material points in the continuum are then calculated. The strains corresponding to the predefined shapes are achieved by applying electric field through the piezoelectric materials, and as a result the truss system undergoes the desired shape changes. The shape changing behaviors in electro-active truss systems are analyzed using a finite element (FE) method, incorporating nonlinear material and geometry. Numerical implementation of the active truss structures is also presented. Two types of truss configurations are considered which are planar and beam configurations. The planar configuration is formed by arrangement of cubical truss elements while the beam configuration consists of several tetrahedral truss elements. Several shape configurations of the planar and beam truss structures are shown as examples. While considerable amount of work has been done with piezo-actuated truss systems under the assumption of linear piezoelectric response, we study the influence of the nonlinear hysteretic electro-mechanical behavior and highlight the differences in the deformations of the truss structures when the nonlinear and time-dependent electro-mechanical and linear electro-mechanical models are considered for the piezoelectric components.

## 1. Introduction

Recent advances in active materials, such as shape memory and electro-active materials, allow for generating autonomous compliant structures, in which the structures can change their shapes from one configuration to another. There have been several approaches presented in order to construct autonomous compliant structures. One approach is by considering truss structures with integrated active components. In truss systems, relatively slender members are connected by pins, which allow for the structures to undergo large deformations through rotations at these pins while each member remains under relatively small strains.

Several concepts of utilizing truss systems for generating adaptive structures have been extensively studied, focusing on deployable structures and robotics applications (Denton [1]; Miura et al. [2]; Chirikjian and Burdick [3]; Pelegrino [4], Hutchinson et al. [5]; Phocas et al. [6]; Chirikjian [7]). These studies focused on the development of kinematics of reconfigurable structures and mechanical deformations of the adaptive structures. For example, Miura and Furuya [2] introduced the concept of a Variable Geometry Truss (VGT) in order to configure flexible and lightweight structures with capability to undergo relatively large deformations. The application of VGT for truss and space crane arms was described in Miura and Furuya [2]. The VGT that was considered in the above paper consisted of the repetition of an octahedral truss to form a beam like truss system, and the deformations were actuated by a mechanical stimulus. They showed that by considering linear deformations, here measured by changes in length of members, the truss could be transformed to varieties of configurations of any desired predefined shapes, such as circular and helical. Later, based on the kinematics of the truss systems in the VGT, Miura et al.

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[8] presented adaptive structures. They introduced a simple prototype of VGT consisting of two octahedral units (building block), and the truss system comprised of active and non-active members. The length of the active members was controlled by mechanisms consisting of DC motors, ball screws, and encoders, allowing for remotely controlling the shape reconfigurations of the truss.

Dynamics responses of the VGT were also investigated by Miura et al. [8] for potential applications as robotic arms in space structures. They examined how the fundamental frequencies of a deployable VGT change with respect to the ratio of length of the truss before deployment to its length after complete deployment (deployment ratio). They used the continuum modeling of repetitive structure for finding the general stiffness of the truss. This method proposed by Noor [9] and was based on representing the axial strain of each member in terms of 3D continuum strains and generating the stiffness coefficient of 3D continuum by summing up the stiffness matrix of each contributing member. A review of Miura's work on the subject of adaptive structures and VGT can be found in [10], where both linear octahedral beam truss and a prototype for a planar truss configuration were discussed. For relatively stiff structures, it is quite challenging to control their deformation; Miura [10] proposed a method to control the stiffness of VGT by using piezoelectric actuators. It is shown that reducing the stiffness of selected active members could reduce the first natural frequency of the VGT. This type of VGT can be used for precisely controlling shapes of antenna reflectors. Moreover, they presented a method for construction of large space structures using adaptive structures in an intelligent robot.

Several designs and motion control methods have also been proposed for adaptive truss structures. Huang et al. [11] and [12] investigated a motion control of free-floating VGTs for space structure. They considered the same configuration as Miura [8] and investigated the kinematics of a free-floating VGT. They formulated equations describing the motion control of a free-floating VGT in three-dimensional spaces and validated the results of their control equations with a computer simulation of free-floating VGT. They also derived inverse equations for free-floating VGT and performed an experiment on a prototype model of VGT in order to validate their equations of motion for space applications. Macareno et al. [13] considered a linear truss system made of three-dimensional (3D) tetrahedral units to form VGTs. They discussed manufacturing of prototype and the actuation methodology of the VGTs. They showed that their VGT configuration made of five-modules, each with an octahedral truss structure, is quite capable for positioning purposes. They also presented the detailed design of their joints and used finite element analyses in order to support the design and motion control of VGTs. Aguirrebeitia et al. [14] and Aviles et al. [15] presented optimization methods for VGTs to in order to minimize the actuators displacement and consequently its energy. This method has been applied to different truss architectures, specifically to modular tetrahedral linear trusses. Recently, Bilbao et al. [16] have considered dynamic analyses of their previously designed modular configuration.

In addition to the typical mechanically driven shape reconfigurations in adaptive truss systems, several active materials, such as piezoelectric, shape memory, magnetostrictive, and electro-rheology materials, have been integrated as sensors and actuators in the adaptive truss systems (Hagood and Crawley [17]; Wada et al. [18]; Sofla et al. [19]). Sofla et al. [19] studies morphing hinged truss structures, where they used shape memory wires in order to activate their structures. They presented an experimental study of their prototype made of tetrahedrons truss elements for different configurations, including twisting and bending. One of the advantages of using shape memory materials is that they have relatively large activation strains, allowing for more flexibility in achieving desired level of control. Experimental studies have shown the ability of integrating piezoelectric materials in controlling the deformations and vibration in the truss systems (Petersen et al. [20]). Several analytical and numerical methods have also been presented for adaptive truss comprising of piezoelectric materials, e.g., Hagood and Crawley [17], Edberg et al. [21], Crawley [22]. Moored et al. [23] designed electro-active truss systems with embedded piezoelectric actuators. They compared this type of actuation with other strategies such as tension wires for tensegrity truss like structures that aims to mimic flapping of an artificial pectoral fin. It is noted that the tensegrity trusses consist of mixture of cable and rod like members. It has to be designed in a very specific way that the cables will be only under tension, this makes the design and assembly rather complicated. They concluded that their approach can reduce power consumption and shows a rather simple design of a high performance tensegrity-based artificial pectoral fin. In all of these studies, a linear electro-mechanical constitutive model is used for the piezoelectric materials, while nonlinear geometry (large deformation kinematics) is incorporated, and the focus with regards to the dynamics responses was on obtaining the fundamental frequency of the structures.

Simulating shape changes in variable geometry trusses has wide applications ranging from capturing robotics motions [7] and generating deployable space structures (Miura et al., [2]). In robotics applications, VGTs are known as stiff actuators capable of offering precise controls. Current works related to shape reconfigurations in VGT have been emphasized on the structural geometries and shapes that can be attained by different truss arrangement, considering mainly linear and time-independent constitutive relations for the materials in the truss members. It is noted that linear constitutive relations are applicable for limited ranges of prescribed external stimuli.

In actuation applications utilizing piezoelectric materials, it might be useful to prescribe relatively large electric field inputs, within the limit of material failure, in order to attain larger deformations. However, large electric field inputs lead to a nonlinear electro-mechanical relation, as experimentally shown in several literatures. Furthermore, piezoelectric materials show hysteretic responses, even when relatively small electric field input is considered, which could be a drawback in adaptive structures (Wada et al. [18]). Their electro-mechanical responses are also time (or frequency) dependent, as discussed in Crawley [24], Anderson [25], Fett and Thun [26], Zhou and Kamlah [27], Ben Atitallah [28], Khan et al. [29]. This time-dependent effect could be an issue for precisely controlling the shape changes in the structures. To the best of our knowledge, analyses of adaptive truss systems considering nonlinear time-dependent electro-mechanical material models, in addition to nonlinear kinematics have not been considered before. It will be discussed later in this manuscript, considering linear electro-mechanical responses in analyzing shape reconfiguration in structures leads to unreasonable magnitude of electric field required to actuate the structures. When appropriate nonlinear electro-mechanical responses are considered, it is possible to attain relatively large deformations with reasonably magnitude of electric field input (within the material limits).

This study focuses on theoretical and computational methods on controlling shape changes in compliant truss systems comprising of electro-active (piezoelectric) materials as actuators. A nonlinear time-dependent electro-mechanical model is used for the piezoelectric components in the truss systems, allowing for capturing frequency-dependent and hysteretic responses. A nonlinear kinematics model is considered for incorporating the large deformations in the adaptive truss systems. A desired shape is defined with respect to reference configuration in the Lagrangian manner. The mapping between reference and current configuration is used to calculate the macroscopic strains. The corresponding strains along the longitudinal axes of the truss members are then calculated. The strains corresponding to the predefined shapes are achieved by applying electric field through the piezoelectric materials, and as a result the truss system undergoes the desired shape changes. The shape changing behaviors in electro-active truss systems are analyzed using finite element (FE), incorporating nonlinear material and geometry.