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Progress on Soft Multibody Dynamics and Its Application in Aerospace Engineering

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EXTENDED ABSTRACT

1 Introduction

Soft multibody systems contain either flexible components or soft materials. They are common in nature but still rare in engineering. There are certain circumstances that require structural softness. For example, soft robots are desired for high adaptability and safe interaction, reconfigurable structures for space expansion, and deformable wings for exceptional aerodynamics. In this report, we present the recent progress in our group on dynamic modeling, computation and design of soft multibody systems. First, a composite plate element with nonlinear elasticity and coupled electricity is proposed based on ANCF (absolute nodal coordinate formulation) [1]. This finite element is suitable for efficient dynamic analysis of multilayer DEAs (dielectric elastomer actuators). Moreover, optimal design of electrode topology of DEAs is presented based on the parameterized level set approach [2]. Second, model order reduction based on proper orthogonal decomposition is proposed for efficient simulation of flexible multibody systems [3]. Third, instability is analyzed and utilized in design of soft multibody systems. Bistability is adopted to design a soft gripper for fast capture in space [4]. Last, optimization of distributed actuation is presented for shape control of membrane space structures [5]. In summary, understanding dynamics of soft multibody systems are essential and powerful for boosting innovation in space technologies.

2 Dynamic modeling and optimization of dielectric elastomer actuators

A multilayer membrane element of ANCF is proposed for dynamic modeling of multilayer DEAs [1]. The coupled dynamics of rigid-body motion and large deformation interacting with electric fields is considered. For the kinematic description, a modified version of the Kirchhoff-Love assumptions is proposed taking the thickness shrinking of the membrane into account. Two material models are introduced based on the Helmholtz free energy in thermodynamics. Afterwards, the generalized internal forces and their Jocabians are given. The system dynamic equations are solved by the generalized-α algorithm. The statics and dynamics of a bending DEA are investigated. And an autonomous membrane system driven by soft DE joints is designed and simulated for space applications.

Optimization of DEAs is also required in more advanced design of soft robots. A computational approach is originally proposed and validated for the topology optimization of electrodes of DEAs [2]. The parameterized level set method is employed to optimize the electrode topology of DEAs. Then, the method of system-wise equivalent static load (ESL) is employed to convert the optimization problem of dynamic responses into the static one. Based on the sensitivity analysis, the normal velocity field for optimizing the electrode topology is derived. Case studies and experiments are presented to validate the proposed method.

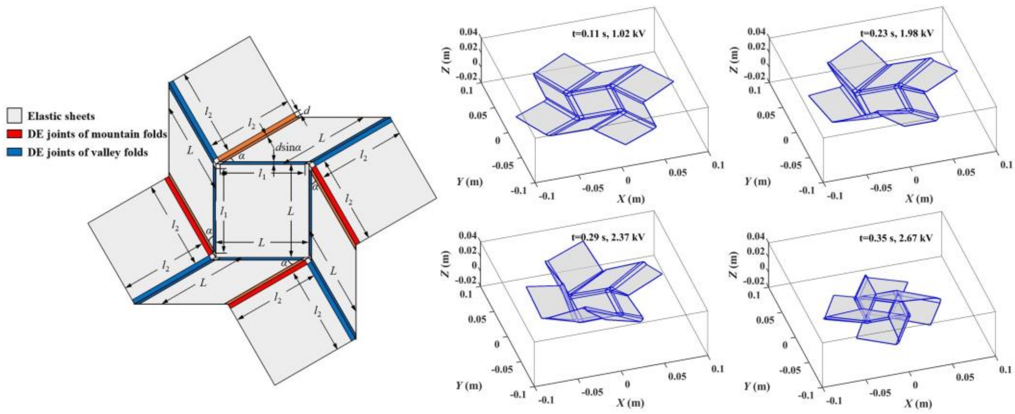

Figure 1: Dynamic simulation of a self-foldable membrane origami driven by DE joints

3 Order reduction of flexible multibody systems based on POD

To improve the computational efficiency of ANCF for a large-scaled flexible multibody system, a systematic method is proposed for model order reduction based on the proper orthogonal decomposition (POD) and Galerkin projection [3]. At first, an approach for the selection of reduced constraint equations is proposed to deal with the singularity of the coefficient matrix of the Reduced-Order Model (ROM). Then, the computation of the reduced stiffness matrix and generalized force vector of the ROM are parallelized via the OpenMP directives. Afterwards, a parametric approach based on manifold interpolation is presented to make the ROM be adaptive to the change of system parameters. Finally, numerical examples are given to validate the efficacy of the proposed method for the dynamic simulations of both rigid and flexible multibody systems.

4 Design of soft gripper for fast capture in space

Actuators for fast capture are essential in the tasks of space structure assembly and space debris disposal. By harnessing the rapid occurrence of structural instability and tuning its triggering conditions, we present a soft and bistable gripper for dynamic capture [4]. The gripper deforms upon collision with other objects, absorbs the kinetic energy of the objects to trigger an instability, and then achieve fast grasping as well as cushioning. The proper pre-deformation to the bistable structure of gripper enables one to dynamically adjust the energy barrier for triggering the onset of instability to achieve the optimal grasping and buffering effect according to the kinetic characteristics of targets. After finishing one grasping task, the bistable gripper can automatically return to its initial state and release the target via a self-designed cable-driven mechanism. The ground-testing experiment demonstrates that the proposed soft gripper is capable to grasp, transfer and release moving targets, and thus possesses great potentials to fulfill challenging operations in space missions.

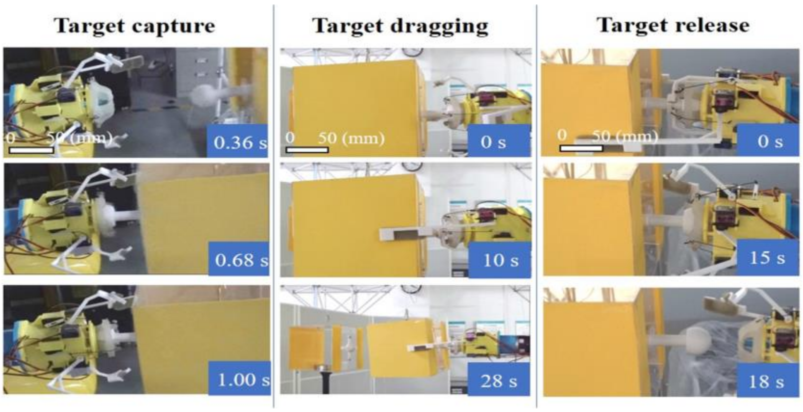

Figure 2: Assembly process of a moving target with the proposed soft gripper

5 Control of membrane structures with distributed actuators

To maintain high surface precision of a membrane reflector, it needs to be actively controlled in orbit via a distributed actuation system. We present the group-control optimization of distributed actuation with a limited number of input channels based on the full-orbital-period thermal analysis and clustering algorithm [5]. The study begins with the analysis of the thermal radiations on an inflated membrane reflector in a geosynchronous orbit, and gives the database of temperature distribution. Then, the mechanics model of the membrane reflector under thermal loads and distributed electric actuation is established based on the modal expansion of Fourier-Bessel series to simulate its thermal deformations. Afterwards, the group-control optimization based on the clustering algorithm and thermal-analysis data is performed to involve successively the various constraint conditions. With the proposed method, a unified control mode of the distributed actuation is derived to remove the necessity of on-line computation for almost all the extreme cases of thermal deformations of the reflector in orbit.

Acknowledgments

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