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Dynamics of Adaptive Structures: Design through Simulations

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1. INTRODUCTION

Mechanisms and static stress analyses have long been the major considerations in the design of many articulated structures or adaptive structures in the past. However, high-performance requirements on these structures have added the dynamics considerations as a new added design criterion in recent years. This is especially true in the design of adaptive or deployable space structures that involve the combined phenomena of the orbital mechanics, structural configuration changes and flexible vibrations in a coupled manner. Hence, little attention has been given to, in the design of reconfigurable flexible space structures, the influence of the accompanying dynamics during the maneuvering as an integral part of the design requirements.

The adaptations of human bodies, animals and bacteria to spatial dynamical motions have been previously studied[1-3]. Recently, several investigators developed the so-called angular momentum preserving rotational maneuvering control algorithms and applied them to robotics and spacecraft attitude controls[4-6]. As a result, the intrinsic adaptations of the momentum conservation (violation for that matter) laws by spring board divers, ice skaters as well as gymnasts are well understood, which have been subsequently utilized for the design of space robotics maneuvering and space rendezvous scenarios. These studies have dealt mostly with rigid bodies linked by frictionless joints and focused on the development of various control algorithms for nonholonomic rigid dynamical system.

The use of a helical bi-morph actuator/sensor concept[7] by mimicking the change of helical waveform in bacterial flagella is perhaps the first application of bacterial motions (living species) to longitudinal deployment of space structures. However, no dynamical considerations were analyzed to explain the waveform change mechanisms[3, 7]. The objective of the present paper is to review various deployment concepts from the dynamics point of view and introduce the dynamical considerations from the outset as part of design considerations. Specifically, the impact of the incorporation of the combined static mechanisms and dynamic design considerations on the deployment performance during the reconfiguration stage is studied in terms of improved controllability, maneuvering duration and joint singularity index. It is shown that intermediate configurations during articulations play an important role for improved joint mechanisms design and overall structural deployability.

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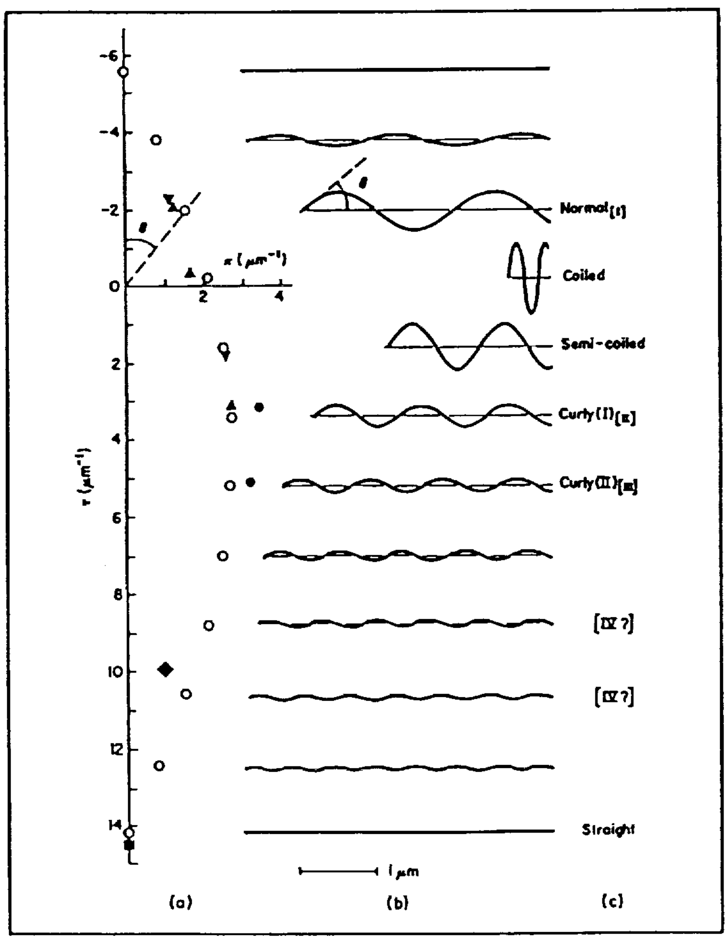
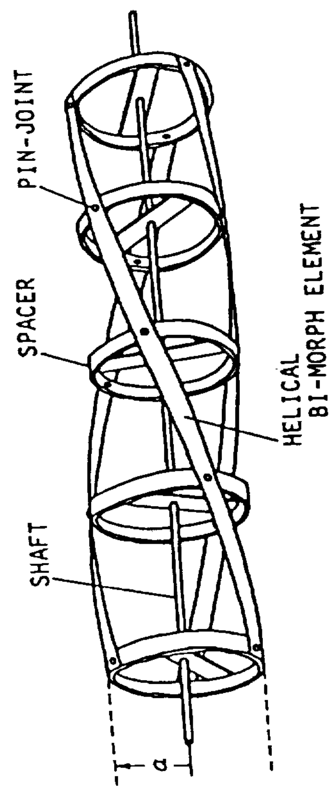
2. EXAMPLES OF ADAPTIVE STRUCTURES

2.1 Bacterial Flagella

In studying the chemotaxis of bacteria such as *Salmonella*, scientists discovered that their motions are intertwined with smooth swimming interrupted by short periods of tumbling[3]. In particular, the change in waveforms do not follow the intuitive way, vz., from one normal wave form to the adjacent discrete wave state. Instead, the transition of the waveform jump from one wave sometimes to its half-length wave. Calladine[3] conjectured that the intermittent existence of bi-stable subunits along the helical flagella structure are responsible for the formation of partly stable curly right-handed helices. It is these bi-stable subunits that cause jumps in the waveform formation.



Courtesy: Caladine[3]



Courtesy: Miura et al[7]

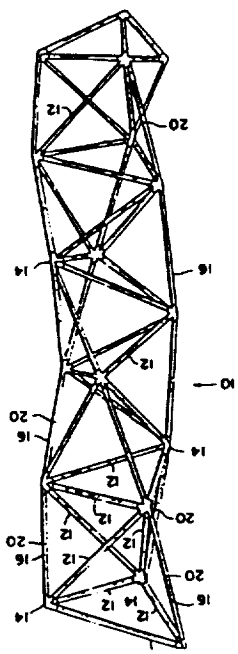
Fig. 1 Possible Waveforms of Flagella of Salmonella

From the mechanical deployment perspectives, the large motions due to the jumps in waveform change in bacterial flagella pose the following questions: 1) how can such large motions be possible what are the sources of the torques that make such large motions possible?; 2) are those motions created by minimizing the energy requirements or by triggering unstable motion paths so that the energy need remains minimal?; 3) can the large motion phenomenon be explained solely by quasi-static equilibrium considerations or be explained only by the dynamical considerations?

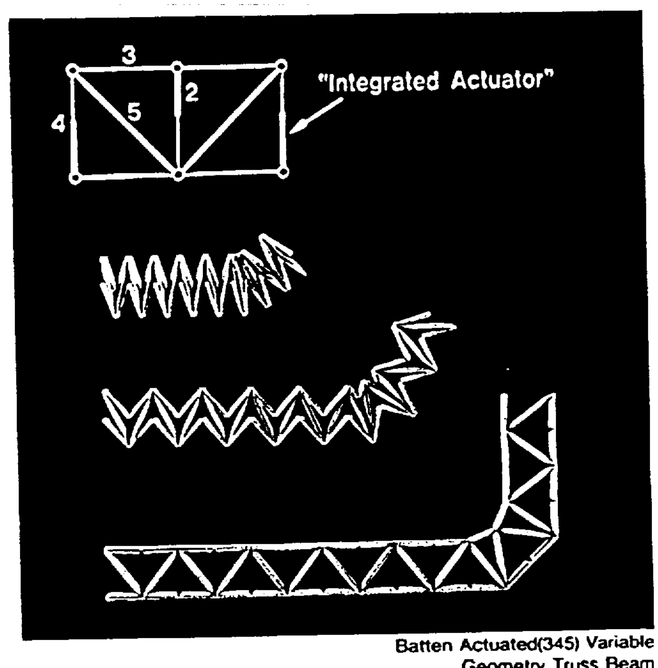
Experiments as well as analytical studies[3] so far identified twelve polymorphic helical forms with a tubular chains of 20 nanometer in diameter as shown in Fig. 1.

2.2 Reconfigurable Truss Beams

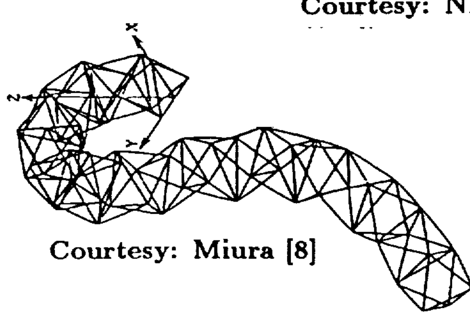
Figure 2 illustrates three representative reconfigurable truss beams. The sequentially deployable maneuvering tetrahedral beam is shown in Fig. 2a and can only be deployed sequentially, hence can't simulate the jumps in waveform of the bacterial flagella.



Courtesy: Mikulas and Crawford[9]



Courtesy: NHK Pub.[10]



Courtesy: Miura [8]

Fig. 2 Various Reconfigurable Truss Beams

By inserting actuator-encorder pairs into some of the truss members as shown in the variable geometry truss (Fig. 2b), it is possible to shape the beam as desired. The batten actuated beam as shown in Fig. 2c is perhaps the simplest reconfigurable truss. In both the last two cases, the actuators may be viewed as bi-stable subunits which, unlike for the case of tumbling motions in flagella case, do require control forces.

3. NONHOLONOMICALLY CONTROLLED RECONFIGURABLE STRUCTURES

The equations of motion for nonholonomically controlled reconfigurable structures can be written as

$$\begin{aligned} \dot{\mathbf{p}} &= \mathbf{f}(t) - \mathbf{S}(\mathbf{q}) + \mathbf{B}\mathbf{u} + \mathbf{C}\boldsymbol{\lambda} \\ \mathbf{p} &= \mathbf{M}\dot{\mathbf{q}} + \mathbf{D}(\mathbf{q}) \end{aligned} \tag{1}$$

with the constraints:

$$\begin{aligned} \boldsymbol{\Phi}_K(\mathbf{q}) &= 0 \quad \mathbf{C} = \frac{\partial \boldsymbol{\Phi}_K}{\partial \mathbf{q}} \\ \boldsymbol{\Phi}_N(\mathbf{q}) &= 0 \quad \mathbf{B} = \frac{\partial \boldsymbol{\Phi}_K}{\partial \mathbf{q}} \end{aligned} \tag{2}$$

In the above equations, $\mathbf{p}$ is the generalized momenta, $\mathbf{f}$ is the applied force, $\mathbf{S}$ is the internal force, $\mathbf{u}$ and $\boldsymbol{\lambda}$ are the nonholonomic and kinematic contraint forces, $\mathbf{M}$ is the generalized inertia matrix, $\mathbf{D}$ is the damping operator, and $\boldsymbol{\Phi}_K(\mathbf{q})$ and $\boldsymbol{\Phi}_N(\mathbf{q})$ are system kinematic and nonholonomic constraint equations. It should be noted that both $\mathbf{u}$ and $\boldsymbol{\lambda}$ can be augmented with active control forces, when necessary.

Figure 3 illustrates a design example that involves the sizing of the double moemnt gyros[11] for effecting the maneuvering as well as the necessary vibration control. The moment gyros can in turn be made of from micro to mini sizes [12], depending upon the torque requirements. In this particular example, the task is to shape the articulated straight beam to form an hexagonal polygonal structure in space or can be shaped to form a helix if desired. Therefore, the role of gyros is to perform triple tasks concurrently: maneuvering, vibration control, and if necessary bi-stable units for easy articulation.

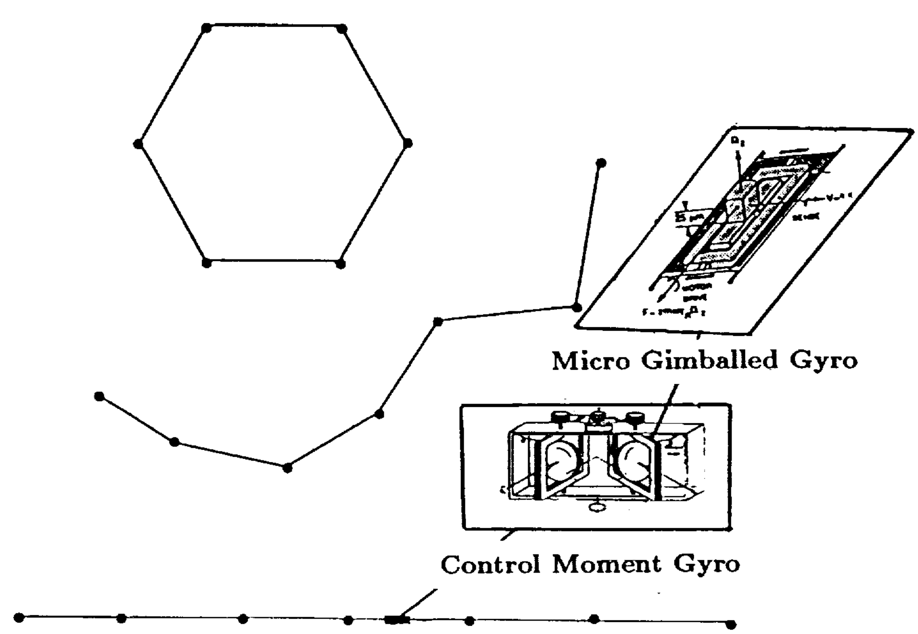


Fig. 3 Articulation of Beam-Like Structure via Control Moment Gyros

It should be mentioned that, for three rigidly linked planar maneuvering that conserves the angular momentum, the problem has been analyzed in [6]. It is for flexible cases the solution can be complicated. These and solutions of other related problems will be reported at the conference.

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