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CPG Control of a Tensegrity Morphing Structure For Biomimetic Applications

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Abstract Rhythmic movements associated with animal locomotion are controlled by neuronal circuits known as central pattern generators (CPG). These biological control systems appear to entrain to the natural frequencies of the mechanical systems they control, taking advantage of the resonance of the structure, resulting in efficient control. The ultimate goal is employing these controls in a biomimetic autonomous underwater vehicle so as to capture, and possibly improve upon, the performance capabilities of animals like the manta ray. To this end, this paper investigates the CPG control of a simple tensegrity structure. The dynamics of a tensegrity structure are linearized about a nominal configuration, and a synthesized CPG is used as the control input. Successful integration is shown by the CPG's ability to tune the structure's first mode.

Introduction

There has been a significant amount of research in the individual areas of neural networks, morphing structures, and underwater robotics. However, our interdisciplinary goal is to establish a framework for connecting these distinct areas in an effort to create a biologically inspired robot that captures the autonomy and robustness of neural networks as well as the high performance capabilities of tensegrity structures.

Rhythmic motion in animals is ultimately controlled by central pattern generators [1]. CPGs are system of neurons connected in such a way that their outputs autonomously oscillate with particular phase relationships between individual neurons. The output is used to control the muscles responsible of the rhythmic motion of an animal's appendages. This motion then rectifies with the environment to produce a biased locomotion. Feedback from the muscles provides the necessary signal to modify the oscillation in response to forces from the environment, allowing the neural network to achieve a high level of autonomy from a central nervous system.

Neural oscillators have been studied extensively in biology. Brown proposed the reciprocal inhibition neuron model as a oscillator, where neurons are connected by inhibitory synapses, resulting in out of phase oscillations [1]. He later included synaptic fatigue and post inhibitory rebound in his models. Friesen discussed reciprocal inhibition in multiple biological systems, including oscillatory control of leech and lamprey swimming [2]. It has been shown in leeches that CPGs are a fundamental control mechanism, and further, sensory feedback from the muscles has the ability to coordinate the control for efficient locomotion [3-5]. These biological studies have been used to validate mathematical and dynamical models.

Of particular interest is the synthesis of these systems to control a biologically inspired robot. Iwasaki has shown, using multivariable harmonic balance, that a CPG can be synthesized, with

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desired amplitude, phase, and frequency relationships between each neuron [6]. It has also been show that sensory feedback is sufficient for entrainment of the neural controls to the mechanical resonance. The objective of this study is to synthesize a CPG in this manner, using it to control a morphing tensegrity structure.

Tensegrity structures are basically systems of bars held in compression by cables in tension. These structures are both statically and kinematically indeterminate, and they are of interest due their high actuation capabilities. Their study began in the 1960's with Buckminster Fuller's patent [7], where the term tensegrity was coined from ``tensile-integrity". Determining the spatial configuration of these structures, i.e. form-finding, becomes a driving problem. Early approaches were purely geometrical [7,8]. Pellegrino showed that this approach is insufficient, noting that the prestress of the system is critical due to the elasticity of the members [9]. Masic and Skelton also investigated tensegrity form-finding including optimal dynamics and controls, specifically finding an optimal prestress for LQR performance [10]. Moored investigated actuator location and effort for desired shape changes, using both designer choice methods and pattern search optimizations [11]. In this study, we use the results of [12] to build a linearized dynamic model of a simple tensegrity structure. The frequency response of the structure is analyzed as well is modes of natural frequency. We then synthesize a CPG to control this dynamical system and investigate resonance entrainment.

Tensegrity Dynamics

Equations of Motion. Tensegrity structures are systems of bars held in compression by cables in tension. The tensegrity system in this study is a Type 2 structure (i.e. the maximum number of bars sharing the same node is two) and is shown in Fig. 1.

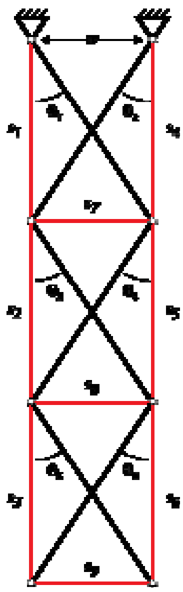

Figure 1: Type 2, 3 cell tensegrity: bars shown in black, cables in red

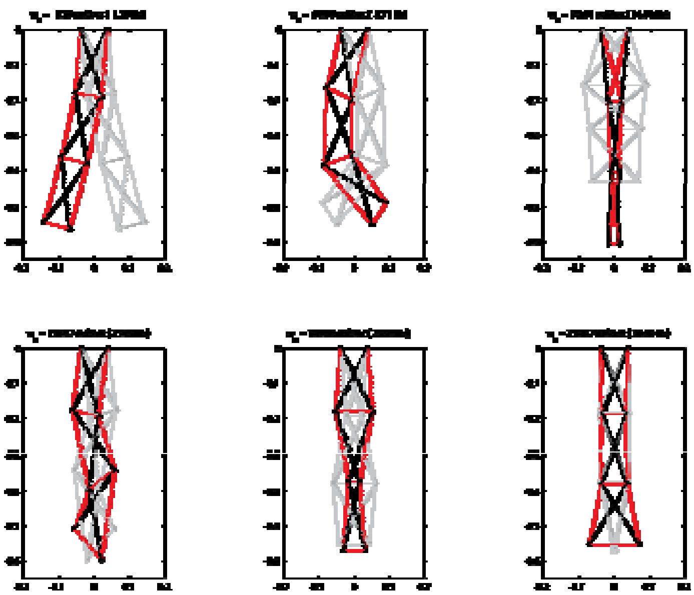

Figure 2: Natural frequencies and their mode shapes

In this study, we consider the bars to be rigid and the cables linearly elastic. Linear kinetic damping, i.e. viscous damping, is present at bar to bar connections in the structure. Constraints are workless, holonomic, schleronomic, and bilateral, and we will neglect body forces such as gravity. With these assumptions, the nonlinear equations of motion take the form [12]:

$$M(q)\ddot{q} + c(q,\dot{q}) + A(q)T(q) + C(q)\dot{q} + H(q)F = 0 \tag{1}$$

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where $q = [\theta_1 \quad \ldots \quad \theta_6]^T \in \Re^6$, *M(q)*, *C(q)*, and *H(q)* represent the mass, damping, and disturbance matrices respectively. *A(q)T(q)* represents the vector of elastic forces resulting from the difference between current (stretched) length l_i and the manufacturing (unstretched) length l_{o_i} of the cable s_i. These lengths can be grouped into vectors $l, l_o \in \Re^9$ respectively. The vector $c(q, \dot{q})$ represents the quadratic elements arising from coupling of the degrees of freedom. This system of equations can be linearized about a nominal configuration q_e, resulting in [13]:

$$
\begin{aligned}
&M_e\ddot{\tilde{q}} + C_e\dot{\tilde{q}} + K_e\tilde{q} + B_e u + H_e f = 0, \{M_e, C_e, K_e\} \in \Re^{6\times 6}, B_e \in \Re^{6\times 9}, H_e \in \Re^{6\times n_f}, \\
&\tilde{q} = q - q_e, u = l_o - l_{o_e}
\end{aligned}
\tag{2}
$$

where M_e, C_e, K_e, B_e and H_e are the linearized mass, damping, stiffness, control, and disturbance matrices. Let l_{o_e} and l_e represent the nominal manufacturing length and nominal stretched length vectors respectively. For our study, we will assume that $f \in \Re^{n_f} \equiv 0$, so that our structure is not affected by outside forces. It is also relevant to note that the our control input is simply the change in manufacturing length of the cables, allowing easy access to the control variables in a physical structure by simply pulling on the cables. This configuration, q_e, must have a valid state of prestress and is therefore not arbitrary. Using the principle of virtual work, we can derive an analytic condition for the state of prestress in our symmetric tensegrity structure:

$$
\begin{aligned}
&\frac{w}{2l_b} < \sin(\theta) < \frac{l_b^{\,2} - w^2}{2l_b w}, T_V^{\,r} = 1, T_{H1}^{\,r} = \frac{2w}{\sqrt{l_b^{\,2} + w^2 - 2l_b w\sin(\theta)}}, \\
&T_{H2}^{\,r} = \frac{2(2l_b\sin(\theta) - w)}{\sqrt{l_b^{\,2} + w^2 - 2l_b w\sin(\theta)}}, [T_{o_V} \quad T_{o_{H1}} \quad T_{o_{H2}}] = \frac{[T_V^{\,r} \quad T_{H1}^{\,r} \quad T_{H2}^{\,r}]}{\left\| \left[\sqrt{6}\,T_V^{\,r} \quad \frac{\sqrt{5}}{2} T_{H1}^{\,r} \quad T_{H2}^{\,r} \right] \right\|}, \\
&[T_V \quad T_{H1} \quad T_{H2}] = P[T_{o_V} \quad T_{o_{H1}} \quad T_{o_{H2}}], T_i = T_V, i = 1,\ldots,6, T_7 = 2T_9 = T_{H1}, T_8 = T_{H2},
\end{aligned}
\tag{3}
$$

where T_i is the tension in the i^{th} string, l_b is the bar length, $\theta_1 = \theta 3 = \theta_5 = \theta$, and $\theta_2 = \theta_4 = \theta_6 = 2\pi - \theta$. Note that T_i is calculated using a prestress factor P. This is, in essence, a scaling factor that sets the tension in the cables, increasing or decreasing the natural frequencies of the structure [13]. Our desired structure has $\sin(\theta) = \frac{l_b}{w}$, as illustrated in Fig. 1. This is the nominal configuration about which the structure will oscillate when controlled by a CPG.

Dynamic Characteristics. With a linearized dynamic model complete, we can analyze the mass and stiffness matrices to shed light on the characteristic (natural) frequencies of the structure. Calculating the eigenvector-eigenvalue pairs of $M_e^{-1}K_e$ results in the associated mode shapes and square of natural frequencies of the structure. In the case of our structure with six degrees of freedom, we obtain the six expected modes of natural frequency show in Fig. 2.

The first mode, which looks similar to the first mode of a beam in bending, will be our targeted resonant mode. Whether or not a CPG can tune to this mode to exploit resonance will dictate a successful integration. Before integrating the controls, insight can be gained from the frequency response of the linearized dynamics. Using a coupled contraction and extension of cable pairs (paired cable sets for our structure will be $\{s_1, s_4\}$, $\{s_2, s_5\}$, and $\{s_3, s_6\}$) we can analyze the response of the stretched cable lengths l. For this study, our input u and output y will be:

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$$u = u_o \left[1 \quad 0 \quad 0 \quad -1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0, y = y_1 - y_4, y_i = l_i - l_{e_i} \right] \tag{4}$$

The above input-output structure isolates the control and response of the base cables ({s_1, s_4}), with equal and opposite length changes of s_1 and s_4. As shown in Fig. 3, we see a resonant peak at our first mode with an associated phase response of -90°, which is to be expected in a linear system at resonance. This is also important because resonance entrainment of the RIO, as explained in the following sections, is expected to occur for systems with this behavior.

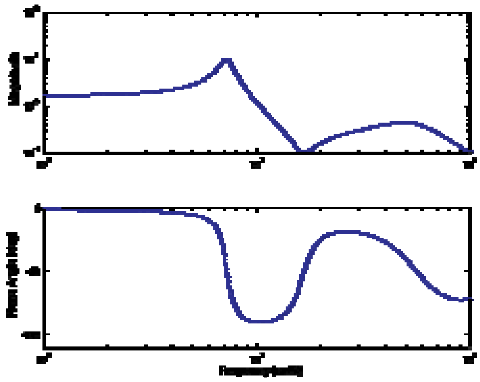

Figure 3: Frequency response *u* to *y*

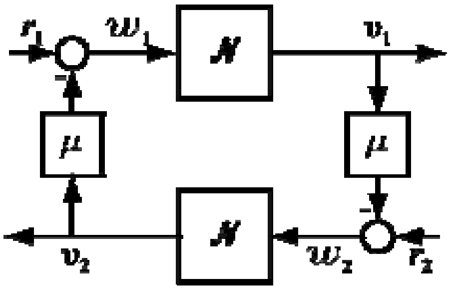

Figure 4: Reciprocal inhibition oscillator

CPG Architecture

With the dynamics of the structure complete, we can move onto the synthesis of a neural control system. Neural controls offer a robust solution to achieve a high level of autonomy in the control of robotic systems. Key characteristics that make artificial neural networks a prime candidate for control of an underwater vehicle are efficiency and adaptability. With the incorporation of sensory feedback, it should be possible for the control system to entrain to the structure's resonance, allowing for large motions with minimal effort [14]. The CPG that will be used for this study is known as a *Reciprocal Inhibition Oscillator* (RIO). It is a system of two neurons with mutually inhibitory synaptic connections. Each neuron, N, can be modeled as mapping from input *w* to output *v* as shown by [14]:

$$v = \psi(q_c), q_c = b(s), b(s) = \frac{2\omega_o s}{(s + \omega_o)^2}, \tag{5}$$

Where $\omega_o>0$. These are the dynamics of a bandpass filter, chosen to capture the lag and adaptation characteristic of neurons. The nonlinearity ψ captures the saturation property of a neuron, and is assumed to be an odd, bounded, and strictly increasing function. It is strictly concave on $x>0$ and $\psi'(0)=1$. A suitable choice for ψ is the hyperbolic tangent function, *tanh(x)*.

We now connect two of these neurons together with inhibitory connections as shown in Fig. 4, where $\mu>0$. The outputs v_i will be used to control the tensegrity structure through a gain g, and sensory feedback will return as r_i through a gain parameter h. It has been shown that the choice of g, h, and μ impacts whether or not the closed loop system (tensegrity and CPG) oscillates, and if so, whether it oscillates near the CPG's intrinsic frequency ω_o, or the structures resonant frequency [14,15]. These results will be used when integrating the CPG controls with the tensegrity structure.

CPG Control of a Tensegrity Structure

As stated earlier, the output from the CPG will be used to control the tensegrity structure. For this study we will consider controlling the base cell of the structure only, that is the manufacturing

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lengths of the $\{s_1, s_4\}$ pair. The RIO output will be the control signal for the tensegrity structure and the current cable length will be the feedback to the RIO:

$$u_i = l_{o_i} - l_{o_{e_i}}, i = 1,4, u_i = 0, otherwise, u_1 = gv_1, u_4 = gv_2, r = hy_1, r_2 = hy_4 \quad (6)$$

We have chosen this value of g so that the maximum total change in manufacturing length is ±2% of the original manufacturing length, which should ensure validity of the linear approximation in the tensegrity dynamics. Whether or not the motion is exact in comparison to the nonlinear dynamics is not crucial, but what is crucial is that strings do not go slack (carry no load), for that could result in drastically nonlinear behavior not accounted for in the linear model. Sensory feedback will be measured as the change in the stretched cable length, and be fed back to the RIO through the gain h.

It is important to note that this control architecture is different than presented in previous studies [15,16]. In these studies, the neural output was directly proportional to force or torque and the sensory feedback was directly proportional to position. In our study, the feedback remains directly proportional to position (stretched length of the cables, l, which is a function of θ_i), but the neural output is also directly proportional to position (manufacturing length of the cables, l_o). The dynamics presented earlier map the response between these two signals, just as torque can be mapped to position in the pendulum system [14]. Because the mapping from l_o to l is dynamic and not simply one to one, the CPG is expected to entrain to the resonant frequency of the response.

With the architecture presented above, we can simulate the closed loop system. Our simulation uses the following parameters: $\omega_o=4$ rad/sec, $g=0.02$, $\omega_1 = \min(\sqrt{eig(M_e^{-1}K_e)})$, and μ=1.1. Comparing different values for h, we can see (Fig. 5) that varying the feedback gain influences whether or not CPG control system is capable of entraining to the resonance of the structure. With a feedback gain of h=-20, the system oscillates at 4 rad/sec, the intrinsic frequency of the CPG. However, an h=-50 results in resonance entrainment, with the system oscillating at approximately 7 rad/sec (near ω_n of the tensegrity).

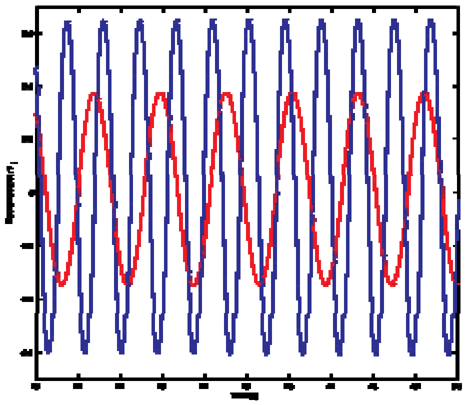

Figure 5: Neural activity v1 for h=-20 (red) and h=-50 (blue)

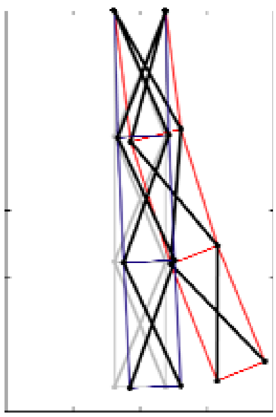

Figure 6: Maximum delfection: static contraction (blue) and resonant control (red)

The impact that operating at resonance has on the system can be seen in Fig. 6, where we notice the amplification in structural deflection. Note that this deflection is not necessarily accurate for the nonlinear dynamics, but rather illustrates that the CPG is able to tune to the linearized tensegrity's first mode.

Conclusion

In this study, we have presented the framework for integrating a biologically inspired CPG control system with a tensegrity structure. First, a nonlinear model of the tensegrity dynamics must

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be derived. It can then be linearized about a nominal and feasible state of prestress. One option is to use the principle of virtual work, but other options can be used for form finding. Next, the linear model is analyzed for its natural frequencies and mode shapes. The frequency response of the structure must also be analyzed to ensure that there is a well behaved resonant response from input to output.

If the above is accomplished, an RIO is synthesized using the framework presented above. This control system is then integrated with the tensegrity. The RIO output dictates the manufacturing lengths of the controlled tendons. After choosing the correct gains, the closed loop system can be simulated, looking for resonant entrainment of the control system.

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