Control of Postural Balance for a Tensegrity-based Vertebral Column Robot

Alex Pitti*, Ihor Kuras, Artem Melnyk*
*ETIS Laboratory, CNRS, UMR 8051, University of Cergy-Pontoise, ENSEA, Cergy-Pontoise, France
alexandre.pitti@u-cergy.fr
artem.melnyk@gmail.com

1 Abstract

We present a neural architecture capable to control synergistically a flexible robotic model of the human vertebral column toward balance and upward posture. The neural controller is composed of non-linear oscillators that control each vertebre of the column constructed on the principle of tensegrity. They play the role of the central pattern generators in the spinal cords to generate rhythmical patterns and to be entrained to the resonant modes of the tensegrity system. After exploration of the different coordination regimes for different coupling parameters, the top-down controller is able to dynamically select, amplify or inhibit each motor synergy for upward postural balance even with respect to external perturbations.

2 Introduction

Animal's musculo-skeletal system is based on a complex network of muscles, bones, nerves, tissues and soft-bodies, which are hard to replicate accurately in robots and to control. The animal's biomechanics are however well-ordered so that the neural control done in the spinal cords can fit its organization and generate the dynamical grouping of the muscles for compliant motion. The hierarchical organization of the motor control a.k.a. the motor synergies has been suggested to diminish the curse of dimensionality of control as enounced by Bernstein. Therefore, the design principles of both the body structure and of the neural model are complementary and have to be considered jointly in order to generate complex motion dynamics.

Considering the body, the musculo-skeletal system is always soft and elastic and positioned in a stable or neutral posture. This property is specific to tensile structures, which most biological systems possess as attribute. Eventhough the redundancy and nonlinearity within such dynamical system might be considered as an obstacle for control, the symmetries of the overall structure and the many resonant modes generated can serve to reduce the dimensionality of the control problem. For instance, the control and discovery of the motor synergies may be easier to find by applying synchronization and resonance to these resonant modes. In previous works, we presented a framework based on feedback resonance of chaotic controllers to excite the passive dynamics of several robotic devices and to tune them dynamically to their resonant modes. The control was done indirectly through the coupling parameters between the robot and the oscillators per se. By doing so, we decreased significantly the dimensionality of the control space. We suggested that the coupling parameters are playing the role of the neuromodulators in the spinal cords, which dynamically trigger the different motor synergies [1].

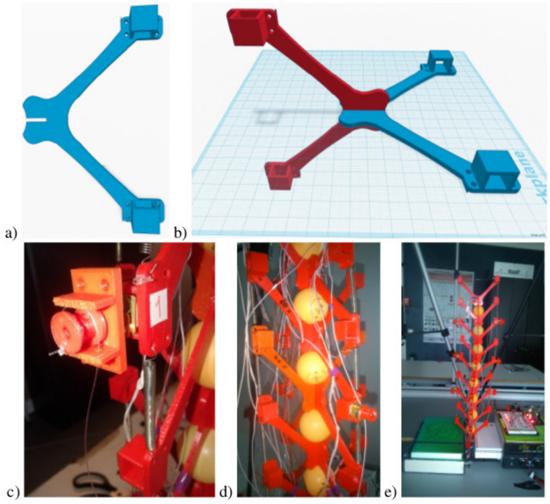

Figure 1: Vertebral column robot. This tensegrity-based robot is compliant and light-weight, mounted with springs in opposition. The motors are mounted in pairs to produce co-contractions. An IMU is placed at the top of the structure for feedback.

As our aim is of integrating the structure and the control, we expand our framework to the control of a dorsal spine robot based on tensegrity, see Fig. 1. The homepage of the project is given at [1] with videos of the vertebral column in different configurations. After exploration and categorization of its resonant modes and of its behavioral patterns within the parameters space for different coupling values, we control the spinal cord robot to return back to its rhythmical modes or to its postural configuration based on external feedback perturbations received.

---

[1] `https://sites.google.com/site/embodiedai/current-research/tensegrityrobots`

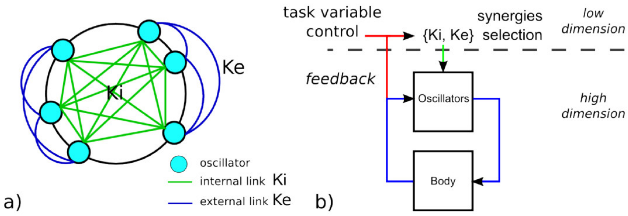

Figure 2: CPG-based control of the structure motor synergies based on the indirect coupling parameters $\{\mathbf{K_{ij}}, \mathbf{K_{ej}}, \mathbf{J_{ej}}\}$, resp. int./ext. coupling and gain.

The top-down controller pre-selects the coupling parameters to the most desired motor synergy based on the magnitude of the external perturbations on the vertebral structure. We suggest that this indirect control may play the role of neuromodulators in the spinal cords to modulate the gain of the sensory feedback on the alpha-motor neurons activity to generate the desired synergy [1, 2]. For a strong external shock, the controller will set the oscillators to a certain regime producing big oscillations, which can absorb the perturbation. At reverse, for tiny perturbations, the controller will set the oscillators to a different regime that can dampen the perturbations.

3 Methods

We present a tensegrity structure based on auto-replicative elements see Fig 1 a) and b).This particular motif reproduces the very stable structure of the tetrahedron (i.e., the pyramides) which can stand easily upward, see Fig. 1 c) and d). The whole structure possesses ten segments connected with springs and omnidirectional joints (ping-pong balls) with six electrical micro motors distributed over all the structure. We used motors with a gear head and a shaft to reel up a 10 cm tendon-like wire. Theses wires generate the local contraction and displacement of each body segment.

We use as controllers the Kuramoto model, which is a limit-cycle nonlinear oscillator employed to model central pattern generators. Each Kuramoto oscillator ϑ is coupled with each other by the phase so that any weak interactions alter the level of phase synchronization between each pair. We add three coupling coefficients, $\mathbf{K_i}$, $\mathbf{K_e}$ and $\mathbf{J_e}$ corresponding respectively to the internal coupling among the oscillators, the external coupling of the external signal to the units and the amplitude level of the ouput signal to the motors.

We draw one diagram of the pre-reflexive control performed by the oscillators on the vertebral column in Fig. 2 a) and b), which are the links in blue. In line with biomechanical studies that suggest muscles are not activated independently but are grouped in modular units, the parameters $\{\mathbf{K_i}, \mathbf{K_e}, \mathbf{J_e}\}$ correspond to the neuromodulators driven by the higher units that impose certain classes of dynamics to the motors; i.e, the motor synergies [1].

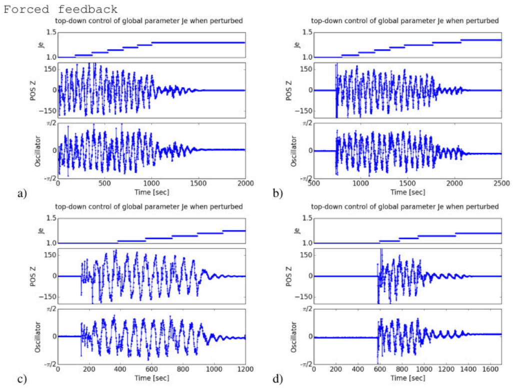

Figure 3: Feedback control of the global parameter $\mathbf{J_e}$. When a strong perturbation is imposed on the structure, an oscillatory regime is established by the top-down controller to absorb the shock with a high amplitude till their attenuation.

In order to achieve a task, controlling the three parameters $\{\mathbf{K_i}, \mathbf{K_e}, \mathbf{J_e}\}$ dynamically can permit to construct a motion pattern by combining and varying the recruitment of the motor modules, see the green line in Fig. 2 b).

4 Results

We plot in Fig. 3 an example of the top-down control strategy used to stabilize the tensegrity robot based on the modulation of $\mathbf{J_e}$ when a strong push has been applied on the structure and for four transitory regimes. The top chart displays the variation of $\{\mathbf{J_e}\}$ over time, the middle chart displays the position of the structure in the Z axis and centered on its vertical axis at 0 and the bottom chart corresponds to the dynamics of one oscillator. When a strong perturbation is applied, the higher controller generates an oscillatory regime to absorb the shock. Depending on the decreasing speed of the parameter $\mathbf{J_e}$, the forced oscillatory regime of the CPGs will be under-damped (long transitory regime) or over-damped (fast transitory regime). The transitory regime varies from an interval length of 20 seconds for the slower decays of $\mathbf{J_e}$, see Fig. 3 (a-b), to the shorter interval lengths of $5-7$ seconds for quicker decays of $\mathbf{J_e}$, see Fig. 3 (c-d). All the oscillations finish with a small vibratory mode around the vertical axis, till its return to a static posture with the release of the motors from co-contraction. This strategy was efficient in ninety percent of the cases, irrespective to the shock level.

References

[1] E. Bizzi, V. Cheung, A. d'Avella, P. Saltiel, and M. Tresch, "Combining modules for movement," *Brain Research Reviews*, vol. 57, no. 1, p. 125133, 2008.

[2] L. Ting, "Dimensional reduction in sensorimotor systems: A framework for understanding muscle coordination of posture," *Prog Brain Res.*, vol. 165, p. 299321, 2007.