

# An Adaptive Neuromechanical Model for Muscle Impedance Modulations of Legged Robots

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## 1 Motivation

Recently, an integrative view of neural circuits and mechanical components has been developed by neuroscientists and biomechanicians [11, 8]. This view argues that mechanical components cannot be isolated from neural circuits in the context of substantially perturbed locomotion. Note that mechanical passive walkers with no neural circuits only show stable locomotion on flat terrain or small slopes [2]. The argument of the integrative view has been supported by a cockroach experiment, which has demonstrated that more modulations of neural activities are detected when cockroaches run over a highly complex terrain with *larger obstacles* (*more than three times cockroach hip height*). Normally, cockroaches are able to solely rely on passive mechanical properties for rapid stabilization while confronted with *moderate obstacles* (*less than three times cockroach hip height*) [10]. In addition, neural circuits and leg muscle activities tend to be entrained by mechanical feedback [11, 12, 14]. Besides, it is well known that neural activities modulate muscle impedance such as stiffness and damping [7, 9, 15], such modulations can be utilized for stabilization in posture and locomotion [3].

Based on these findings, we propose an *adaptive neuromechanical model* with active muscle impedance modulations by external feedback, which can directly vary over neural activities. This model can effectively modulate the stiffness and damping parameters of a pair of *virtual* agonist-antagonist muscles. At the same time, it can generate appropriate muscle activities entrained by external feedback. Besides, it also enables the robot to produce variably compliant motions. Note that “*virtual*” here means motions of joints imitate muscle properties without any physical passive mechanisms such as springs.

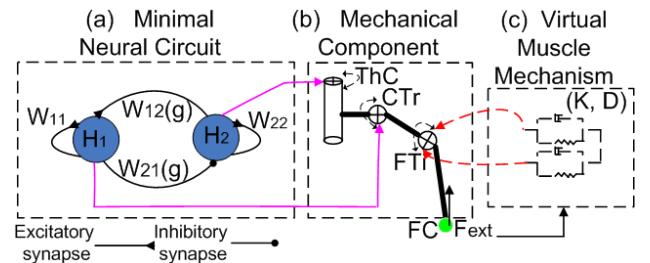
## 2 State of the Art

There are a great number of neuromechanical models that have been developed. Most of them have been presented using simulations; e.g., salamander locomotion [6], human locomotion [4] and single leg control [13]. However, few researches clarify active muscle impedance modulation by neural activities in the context of real robot locomotion. In fact, the interplay between neural circuits, muscle mecha-

nisms is substantial in legged locomotion, in particular in gait adaptation and energy efficient locomotion [5].

## 3 Adaptive Neuromechanical Model

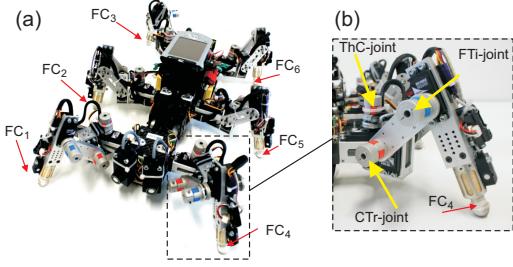
The adaptive neuromechanical model has a set of distributed and nested loops consisting of a minimal neural circuit and virtual muscle mechanisms as well as mechanical components (see Fig. 1). The neural circuit is a minimal central pattern generator (CPG) including only two neurons with full connectivity. The circuit handles the inter-leg and intra-leg coordination of locomotion. The different gaits can be easily generated by only one parameter of the CPG. The CPG activates joints, where some of them are driven by virtual muscle mechanisms. Through the external feedback, joints cannot only produce adaptive and compliant motions with actively tuned virtual muscle impedance, namely the stiffness and damping. Besides, they can also yield muscle activity entrainment varying over different walking gaits. Here, external feedback originates from interactions between mechanical components and the environment.



**Figure 1:** Adaptive Neuromechanical Model Implemented on AMOSII. (a) Neural CPG circuit controlling all ThC- and CTr-joints. The synaptic weights  $W_{11,22}$  of the CPG circuit are set to 1.4 while others  $W_{12,21}$  are regulated by a parameter  $g$ . This way, it generates various periodic outputs leading to different gaits. (b) The mechanical leg of the hexapod AMOS II consisting of three joints (ThC-, CTr- and FTI- joints, see Fig. 2 for the complete AMOS II). (c) Virtual muscle mechanism generating variably compliant motions of FTI joints. The mechanism is activated by a contact force signal  $F_{ext}$ .

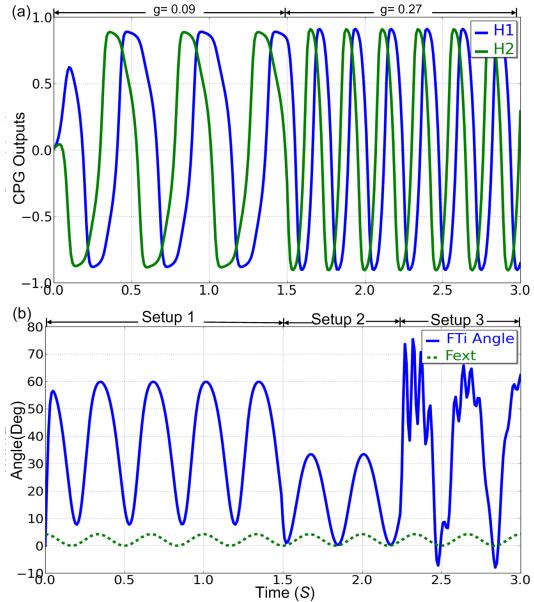
The adaptive neuromechanical model has been implemented

on AMOSII (Advanced MObility Sensor driven-walking device, see Figs. 2 and 1). This robot mimics the structures of walking animals, i.e. a cockroach.



**Figure 2:** (a) The six-legged walking machine AMOSII inspired by the morphology of the American cockroach, which has a foot contact sensor  $FC_{(1,\dots,6)}$  for each leg. (b) Each leg has three joints including ThC, CTr and FTi.

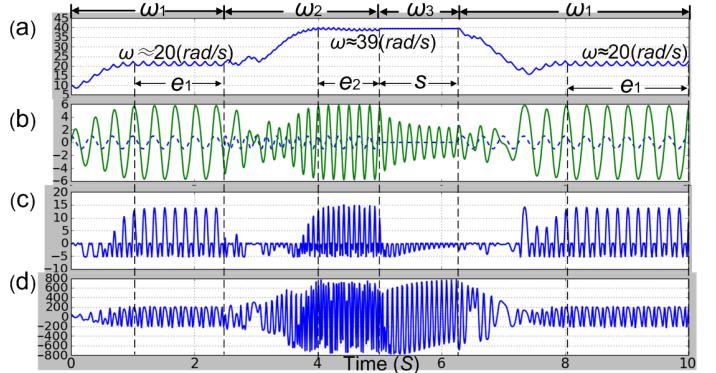
The real robotic implementation allows us to (i) demonstrate that our adaptive neuromechanical model can generate different gaits by a changing parameter of  $g$  in a minimal CPG (see Fig. 3 (a)), (ii) present variably compliant FTi joint motions by a pair of modulated parameters ( $K, D$ ) (see Fig. 3 (b)),



**Figure 3:** CPG and Muscle Outputs. (a) The periodic output signals of CPG with different values of the parameter  $g$  (e.g., 0.09 and 0.27). (b) A pair of virtual agonist-antagonist muscles is activated by a contact force signal  $F_{ext}$ . The virtual muscles can produce variably compliant motions observed through FTi joint motions, where the parameter set is given as, e.g., Setup 1 ( $K = 15, D = 0.6$ ); Setup 2 ( $K = 45, D = 0.6$ ); Setup 3 ( $K = 15, D = 0.01$ ).

(iii) show mutual entrainment between FTi joint motions driven by virtual muscles and a contact force signal  $F_{ext}$  of

the mechanical system (see Fig. 4(b)), (iv) show that the virtual muscles can still yield robust motions even though contact foot sensing fails during locomotion (i.e.,  $F_{ext}$  is zero, see  $s$  in Fig. 4(b)). In this situation, the angular frequency of muscle signals can still follow a previous frequency (i.e.,  $\omega \approx 39\text{rad/s}$ , see  $s$  in Fig. 4(a)), and (v) illustrate a nonlinear adaptation method for effectively adjusting virtual muscle impedance at different speeds or gaits (see Fig. 4). Note that the virtual muscle impedance here encompasses the stiffness and damping (see Figs. 4(c) and (d)).



**Figure 4:** Virtual Muscle Impedance Modulations. Virtual muscle impedances are actively modulated by parameters  $[K, D]$ . These modulations can be achieved by the entrainment between FTi joint motions driven by virtual muscles and a contact force signal  $F_{ext}$  with different angular frequencies  $\omega_{1,2,3}$ . (a) The angular frequency adaptation of muscle signals. (b) The entrainment between muscle (solid green) and  $F_{ext}$  (dashed blue) signals. (c) The damping parameter of muscles  $D$ . (d) The stiffness parameter of muscles  $K$ . Where the angular frequency of  $F_{ext}$  set is:  $\omega_1 = 6\pi(\text{rad/s}) \approx 18.85(\text{rad/s})$ ,  $\omega_2 = 12\pi(\text{rad/s}) \approx 37.70(\text{rad/s})$ .  $\omega_3$  means ( $F_{ext} = 0$ ), but virtual muscles can still produce usable signals (see the  $s$ ). With angular frequencies of  $F_{ext}(\omega_1$  and  $\omega_2$ ), virtual muscle frequencies converge to  $\omega \approx 20(\text{rad/s})$  and  $\omega \approx 39(\text{rad/s})$  respectively. After frequency adaptations, virtual muscles are entrained with the contact force signal  $F_{ext}$ , see  $e_1$  and  $e_2$ .

#### 4 Acknowledgements

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#### 5 Discussion Outline

*Why do virtual muscle mechanisms still work when contact foot sensing fails during legged locomotion?*

This is because the nonlinear adaptation algorithm is used for mutual entrainment between virtual muscle mechanisms

and external feedback. After mutual entrainment, the virtual muscles mechanisms can still generate usable motor commands even though there is no contact foot sensing any more (see Fig. 4). This property enables robots to yield more robust and efficient locomotion over environment. Memory recalling is an alternative way for rebuilding external sensing.

*Why do you choose mutual entrainment to modulate muscle impedance?*

Mutual entrainment between controllers (e.g., CPG circuits and virtual muscle mechanisms) and mechanical components can produce adaptive compliant motions over natural environment leading to optimal energy consumption. Besides, recent physiological experiments have shown that the leg muscle activities in animal locomotion are actively entrained by sensory feedback, which directly varies with CPG activities [1].

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