Biologically-Inspired Control Architecture for an Upper Limb, Intelligent Robotic Orthosis

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Abstract—This paper describes a biologically inspired control architecture for the McKibben actuated limbs of a humanoid robot and its application in an upper limb, intelligent robotic orthosis. The antagonistically driven joints are actuated using a biological control model. This model is observed in the measurement of human muscle elctromyograms (EMG) during reaching movements in the vertical plane. The paradigm uses the summation of tonic and phasic EMG signals to activate the human muscles. The humanoid robot's muscles, actuated by pressure control, are controlled with feedforward pressure patterns analogous to the tonic and phasic activation in the human model.

A result of this control paradigm is the realization of actuation with lower stiffness and therefore safer operation for human-humanoid interaction. It is expected that such a motion of the humanoid will closely resemble human motion and will facilitate a more human-friendly human-robot interaction. This leads to our illustration of applying the architecture to a proposed upper limb, robotic orthosis. Such an orthosis will be described in the latter part of this paper.

1. Introduction and Biological Inspiration

This paper presents an approach to humanoid robot arm control that incorporates a *biomimetic* paradigm modeled after electromyogram (EMG) signals. These signals were measured from human antagonistic muscle pairs during reaching movements in a vertical plane. When human muscles are activated to produce movement, the high frequency nerve pulses that innervate the muscles can be measured with EMG equipment. These signals are typically rectified, averaged, and smoothed [1], which results in an EMG signal that is the envelope of the high frequency nerve pulse train. The EMG signal represents the activation of the muscle.

Flanders, Pellegrini, and Geisler [1] proposed that muscle activation for reaching in the vertical plane is comprised of two principle components: (1) *Tonic* activation, which is the muscle activation for movement that is prolonged and deliberate. (2) *Phasic* activation, which is the muscle activation associated with the speed and duration of movement. In their research, they measured the EMG activation levels of the muscles involved with goal-directed reaching. Tonic EMG signals were measured during slow reaches (30cm in 1 sec) to determine the muscle activation levels required to slowly move the arm. Meanwhile, gravitational torque contributes to the majority of the tension within the muscles. Then EMG signals were measured during fast reaching movements (~ 400ms) toward the same target. The fast movement EMG signal is comprised of the tonic and phasic muscle activation levels. The phasic activation signal was mathematically determined by time scaling the tonic activation signal and subtracting it from the fast movement EMG signal. The phasic signal has a characteristic shape that has three phases. Hannaford and Stark describe the roles of the three phases, or triphasic signal, in [2]. The first phase, an agonist EMG burst, causes the joint to accelerate toward the contracting agonist muscle. The second phase, an antagonist EMG burst, causes the joint to decelerate. The third phase, a second agonist EMG burst, typically overlaps the final portion of the second phase, causing co-contraction of the antagonistic muscle pair. The co-contraction stiffens the joint and provides stabilization during the cessation of movement.

Figure 1, adapted from [1] depicts the tonic, total, and mathematically determined phasic EMG patterns of the anterior deltoid during an upward forward reaching movement. This muscle is activated as an agonist during an upward forward reaching movement corresponding to this EMG measurement. Flanders et al point out that each muscle has different triphasic patterns (duration, height, and latency of each phase) and that these patterns differ with variation of movement direction and velocity. The activation patterns will also vary for different loads being carried during a reaching movement.

For a robot with artificial muscles, a biologically motivated control paradigm can be constructed by reversing the process outlined in Flanders' work. The purpose of using this paradigm is to allow the robot to actuate its muscles in a human-like manner.

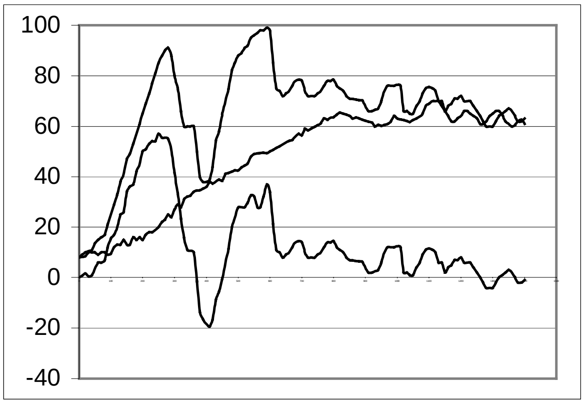

Figure 1. Adapted from Flanders, Pellegrini, and Geisler's [1]. Method for mathematically determining the Phasic Activation Signal from EMG records of human reaching movements. The top curve is the anterior deltoid EMG for a fast (400 ms) upward forward reach; the middle curve is a time-scaled EMG from slow movement (1 sec); the lower curve is the phasic EMG determined from subtraction of the time-scaled slow movement EMG from the normal speed EMG trace. (ordinate units: arbitrary, abscissa units: 100ms per tick mark).

The biological paradigm allows the robot to actuate with lower stiffness. This results in more fluidity and motion that appears more natural to the humans interacting with the robot.

2. The Humanoid Robot Arms

The humanoid robot ISAC (Intelligent Soft Arm Control) at Vanderbilt University's Intelligent Robotics Lab (IRL) has two six-DOF McKibben actuated arms, a four-DOF stereo vision head, voice recognition and localization [3]. McKibben artificial muscles antagonistically actuate each joint of the robot arms. McKibben artificial muscles are pneumatic actuators composed of rubber inner tubes covered externally by nylon braided sheaths. When pneumatic pressure is increased, the inner tube expands in a radial direction causing the angles of the braided sheath to flatten and the sheath's outer fabric to contract in the axial direction. The main advantages to the McKibben artificial muscle are that the actuator has a high force to weight ratio yet it remains pliable throughout its range of motion (For a more complete description of McKibben artificial muscles please see http://www.shadow.org.uk or http://www-rcs.ee.washington.edu/BRL/). Using the actuators as antagonistic pairs enables ISAC to have naturally compliant joints whose stiffness and angular position can be independently varied. That is, a particular position can be maintained at several levels of stiffness by simply varying the degree of co-contraction between the agonist and antagonist muscles. Figure 2 shows the humanoid form of ISAC reaching with its shoulder and elbow joints.

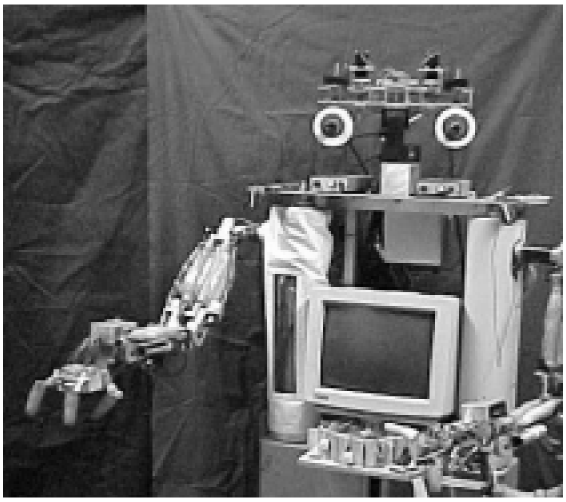

Figure 2. ISAC, the humanoid robot, shown reaching with its right arm. The muscles for the shoulder joint of the right arm are inside the vertical column to the right of the monitor.

3. The Bio-Inspired Control Architecture

The biologically-inspired control architecture is inspired by the work of Flanders (et. al.) in their measurement of human EMG signals for reaching in the vertical plane. Their findings showed that the control signal is comprised of a tonic and a phasic contribution. In their work, they measured the tonic and total activation of the muscles during reaching movements. Then they derived the phasic activation signal. This process is reversed in the control architecture being presented in this paper. For the humanoid robot, the tonic activation levels are measured, and then the phasic activation levels are estimated based upon the human phasic activation findings. The tonic and phasic activation signals are combined to activate the McKibben artificial muscles of ISAC for reaching in the vertical plane. After a reach is performed, the trajectory is compared to the bell shaped speed profile of the human hand during reaching (Abend et al. 1982 [4]; Karniel and Inbar 1997[5]; Brooks 1986 [6]; McMahon 1984 [7]). If necessary, the phasic activation pattern is adjusted to change the degree of acceleration, deceleration, or stabilization of the movement. To gain a greater understanding of the relationship between the phasic activation paradigm and the movement of the humanoid arm, measurements are proposed for variations in: reaching direction, speed, and load. While all of these variables will affect the phasic activation pattern, the latter, will also affect the tonic activation level. For a given reaching direction, the tonic activation level will change if the load is changed. It is also true that every reaching direction will result in a different tonic activation for each muscle.

For the robot ISAC, the tonic activation patterns for each muscle can be measured by slowly moving the robot's arm with a known load along a prescribed path using traditional closed loop control methods. The phasic activation patterns of all the muscles, however, must be trained for each reaching direction, load, and movement speed. In a human, both the tonic and phasic activation patterns are learned by experience

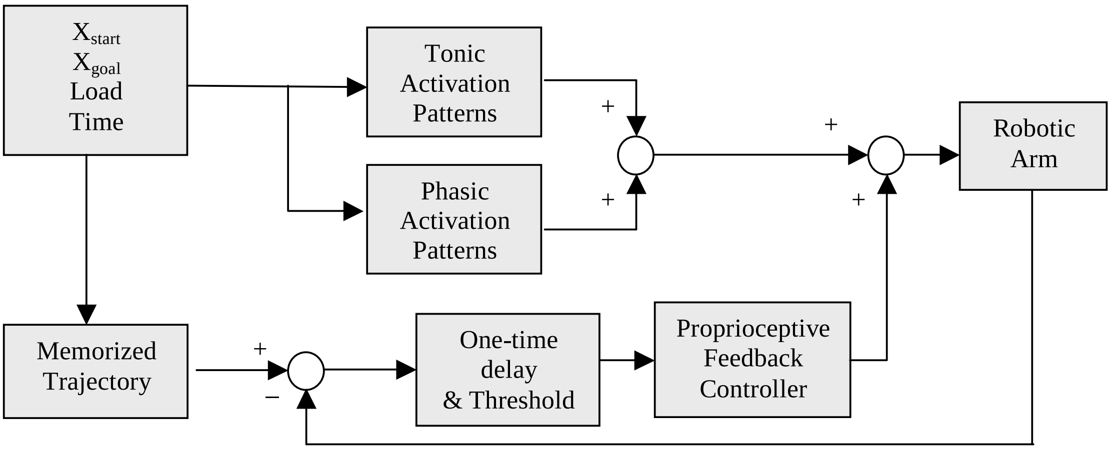

Figure 3. Biologically-Inspired Control Architecture for a Humanoid Robot. The architecture contains open-loop feedforward Tonic and Phasic activation patterns that are functions of desired reaching movement direction, reaching time, and the mass of a load that may be carried.

and are stored as adjustable motor patterns in the central nervous system. Keifer and Houk [8] suggest that during fast movements the control system for human limbs be operated *"generally in an open-loop feed-forward manner*." Berthier et al. [9] proposed that the process of reaching is essentially controlled by invoking motor programs that consist of adjustable pattern generators (APG). In their research, Berthier used an array of APG's whose collective activity controlled the motion of a two degree-of-freedom simulated limb. Their purpose was to use the APG to gain a more comprehensive understanding of how the neural mechanisms may generate motor programs. They argue that proprioception (perception of load or effort) is used to pre-select the appropriate motor programs that are stored in the parallel fiber synapses. After the program is invoked, the motion is carried out in an essentially open-loop feed forward manner. Proprioception would be used to adjust the patterns if large errors or load changes occurred.

The approach of the biologically inspired control architecture and paradigm described in this paper is motivated by the work of Flanders, Keifer and Houk, and Berthier. It is basically an approach to train the activation patterns (both tonic and phasic) required to realize reaching motions with the McKibben actuated humanoid robot, ISAC. The Control architecture works as follows (see Figure 3): A goal position (the coordinates the robot wants to reach), the desired reaching speed, and the perceived load are the inputs to the controller. These inputs are used to pre-select activation patterns for the arms muscles. Both tonic and phasic activation patterns for the agonist and antagonist muscles of each joint are pre-selected. Associated with these patterns, is a memorized trajectory (i.e., the expected trajectory for the given activation pattern) for both Cartesian and joint space. After a one time proprioceptive delay (analogous to the delay of feedback signals of the human nervous system), the proprioceptive controller compares the realized trajectory to the memorized trajectory. If error occurs in excess of a threshold, the proprioceptive controller will adjust the activation pattern of agonist and/or antagonist muscles. This adjustment will depend upon where the hand is in its reaching path. For instance, if the arm is in the acceleration phase, and the trajectory is lagging the memorized trajectory, the agonist activity will be increased. But, if the arm is in the deceleration portion of movement and the arm is lagging the memorized trajectory, then the antagonist activity will be decreased. Therefore, unlike a traditional feedback controller, the proprioceptive controller is not simply error driven, but also accounts for the context of the movement (e.g. acceleration or deceleration) in which the arm is during the reach.

In order to implement this control architecture, training of the patterns is required. This is an arduous task because there are many possible combinations of triphasic activation patterns for a complete range of motion of the muscle pairs of the shoulder and elbow joints of the robot.

4. Experimental Approach

The experimental approach to implementing the biologically-inspired control architecture involves three steps. First, the tonic activation levels for the reaching paths must be empirically determined. Second, the phasic activation patterns must be trained by trial and error, albeit with some knowledge of the results from biological experiments. (E.g., Faster reaching may require a higher amplitude in the phasic activation during acceleration of an upward reach and also require an earlier onset of the activation during.) Finally, the proprioceptive controller must be tested to tune the adjustments that are made during reaching movements. Specific details of this approach along with the experimental results from applying this approach to ISAC can be found in Northrup [10].

5. Intelligent Robotic Orthosis

Extrapolating beyond the application of the biologically inspired control algorithm with ISAC, it is easy to see how this architecture could be applied to a McKibben muscle based orthosis. In the Intelligent Robotics Laboratory, we seek to develop an intelligent orthotic system that incorporates myoelectric signals from muscles to achieve a symbiotic relationship between the user and the orthosis (Figure 4). Human-machine interfacing and system integration is extremely important in the development of the intelligent orthosis [12]-[15]. A primary function of the intelligent orthosis is controlling the gas pressure sent to the McKibben artificial muscles via the processing of EMG signals from the user. In accomplishing this action, the user can control the force applied to an object he/she wishes to grasp. Ideally, the more effort a patient applies to an object, the more force can be derived from the orthosis. The idea is not to separate the individual from the environment, but to use as much of the paralyzed person's remaining limb sensation to perform the desired action with a proportional amount of force.

Thus, our orthosis will be used to safely augment the residual arm function of a person with upper extremity paralysis. Increasing the user's strength allows the individual to take control over the desired action. Augmenting residual limb function invariably adds to the psychological effectiveness of the orthosis. The disabled individual feels more independent and empowered as though he/she is performing the task and not the device.

This orthosis may also serve as an exercise tool for someone who doesn't have a muscular atrophying disease but still needs to strengthen his or her limbs. The orthosis would decrease its assistance and resist the user as that person gets stronger. This is a feature McKibben artificial muscle systems are well suited for.

6. Discussion

This paper presents a biologically-inspired control architecture for a humanoid robot that can also be used in the development of a robotic orthosis. Since the humanoid robot's arms are actuated with agonist-antagonist artificial muscle pairs, the control paradigm is based on the biological model of triphasic activation. In this model, the muscles activate in the sequence: agonist, antagonist, and agonist. Humans use the three phases to control the acceleration, deceleration and stabilization of the joints. This control paradigm would be substantially beneficial in the design of an intelligent orthosis.

The biologically inspired control architecture has two main advantages compared to traditional feedback control architectures: (1) The co-contraction and therefore, the stiffness is reduced during reaching movements. (2) The proprioceptive feedback will adjust the activation based on where the arm is during the reach. The reduction of co-contraction and lower stiffness results in safer operation for human-humanoid interaction. It also contributes to movement that is smoother because the muscles do not pull against each other more than is necessary to produce the motion.

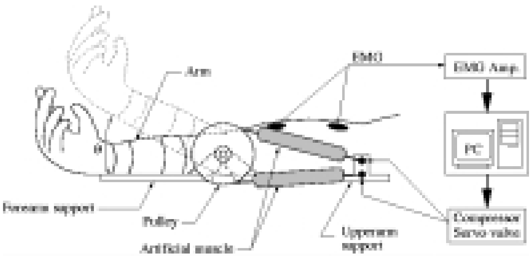

Figure 4. Intelligent Robotic Orthosis

In conclusion, this paper also proposes an intelligent, robotic orthosis that is externally powered and actuated through the use of McKibben artificial muscles. The orthosis is portable, lightweight, sturdy, and safe, thus alleviating the difficulties of more bulky orthoses and offering a useful aid that is also comfortable and aesthetically appealing. In addition, our proposed orthosis will be used to safely augment the strength of individuals with muscular atrophying diseases using myoelectric signals.

The proposed device also has benefits beyond the field of orthotics itself. It may be used as an exercise and rehabilitation device for a patient without a muscular atrophying disease but who still needs to strengthen his or her limbs. The device could be used to provide either assistance in a task, or resistance, as needed for rehabilitation. Additionally, the orthosis also has promise as a virtual reality input/output device, providing the user with force sensations associated with arm movements to sense the dynamics of the user's environment.

Finally, the use of the biologically inspired control paradigm provides an architecture that achieves better human-machine interaction. It offers more human-like, fluid motion for the orthosis. Thus, this paradigm is extremely beneficial and appealing since it increases the ease of use and functionality of the orthosis for the user.

7. Acknowledgements

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