Biologically-Inspired Control Architecture for a Humanoid Robot

Steve Northrup, Nilanjan Sarkar, and Kazuhiko Kawamura

Center for Intelligent Systems,
Vanderbilt University, Nashville, TN 37235
snorthru@vuse.vanderbilt.edu

Abstract

This paper describes a biologically-inspired control architecture for the McKibben actuated limbs of a humanoid robot. The antagonistically driven joints are actuated using a biological control model 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. Proprioceptive feedback is utilized in the control architecture to correct for misperceived loading conditions and time variance of the actuators.

The control architecture, initial experimental results, and experiments are discussed in this paper. 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.

1. Introduction and Biological Inspiration

This paper presents an approach to humanoid robot arm control that uses a *biomimetic* paradigm modeled after the electromyogram (EMG) signals measured in human antagonist muscle pairs during reaching movements in the 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 planed 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 while gravitational torque contributes the majority of the tension to 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. The roles of the three phases, or *triphasic* signal, are described by Hannaford and Stark 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. The bio-

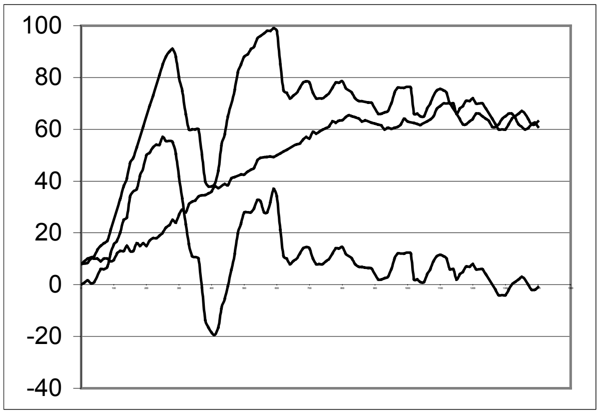

Figure 1. Adapted from Flanders, Pellegrini, and Geisler's [1]. Method for mathematically determining the Phasic Activation Signal from EMG records of human reaching movements. The top curve is the anterior deltoid EMG for a fast (400 ms) upward forward reach; the middle curve is a time-scaled EMG from 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).

logical paradigm allows the robot to actuate with lower stiffness, which 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 with rubber inner tubes and a braided external tube. When pneumatic pressure is increased, the inner tube expands in the radial direction causing the braid angles flatten and the 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.

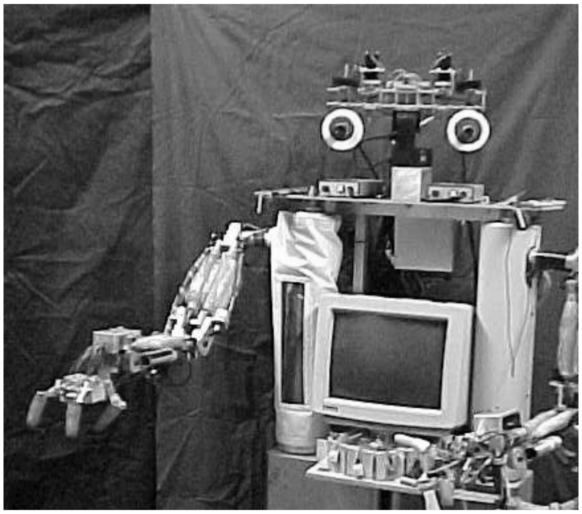

Figure 2. ISAC, the humanoid robot, shown reaching with its right arm. The muscles for the shoulder joint of the right arm are inside the vertical column to the right of the monitor.

3. The Bio-Inspired Control Architecture

As eluded to in the introduction, this 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, 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 know 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 and are stored as adjustable motor patterns in the central nervous system. Keifer and Houk [8] suggest that the during fast movements the control system for human limbs is 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.

4.1 Tonic Activation Measurement

To measure the tonic activation of the humanoid robot arms, a closed-loop PID controller was utilized to move the hand along a Cartesian path very slowly. Both movement direction and load are varied for several combinations within the range of the workspace and robot's load capacity. During the movement, we recorded the activation levels (pressures) of the muscles used to counteract the gravitational torque exerted on the joint. The pressure sequence was compressed in time to match the duration of a fast reach.

4.2 Phasic Activation Training

To train the phasic activation of the arm, a triphasic pattern was generated using Gaussian distributions for the three phases. The height, width, and latency of each of the three phases were varied. The triphasic activation pattern was summed with the time-scaled tonic activation pattern and sent to the arm while the arm was in an initial posture holding a known load. The motion that resulted was a fast reach generally along the path of the tonic activation measurement path. The trajectory of the resulting motion was measured for directional accuracy and to determine whether (and how well) the speed of the hand follows a bell-shaped curve and how similar the curvature of the reaching path was to

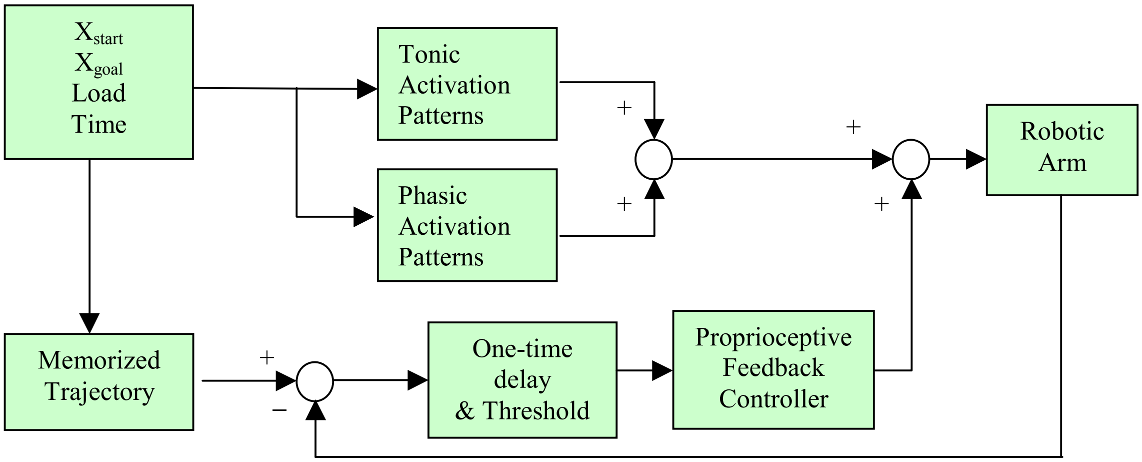

Figure 3. Biologically-Inspired Control Architecture for a Humanoid Robot. The architecture contains open-loop feedforward Tonic and Phasic activation patterns that are functions of desired reaching movement direction, reaching time, and the mass of a load that may be carried.

reaching paths observed in human subjects. If the resulting path is not accurate for speed and direction, the triphasic pattern was adjusted and the trial was repeated. The procedure was repeated until the movement was sufficiently close to a human model of movement. The model for movement direction was derived from Flanders [1] and the model for movement speed was the bell-shaped speed profile.

4.3 Proprioceptive Corrections

The control architecture shown in Figure 3, includes a proprioceptive feedback controller to correct for variations in system properties and for unexpected load changes or misperceived load size. System properties that may vary slightly include the input pressure to the valves that control the actuator pressures. This is analogous to fatigue in human muscles. When a human muscle is fatigued, a given activation will not result in the same force output as is expected when the muscle is not fatigued.

5. Experimental Results

The testing for the tonic and phasic activation paradigm was performed for reaching directions of –30 to +30 degrees from the horizontal plane in 15-degree increments with reaching times of 0.6 seconds and 1 second and with loads up to two pounds. Thirty different combinations of reaching direction, reaching speed and load were tested. The tests were performed as open-loop experiments in order to determine the proper phasic parameters for each reaching experiment. Most of the reaching experiments resulted in hand trajectories that closely followed a bell-shaped Cartesian velocity. The tuning of the Gaussian phasic parameters was also used to create timing offset between the elbow and the shoulder rotations. The purpose of the timing offset was to produce hand paths that had curvature similar to the curvature observed in the reaching tests that were performed on human subjects in [1].

Figure 4 shows ideal and experimental data for the 0.6-second reach in the +15-degree direction: the angular trajectory data, Cartesian trajectory data, and the tonic, phasic and combined activation of the shoulder agonist. This data is displayed because +15-degree reaching in human subjects had the smallest amount of curvature. Therefore, the trajectory data should be very close to the ideal trajectories where a reaching path of the hand traverses (in Cartesian coordinates) a straight path with bell-shaped velocity. The top graph of Figure 4 shows that ISAC's elbow and shoulder joints closely followed the ideal trajectory. The middle graph shows that the Cartesian hand path was quite accurate in the X component of the trajectory, but that the Z component of the trajectory was lagged and then led the ideal trajectory. This caused the hand to traverse an S-shaped path in the X-Z plane. The bottom graph in Figure 4 depicts the shoulder agonist muscle tonic, phasic, and combined activation. The activation pattern is similar to the two agonist phases of the triphasic EMG activation pattern observed in human reaching experiments. The movement onset of ISAC's arm is about 200 milliseconds after the activation pattern begins.

The experimental design included a triphasic model for the shoulder and the elbow with three Gaussian parameters (amp, time delay, and width) for each of the phases. The total number of phasic parameters was 18. During the experiments to determine the correct values of the parameters for each reach, we found that only 12 parameters were necessary to control the reaching trajectories of ISAC's hand.

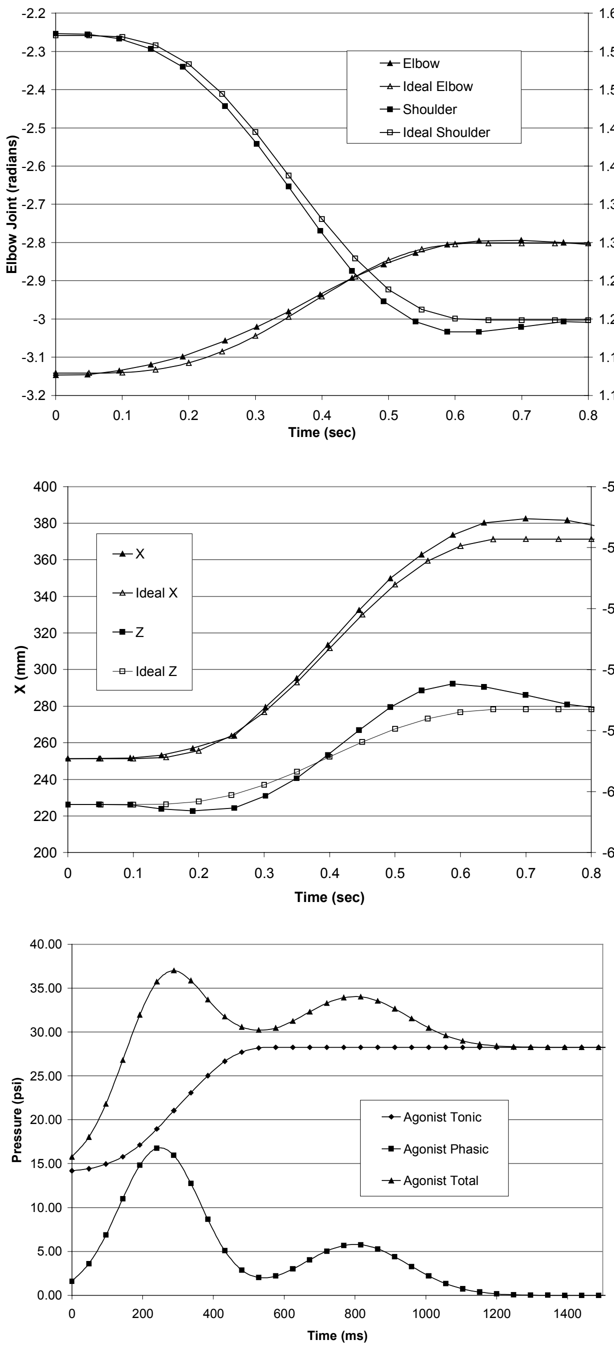

Figure 4. Experimental Results for unloaded, +15-degree reaching with 0.6-second reaching time. Top: Ideal and experimental angular trajectories of the elbow and shoulder joints. Middle: Ideal and experimental Cartesian trajectories. Bottom: Tonic, phasic, and combined activation of shoulder agonist muscle.

Regression analysis was performed on these phasic parameters to determine the relationships between the phasic parameters and the reaching direction, reaching speed, and weight being carried. Eleven of the twelve regression models were significant with a value of $p<0.0006$. This value indicates the probability that the independent variables (speed, direction, and weight) contributed to the regression models strictly by chance. The one dependent variable with an insignificant model was the width value for the third phase of the shoulder. The reason for this is that this variable was constant within each of the speed levels. Since there was no variation within each speed, the regression model was not valid. Table 1 summarizes the regression coefficients for the phasic parameters (dependent variables) in the open-loop reaching experiments. Amp Mu and Sigma refer to the amplitude, time delay, and width parameters of the Gaussian phases. The number after the variable is the phase number.

The proprioceptive feedback controller was tested to determine show that adding the feedback would eliminate any steady-state error. Figure 5 shows the results of the test for a –30-degree, unloaded, 1-second reaching movement.

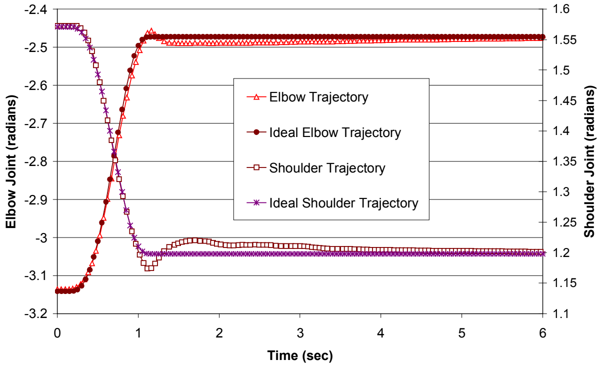

Figure 5. Proprioceptive feedback added to tonic-plus - phasic feedforward control architecture.

6. Discussion

This paper presented a biologically-inspired control architecture for a humanoid robot along with the results of initial experiments. 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, agonist. Humans use the three phases to control the acceleration, deceleration and stabilization of the joints.

Table 1. Regression Coefficients for the Dependent Variables (phasic parameters).

Dependent Variable	Intercept	Speed	Weight	Direction
Elb. Mu1	924.6	-933.3	8.8	-1.22
Elb. Mu2	-499.6	1187.5	-11.3	-0.39
Elb. Amp1	1984.2	-1941.6	-42.50	-5.39
Elb. Amp2	-340.4	115.0	24.75	5.49
Elb. Sigma1	710.7	-712.5	2.75	-1.43
Elb. Sigma2	117.5	87.5	0.0	0.83
Shld. Mu1	-224.3	846.6	-25.8	-1.33
Shld. Mu3	2164.6	-2183.3	18.8	-0.75
Shld. Amp1	1361.6	-1089.2	33.5	0.66
Shld. Amp3	551.7	-541.7	-10.0	0.06
Shld. Sigma1	-62.5	304.2	-5.0	-0.11

The initial open-loop experiments have been used to learn the affects of speed, direction, and load on the tonic and phasic activation paradigm. Once the activation patterns were determined for the reaching movements, the patterns and their expected responses were stored for recall when a reach was invoked by higher level control. When the reach trajectory did not closely match the expected response that was associated in memory, the proprioceptive feedback controller adjusted the phasic activation patterns as necessary. The proprioceptive controller was able to eliminate steady-state error. Future testing will be conducted to examine the effects of misperception of loading conditions.

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 and in movement that is smoother because the muscles do not pull against each other more than is necessary to produce the motion. The proprioceptive adjustments to the activation insure that the correct amount of activation is added/subtracted to/from the muscles based upon their present function (i.e., whether the muscle is causing acceleration, deceleration, or stabilization) during a reach and not solely upon the basis of the instantaneous positional error or history thereof.

7. Acknowledgements

This work was partially supported by DARPA under contract DASG 60-01-1-0001.

8. References

[1] M. Flanders, J. J. Pellegrini, and S. D. Geisler, "Basic features of phasic activation for reaching in vertical planes," *Experimental Brain Research,* 110, pp. 67 – 79, 1996.

[2] B. Hannaford and L. Stark, "Roles of the elements of the triphasic control signal," *Experimental Neurology,* 90, pp. 619 – 634, 1985.

[3] K. Kawamura, R.A. Peters II, D.M. Wilkes, W. Alford, T. Rogers, "ISAC: Foundations in Human-Humanoid Interaction", *IEEE Intelligent Systems & their* applications, vol. 15, no. 4, pp. 38-45, Jul/Aug, 2000.

[4] W. Abend, E. Bizzi, and P. Morasso, "Human arm trajectory formation," *Brain*, vol. 105, pp. 331 – 348, 1982.

[5] A. Karniel and G. F. Inbar, "A model for learning human reaching movements," *Biol. Cybern.*, vol. 77, pp. 173 – 183, 1997.

[6] V. B. Brooks, *The Neural Basis of Motor Control*, Oxford University Press, New York, 1986.

[7] T. A. McMahon, *Muscles, Reflexes, and Locomotion.* Princeton University Press, Princeton, 1984.

[8] J. Keifer and J. C. Houk, "Motor function of the cerebellorubrospinal system," *Physiol. Rev.*, vol. 74 pp. 509 – 542, 1994.

[9] N. E. Berthier, S. P. Singh, A. G. Barto, and J.C. Houk, "Distributed representation of limb motor programs in arrays of adjustable pattern generators," *Journal of Cognitive Neuroscience,* 5, pp. 56 – 78, 1993.

[10] G. K. Klute, J. M. Czerniecki, and B. Hannaford, "McKibben Artificial Muscles: Pneumatic Actuators with Biomechanical Intelligence," *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM '99)*, (Atlanta, GA), 1999.