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MYOELECTRIC CONTROL USING MODULATED MINIMUM JERK MOVEMENT

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ABSTRACT

A new control system for elbow prostheses is proposed. The system would use myoelectric activity (MEA) measurements to modulate the execution of a maximally smooth, minimum jerk movement. A prosthesis controller may extract information from MEA measurements about both the intended movement, for example elbow flexion, and about the time course of the movement including, for example, average speed and duration.

Recent advances in myoelectric signal measurement have identified a deterministic portion of MEA at the onset of movement. This information has been used to determine gross movement information, including movement direction and joint selection. Common prosthetic control schemes would then generate a movement with either constant velocity or with the velocity proportional to measured MEA. These movements are simple in concept but appear unnatural and are difficult to control during interactive tasks.

In contrast, a minimum jerk movement has interesting properties that make it a plausible choice as a movement primitive. Each minimum jerk segment can be parameterized with three parameters. Commonly these are chosen to be start time, finish time and average velocity. Researchers have proposed methods by which these movements can be combined by straightforward super-position techniques to yield natural movements. This paper discusses minimum jerk movements as prosthesis movement primitives and presents a control system architecture that uses deterministic information from MEA for movement selection and MEA amplitude estimates for on-line modulation of movement parameters. Application of this type of control system should result in smooth prosthetic movements.

IMPORTANCE OF THE CONTROLLER

There are several important features of a practical control system design. In controllers for use in powered limb prostheses a fundamental decision is the source of input. Typically, it is either derived from myoelectric signals from the amputee's remnant muscles or from position or force sensors in a harness system. From the point of view of the amputee and prosthetist, the decision on which signal to use as a control input primarily affects the level of difficulty of use.

From the point of view of the control engineer, several other features are also important [see,

for example, 1]. Any controlled system must exhibit stable behaviour and this is the fundamental concern in all control system designs. The input signal must contain enough 'information' to cause the controlled device to perform as the amputee desires. Broadly speaking, controllers can be divided into classes: regulators which are designed to maintain variables at a certain predefined constant level (the equivalent of maintaining posture) and servo systems which are designed to provide an output response that tracks a commanded input with a high degree of precision. This is often referred to as "tracking" by control system engineers.

Myoelectric prostheses are therefore servo systems where the movement, usually the velocity, of the device is required to follow an input signal based on measured myoelectric activity. The relationship between myoelectric activity and movement is usually not based on physiological relationships but on algorithms that are simple enough for an amputee to easily grasp and comprehend and that the amputee can learn to use with minimum difficulty.

A major concern of the amputee is that his replacement arm "look" normal. Impressions of what "looks normal" are based not only on colour and texture but on movement. Prostheses that have jerky movements with sudden stops and starts appear very non-human no matter how faithfully they reproduce the appearance of the human limb. Because a control system fundamentally changes the dynamic characteristics of the arm it can have a major effect on the movement of the prosthesis and on the amputees acceptance of the device.

GOALS IN SELECTION OF A CONTROLLER

The goals of a myoelectric control system for a powered prosthesis can be summarized as:

- stable performance
- ease of use
- adequate tracking
- apparently 'normal' motion patterns, smooth movements
- suitability for general task execution
- adequate noise and disturbance rejection
- insensitivity to model errors or changes caused by the manipulation of a load

NATURE OF FEEDBACK CONTROL

Common control systems used by engineers employ feedback. Based on information gained through a measurement of the variable(s) to be controlled and their desired values an error signal can be generated (by subtraction). A feedback control system uses this error signal to determine the appropriate command that will reduce the size of the error to zero. Zero error means perfect correspondence between command and reality.

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The major problem with feedback control is that too much of it usually results in an unstable system. Consider that if the command generated by a small error is too large, the system may react too strongly and generate a larger error in the opposite direction. This process can continue and generate an unbounded oscillation.

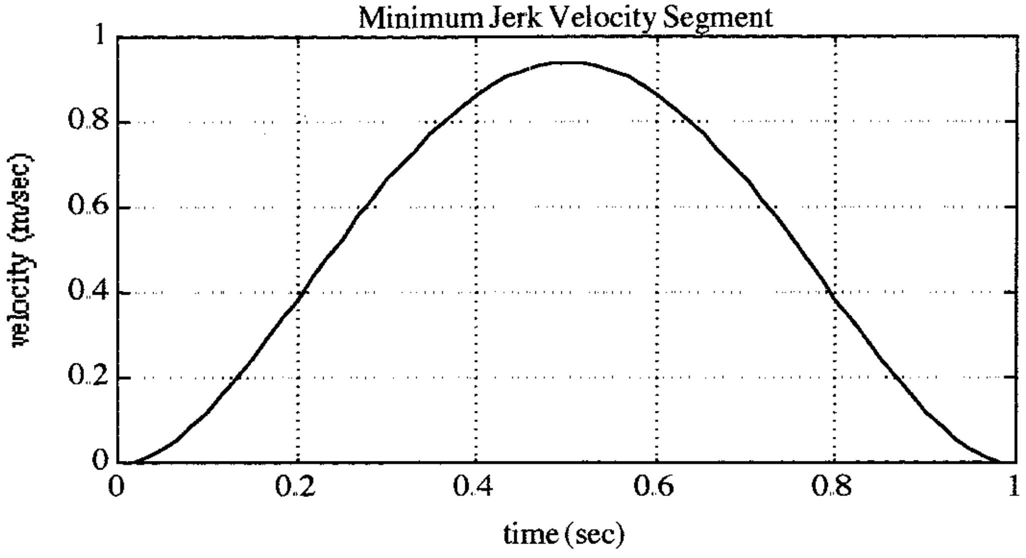

Figure 1. Single Minimum Jerk Velocity Segment. Note the smooth movement and the start and end of the motion. (Start time = 0.0 sec, stop time = 1.0 sec, average velocity = 0.5 m/sec)

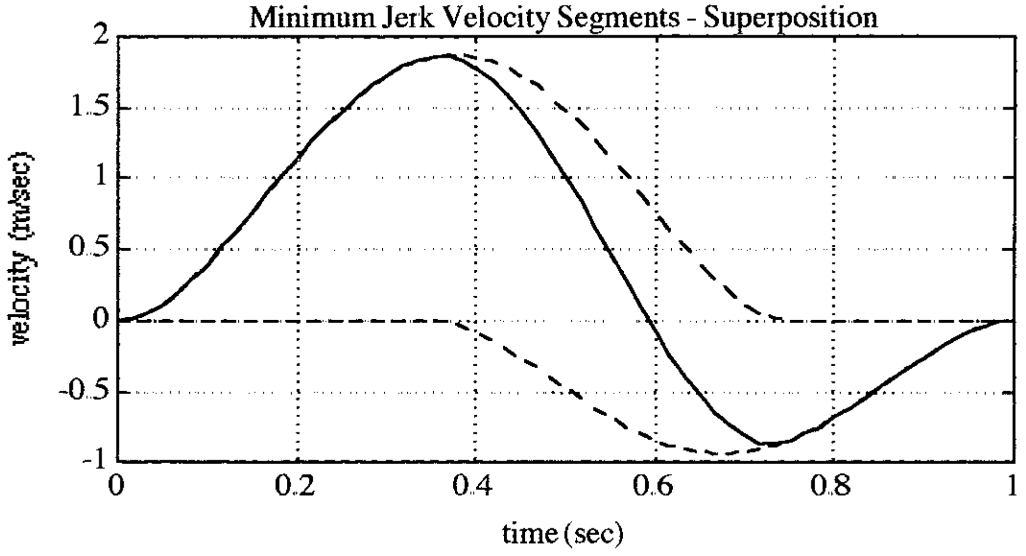

Figure 2. Two Minimum Jerk Velocity Segments Superimposed. Note the smooth movement and the start and end of the motion. (First segment: Start time = 0.0 sec, stop time = 0.75 sec, average velocity = 1.0 m/sec; Second segment: Start time = 0.35 sec, stop time = 1.0 sec, average velocity = -0.5 m/sec)

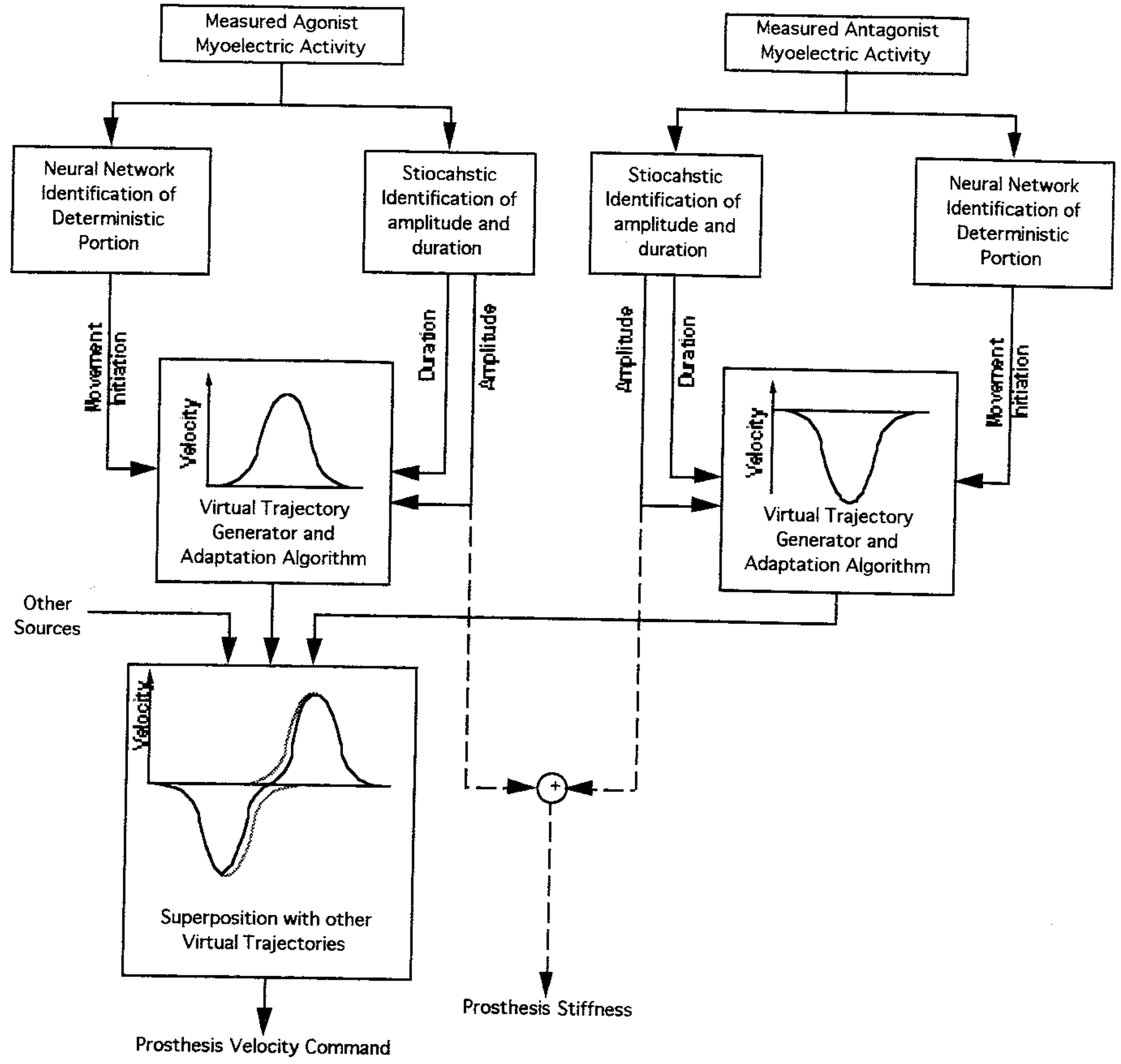

Figure 3: Schematic of the Proposed Control System Structure. Measured myoelectric activity is processed to select a desired movement. This generates a movement segment. Features of the myoelectric signal are further used to modify the segment based on adaptive control techniques. The segment is then combined with other segments, either generated previously or generated through other input sources, before the velocity command is sent to the prosthesis. In this case, by using an agonist-antagonist pair, stiffness command information can be generated as well.

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ADAPTIVE CONTROL AND MINIMUM JERK SEGMENTS

The exact relationship between myoelectric activity and desired movement is complex and unknown. Experiments have shown that the concept of a virtual trajectory is very useful in understanding movement patterns [2]. The virtual trajectory represents the path of the equilibrium position of the limb, that is, the progression of positions that the limb would take if all external forces are removed. External forces together with the impedance of the limb generate the actual position of the limb. Several experiments have been performed that indicate the virtual trajectories have a distinctive appearance for simple movements [3]. The movements are well described by single unimodel velocity profiles. One possible description of the shape of these profiles is based on a maximally smooth movement, which, when smoothness is defined in terms of minimum jerk (the derivative of acceleration) result in solid agreement between theory and data [4]. Other research has shown that minimum jerk movements are related to minimum power [5]. Simple superposition techniques have been suggested as possible techniques for combining multiple trajectories [2]. This situation might arise, for example, when there is a change in task after a movement has begun.

Adaptive control, not well defined, generally considers systems for which the parameters of the controller are varied in response to commands or performance measures [6]. In this case a controller is proposed that would modify the parameters of a commanded minimum jerk movement. At the onset of myoelectric activity, a neural network or equivalent circuitry would identify an intended movement based on the initial deterministic portion of the signal. The control system would then initiate a minimum jerk command trajectory to the appropriate prosthesis actuator. Continued measurement of myoelectric activity would be used to modulate the magnitude of the peak velocity of the movement, based for example on filtered rectified magnitude information, and the duration of myoelectric activity might be related to the duration of the commanded movement.

As the controller issues a commanded movement to the prosthesis the stiffness of the prosthesis and the level of external load would determine the actual position of the prosthetic limb. This is very similar to the way in which an intact limb may function. A final additional feature of the proposed control system would allow readjustment of the movement after a movement has been initiated. Before the commands are sent to the actuator, the minimum jerk profile is superimposed with previously initiated movement initiated from either a previous period of myoelectric activity from the same muscle or from an antagonist muscle. The commanded movement from an antagonist muscle would be in the opposite direction as a command from the agonist muscle. This feature would mean that coactivating an agonist-antagonist pair would result in no movement (the two trajectories would cancel each other because of the opposite directions of movement) and allow the use of coactivation to modulate the limb impedance.

ADAPTATION AND THE VIRTUAL TRAJECTORY GENERATOR

The critical element in the implementation of the proposed system is the virtual trajectory generator. It must generate a movement profile that has the minimum jerk form and allow that form to be adaptively changed without deviating significantly from the required shape. Two possible approaches to this problem are currently under consideration.

The first approach involves using and modifying an algebraically defined minimum jerk movement segment in the controller. Minimum jerk movements are defined by minimizing the integral of the least square of the jerk throughout a movement. Jerk is the derivative of acceleration. Mathematically, the value of J is to be minimized where J is defined as:

$$J = \int_{start}^{finish} (\dddot{x})^2 \, dt \qquad 1.$$

Using the calculus of variations and solving, the velocity of the movement is found to be governed by a fourth order polynomial in time. Assuming that a well defined movement segment starts at position x_0 and time t_0 and stops at position x_1 and time t_1, the minimum jerk velocity profile can be shown to take the form:

$$V(t) = 30(V_{avg}) \frac{(t - t_0)^2 (t - t_1)^2}{(t_0 - t_1)^4} \qquad 2.$$

Where,

$$V_{Avg} = \frac{x_1 - x_0}{t_1 - t_0} \qquad 3.$$

Note that the velocity profile can also be characterized in terms of the RMS velocity or the peak velocity. For minimum jerk segments it can be shown that:

$$\frac{V_{RMS}}{V_{Avg}} = \sqrt{\frac{10}{7}} \quad \text{and} \quad \frac{V_{peak}}{V_{Avg}} = \frac{15}{8} \qquad 4.$$

The adaptation algorithms that could be used to modulate a minimum jerk trajectory would use measured characteristics of the myoelectric signal in order to modify the parameters V_{Avg}, t_1 and, possibly, t_0. Consideration of the dynamics that would result in a minimum jerk movement illustrate some potential problems. A minimum jerk movement, once underway, can be analyzed from a control system point of view as follows. Setting t_0 to equal zero to avoid unnecessary algebra means that t_1 represents the duration of the movement segment. This can be done without loss of function-

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ality since the control system will not require a delay between the time when the detection algorithm detects a deterministic indicator in the measured myoelectric activity and the actual start of the segment. Under these conditions, the Laplace transform of the controller output (a minimum jerk segment) can be shown to be:

5.

These dynamics consist of five poles at the origin and two right half plane zeros. Placing a stable feedback loop around such a system is difficult. Further, it would also be difficult, without carefully designed mechanisms, to have usable feedback signals present in the system.

An alternative approach is based on preliminary results from Mansfield [5]. Analysis was performed that indicated for simple systems that minimum jerk movement patterns have a strong analytical relationship to movements in which power is minimized. While further analysis is required to develop these ideas for complex manipulation problems, they can be applied to the present problem. A control scheme could be developed to minimize the power used by a prosthesis. Such a control scheme would be based on combined techniques of optimal and adaptive control theory. A formulation of the control problem is desired which would include in the cost function to be minimized some measure of myoelectric activity. In this way the system would continually search for the minimum power solution with myoelectric activity measurements as one input. The resulting system should, based on extrapolating the relationship between minimum jerk movements and minimum power movements hypothesized in Mansfield, result in movements with natural characteristics.

FUTURE WORK

This paper presents an outline of a possible new and advanced technique for controlling powered prostheses based on myoelectric signals. Much work is required, and is underway, to define stable adaptive control algorithms for use in generating minimum jerk virtual trajectories. Note that this control scheme is ideal for use in combination with a mechanism that employs real, physical impedances for optimal energy [7] since a stiffness command is created independently of the virtual trajectory.

$$V(s) = 60V_{Avg}\frac{\left(s-\left[\frac{3}{t_1}+\frac{\sqrt{3}}{t_1}i\right]\right)\left(s-\left[\frac{3}{t_1}-\frac{\sqrt{3}}{t_1}i\right]\right)}{t_1^{2}s^{5}}$$

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