Research report

Does the brain make waves to improve stability?

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Abstract

In many ways, roboticians and the human brain are faced with the same problem: How does one control movement from a distance? In both cases, delays in the transmission of information play an important role, either because the distances to be covered are long (imagine controlling a robot arm on the moon from a command center on Earth), or because the underlying hardware is slow (nerves transmit information much more slowly than wires, radio waves or light). Delays have a debilitating effect on feedback control systems; causes and effects can bounce back and forth between distant sites, resulting in oscillatory behavior that can grow without bound. Control engineers have developed the concept of wave variables to combat this problem—by mimicking a flexible rod, wave variables constrain movement of the master and slave during the delay, ensuring stable overall behavior [G. Niemeyer, J.J.E. Slotine, Stable adaptive teleoperation, IEEE J. Ocean Eng. 16 (1991) 152–162; G. Niemeyer, J.J.E. Slotine, Toward bilateral internet teleoperation, in: Beyond Webcams, an Introduction to Online Robots, MIT Press, 2002]. Mother Nature may, however, deserve the patent on this solution. As we show here, the properties of nerves, muscles and sensory organs combine to form a natural wave variable control system that is immune to the problems of feedback delays.
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Keywords: Human brain; Motor control; Muscle; Proprioception; Spinal cord; Reflexes

1. Introduction

In a teleoperation system, the operator controls a slave robot by manipulating a local master device (Fig. 1A). Forces applied by the operator to the master are transmitted to the slave which then applies an equivalent force to the external load. Resulting movements of the slave are measured and used to control the movements of the master, giving a sense of remote presence to the operator. Ideally, the operator would be free to control the master as if acting directly on the load itself. Transmission delays, however, severely limit how the operator can manipulate the master controller. The reason is intuitive: the operator will push the system towards a desired position, but will detect that the desired position has been achieved only after a delay. By the time the command to stop moving has been transmitted, the slave will have overshot the desired point, requiring a backwards correction. If the delay is long, corrections by the operator will be applied out of phase with the overshoots, leading to oscillations that grow without bound.

Wave variables [19–22] can be used to maintain stability in teleoperated systems by mimicking the behavior of a flexible rod (Fig. 1B). If one deflects the near end of the rod, the effects will not be felt at the far end instantaneously. Instead, the deflection will travel the length of the rod in the form of a wave, thus introducing delay into the system; the longer the rod, the longer the delay. In contrast, however, to pure delays that electromechanical circuits can produce, the rod is an intrinsically passive device. It cannot add energy to the system and so, by basic physical principles, cannot introduce instability to the coupled system [1,7]. More intuitively, the rod constrains the movements of the master even before force and movement information has had time to travel to and from the slave. This prevents corrective actions of the operator from getting out of phase with actions of the slave, thus avoiding unstable oscillations.

The proof that wave variables are useful for the control of teleoperated systems lies in the fact that such control schemes have actually been put to use. Wave variables have successfully been employed to control teleoperated systems with significant delays, such as internet-base telemanipulators [21]. But what about biological control systems? First, muscles act as natural

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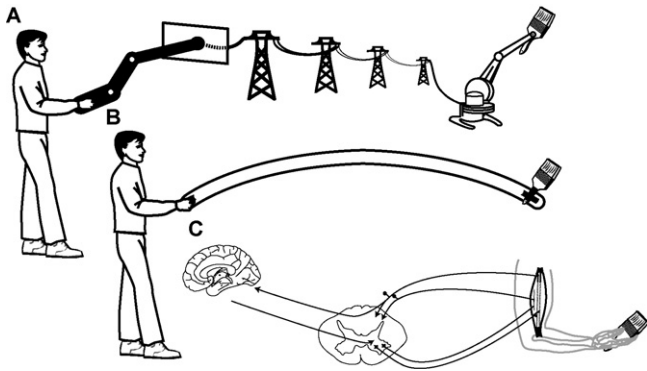 *E-mail address:* joe.mcintyre@univ-paris5.fr (J. McIntyre).

Fig. 1. (A) *Typical teleoperation system.* The operator interacts with a distant device through a force-reflecting master joystick. The slave mimics the movements of the master through a local servo loop and feeds back measurements of the forces required to do so, giving the operator a sense of effort. Transmission delays may make the system unstable. (B) *Flexible rod analogy.* Commands to move or push and sensation of resulting forces and displacements travel up and down the rod as waves. The rod creates delays but cannot induce instability. (C) *Biological control systems.* The visco-elastic properties of muscles treat nerve activity like a wave variable and sensory organs in muscles, tendons and joints provide the complementary feedback wave. Muscles and nerves thus act like the flexible rod such that position, velocity and/or force can be controlled without regard to transmission delays.

wave variable processors. Activating a motor neuron in the spinal cord is analogous to moving the proximal end of the rod—the distal end will either move the same distance, if free to do so, or, through flexion of the rod, will push against the constraint. This is the defining feature of wave variables: a wave variable command signal will cause a change of force *or* a movement, or both, depending on the interaction with the environment. But to show that biological systems act like wave variable controllers, incoming and outgoing signals must act like *complementary* wave variables. To a first approximation, the outgoing muscle command can be described as a weighted *difference* of length and force, i.e. $\Delta u \propto \Delta f - \Delta l$, such that increasing the motor command u induces either an increase in muscle force f or a decrease in muscle length l. To meet the wave variable criterion the returning sensory signals must therefore reflect the weighted *sum*, i.e. $\Delta v \propto \Delta f + \Delta l$. A combination of sensory signals from muscles and tendons meet this criterion: fibers from spindle organs measure changes in length, while nerve fibres from Golgi tendon organs respond to changes of muscle force. As we will show in more detail below, the basic structure of the peripheral motor system in humans and other animals follows the design rules of a wave variable control system and therefore benefits from its inherent stability despite delays.

2. Principals of wave variable-based control

A more detailed analysis of wave variable theory shows how this approach differs from more classical teleoperation schemes (see Fig. 2): First and foremost, commands from master to slave and sensor information from slave to master are transmitted via complementary wave variables u and v, respectively. At each instant the position and velocity of the master controller ($\pi_m = \dot{p}_m + \lambda p_m$) is combined with the delayed sensor signal v_m to

form the outgoing command u_m:

$$u_m = v_m + \sqrt{2b}\pi_m \qquad (1)$$

Parameter b is the "wave damping" factor of the equivalent rod which, as we will see further on, plays an important role in the tuning of the control system to a particular task. The simultaneous encoding of position and velocity in a single quantity π is reminiscent of the phasic/tonic properties of many neural signals. This extension to the basic wave variable design gives the added advantage of both position and velocity control at the endpoint.

The slave servo controller interprets the delayed signal u_s as a command to move or push, depending on the interaction with the environment [21]. The slave then combines sensor information about the force it is applying f_s with the command signal u_s to form the feedback wave v_s:

$$v_s = \sqrt{\frac{2}{b}}f_s - u_s \qquad (2)$$

Because velocity and force pass through the delay together, power in equals power out such that no energy is created.[1]

Fig. 3 illustrates the potential benefits of the wave variable approach in the face of feedback delays. Gain values that produce stable behavior in the traditional architecture without delay, but unstable behavior with delay, become stable again when implemented via a wave variable control scheme. The master controller can treat the variables π_m and f_m as reflections of the position + velocity (π_s) and force (f_s) of the remote system, without regard to delays.

3. Wave variable-based biological control?

Can an analogy be made between the workings of a wave variable-based teleoperated system and the control of movement by the brain (Fig. 1C)? To address this question, we consider what is known about biological sensors and actuators.

First, muscles emerge as natural wave variable processors in that the commands sent to muscles specify an ambiguous combination of force, position and velocity information. Based on Fig. 2, the forces produced by the slave in the teleoperated control system follow the control law:

$$f_s = \frac{B}{B+b}\left[\sqrt{2b}u_s - b\pi_s\right] \qquad (3)$$

where B (stiffness and damping of the slave) and b (wave damping factor) are both positive. Remembering that π carries both position and velocity information ($\pi = \lambda p + \dot{p}$) and that increasing the external joint angle of the arm decreases muscle length in a flexor muscle ($\Delta l = - r \Delta p$, where r is the moment arm of the muscle around the joint and p is the joint angle), we have:

$$f_s = \frac{B}{B+b}\left[\sqrt{2b}u_s + br\frac{\partial l}{\partial t} + br\lambda l\right] \qquad (4)$$

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[1] For a more complete description of wave variable principles as applied to teleoperated systems, see works by Niemeyer and Slotine [19–22].
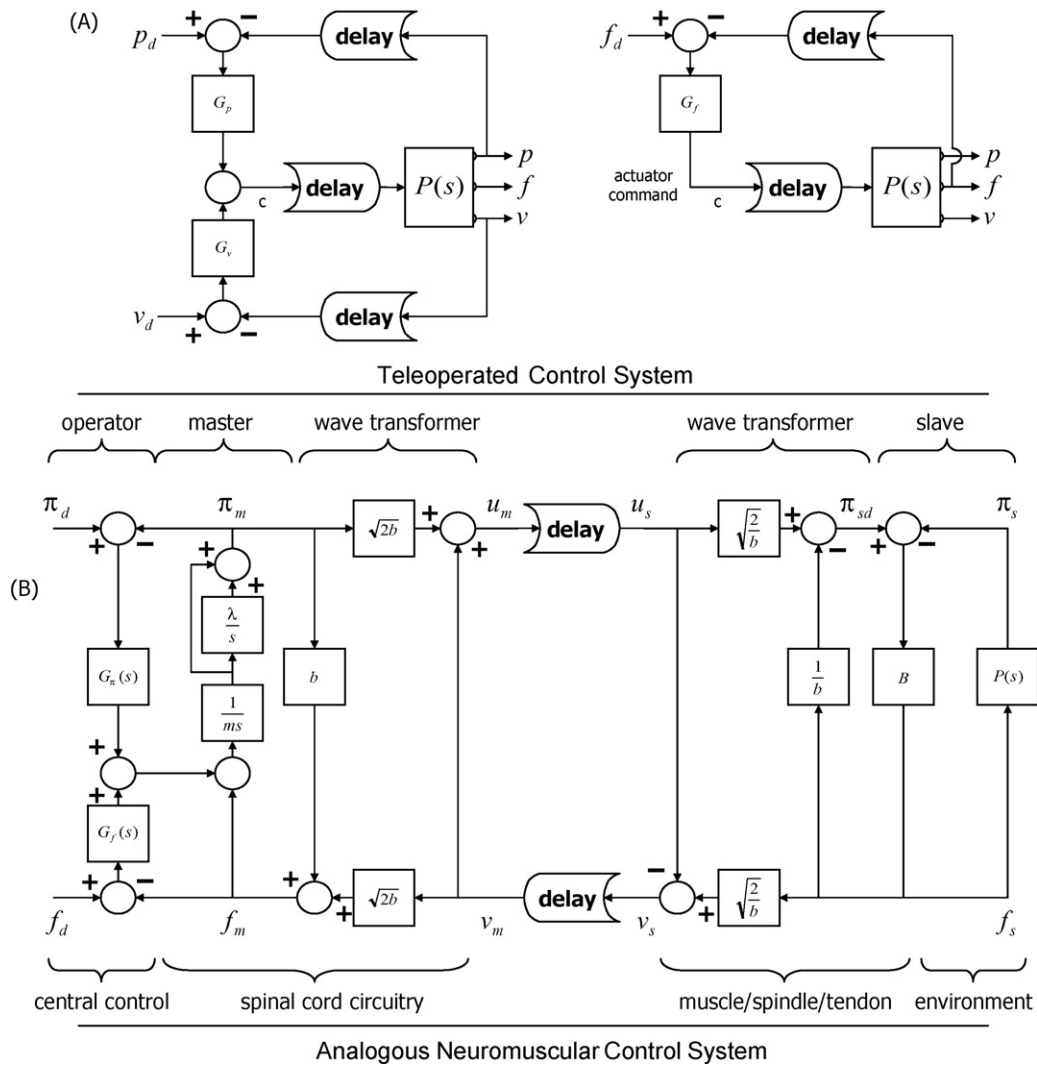
Fig. 2. (A) *Traditional feedback control systems*. Motor commands (*c*) are sent to the actuators of the plant *P*(*s*) to cause a displacement of the controlled system (*p,v*) and/or a force (*f*) exerted against the environment. The command signal *c* may be computed based on errors between the desired and measured position and velocity or force. Feedback gains determine the tracking precision with respect to the desired values. (B) *Wave variable implementation*. Position (*p*) and velocity (*v*) are encoded as a single composite variable $\pi = \dot{p} + \lambda p$. Sensory and control signals are transmitted between master and slave via wave variables *u* and *v*, each of which contains information about position and velocity (*π*) and force (*f*).

This equation captures the essential features of a muscle: an increase of neural activation u_s, an increase of the muscle length *l* or an increase of lengthening velocity d*l*/d*t* all result in an increase of muscle force f_s.

The above formulation shows that the motor command to the muscle matches the criteria for a wave, but wave-like behavior of one control signal is not sufficient to guarantee stability. To prove the hypothesis of a wave variable control system, the feedback control signals must act like the *complementary* wave *v*. On the sensory side of Fig. 2 we have:

$$v_s = \frac{B-b}{B\sqrt{2b}}f_s - \sqrt{\frac{b}{2}}\pi_s \tag{5}$$

which, by appropriate substitution, gives:

$$v_s = \frac{B-b}{B\sqrt{2b}}f_s + \sqrt{\frac{b}{2}}r\frac{\partial l}{\partial t} + \sqrt{\frac{b}{2}}r\lambda l \tag{6}$$

This too can be related to signals from muscles and tendons: type II and Ia nerve fibers from spindle organs signal quantities related to static length (*l*) and lengthening velocity ($\partial l/\partial t$), respectively, while type Ib fibers from Golgi tendon organs respond to muscle force (*f*). Of course, the type of information carried by each fiber is not nearly so distinct; all three respond to a combination of force and length changes. It is clear, however, that the signals carried in the sensory nerve provide the same information as the wave variable v_s. The fact that different signals are carried by different fibers is of no importance, so long as all three types of signals are delayed by a similar amount. Nor is it required that biological systems be linear or that the weighting factors in Eqs. (4) and (6) be exactly matched. As long as Eqs. (4) and (6) hold *differentially* (i.e. for small displacements around any given operating point) wave variable stability will be afforded. Thus, the basic structure of the peripheral motor system in humans and other animals follows the design rules of a wave variable control system and therefore benefits from its inherent stability despite delays.
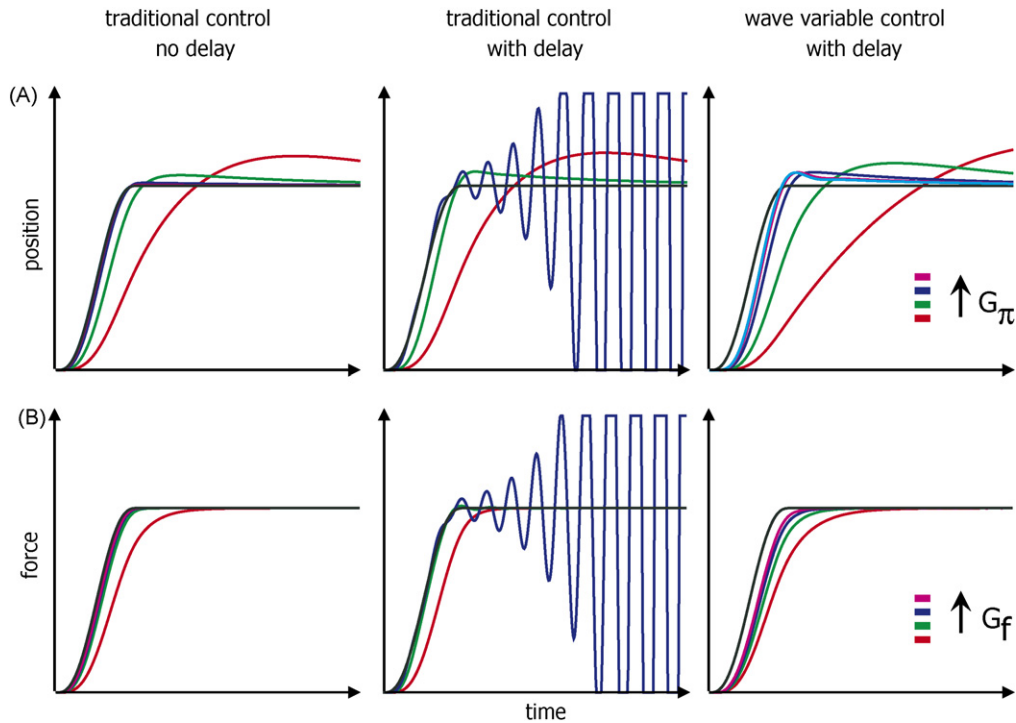
Fig. 3. *Performance of traditional feedback control vs. wave variable control*. Increasing feedback gains for a position/velocity controller (A) or an integral force controller (B) can remain stable without feedback delays (left) but quickly becomes unstable for moderate feedback delays for traditional feedback control (center). The wave variable control scheme (right) ensures stability despite the feedback delays. Any feedback control system that would be stable acting directly on π_s and f_s without delays will also be stable in the presence of delays when applied to π_m and f_m.

4. Model predictions

The observations about biological sensors and actuators noted above are not new. While the precise characteristics of these elements are still the topic of hot debate amongst Neuroscientists, the generalizations expressed above are based on more-or-less accepted viewpoints on the characteristics of each of these elements. The value of applying a wave variable analogy to these observations lies in its ability to explain or predict the structure of neuronal circuits in the spinal cord.

4.1. Positive force feedback

First, one can see that the returning wave v_m adds positively to the central command π_m to form the descending command u_m. This implies that activity in Ia, Ib and II nerve fibres can all increase the activity of the muscle (depending on the relative value of b and B). This is logical for muscle length and velocity components provided by Ia and II fibres: the classical stretch reflex provides negative feedback that stabilizes limb posture in space. More curious, however, is the potential positive influence of type Ib fibres on the motor command. Positive force feedback would normally de-stabilize a control system and yet has been observed in biological systems [6,12,13]. The wave variable approach reconciles this phenomenon with stability constraints. The summation of force, position and velocity may result in positive force feedback, but the wave variable structure nevertheless stabilizes the system in the face of transmission

delays. Furthermore, wave variables may account for switches from positive to negative feedback in some spinal reflex loops [12,13,24]. In wave variable terminology, the parameter b of Eqs. (1)–(6) represents damping inherent in the flexible rod. This parameter may be adjusted to optimize the interaction between the control system and the environment in a process known as impedance matching [19]. Because the magnitude of b relative to B determines the sign of the force contribution to the returning wave v, a large (small) b will result in negative (positive) force feedback.

4.2. Spinal cord dynamics

The wave variable approach also requires stable dynamics on the master side of the control system [20]. In a teleoperation system, this requirement is fulfilled by the force-reflecting joystick that the operator manipulates. Of course, a similar mechanical device does not exist in the spinal cord, but dynamical circuits that mimic its action might. If so, one can predict what would happen if one opens the loop and artificially injects a returning wave signal. In the case of the telemanipulator, the return wave v_m adds to the position + velocity π_m of the joystick to proportionally increase the outgoing u_m. But the return wave also generates force against the mass of the joystick. A constant value of v_m causes π_m to increase exponentially if unchecked, which in turn causes u_m to increase even more, albeit with some latency. Opening the loop in a biological system is equivalent to cutting the sensory fibers and stimulating them directly. Under

these conditions one would also expect to observe two temporal components in the resulting modification of the outgoing motor command: a short-latency proportional response and a long-latency exponential response. While this hypothesis needs to be tested more specifically in the context of the wave variable hypothesis, both such effects have been observed experimentally in different paradigms [6,12,13].

4.3. Deafferentation

Another virtual experiment can be performed by opening the feedback loops during position/velocity control. For the classical position controller of Fig. 2A, if p is erroneously measured to be 0, then for any value of p_d other than zero, a constant force will be generated that will drive the limb to its limits. In contrast, the dynamic properties of the master control circuitry in Fig. 2B are self-limiting even when the feedback loop is cut (i.e. even if v_m is set to 0 independent of the true value of v_s). The master controller defines a stable equilibrium position π_m that will be followed by the slave, albeit with some additional error. This feature of the wave variable control scheme can explain how patients and animals deprived of proprioceptive feedback manage to produce stable, targeted arm movements [11,26].

5. Discussion

It should be noted that the properties of biological control systems that lend themselves to the wave variable architecture are well known. The idea that motor commands specify either a push or a movement was recognized by Bernstein [2] and later developed into equilibrium point (EP) [4,5,8,9,23,25] and impedance control [14–16] hypotheses. The importance of the visco-elastic properties of muscles to the stable control of movement forms an integral component of one EP model [3,25] while the definition of an overall equilibrium via reflex pathways is the basis of another [8–10]. The dilemma posed by positive force-feedback loops in biological control systems has also been studied empirically, showing that positive force feedback coupled with negative position feedback can yield a stable system [17,27,28], but the fundamental reason as to *why* the CNS would employ such a strategy has not heretofore been clearly elucidated. The wave variable hypothesis recasts the principles behind these theories in a new light in which properties of muscles and sensory organs work together to yield robust control despite feedback delays. Shown here to be applicable to muscles and spinal reflexes, this concept can be extended to more complex neural circuits [29]. In fact, it has also been proposed that the cerebellum acts as a wave variable processor [18]. Wave variables therefore represent a new way of looking at an old problem. The wave variable framework promises to provide further insight into the workings of the human motor control system.

Acknowledgements

References

[1] R. Anderson, M. Spong, Bilateral control of teleoperators, IEEE Trans. Auto. Contr. 34 (1989).

[2] N.A. Bernstein, On the Construction of Movements, Medgiz, Moscow, 1947.

[3] E. Bizzi, N. Accornero, W. Chapple, N. Hogan, Posture control and trajectory formation during arm movement, J. Neurosci. 4 (1984) 2738–2744.

[4] E. Bizzi, N. Hogan, F.A. Mussa-Ivaldi, S.F. Giszter, Does the nervous system use equilibrium-point to guide single and multiple joint movements? Behav. Brain Res. 15 (1992) 603–613.

[5] E. Bizzi, S.F. Giszter, E. Loeb, F.A. Mussa-Ivaldi, P. Saltiel, Modular organization of motor behavior in the frog's spinal cord, Trends Neurosci. 18 (1995) 442–446.

[6] R.M. Brownstone, J.P. Gossard, H. Hultborn, Voltage-dependent excitation of motoneurones from spinal locomotor centres in the cat, Exp. Brain Res. 102 (1994) 34–44.

[7] J.E. Colgate, N. Hogan, Robust control of dynamically interacting systems, Int. J. Contr. 48 (1988) 65–88.

[8] A.G. Feldman, Functional tuning of the nervous system with control of movement or maintenance of steady posture. ii Controllable parameters of the muscles, Biophysics 11 (1966) 565–578.

[9] A.G. Feldman, Once more on the equilibrium-point hypothesis (λ model) for motor control, J. Motor Behav. 8 (1986) 17–54.

[10] A.G. Feldman, D.J. Ostry, M.F. Levin, P.L. Gribble, A.B. Mitnitski, Recent tests of the equilibrium-point hypothesis (lambda model), Motor Control 2 (1998) 189–205.

[11] C. Ghez, R. Sainburg, Proprioceptive control of interjoint coordination, Can J. Physiol. Pharmacol. 73 (1995) 273–284.

[12] J.P. Gossard, R.M. Brownstone, I. Barajon, H. Hultborn, Transmission in a locomotor-related group Ib pathway from hindlimb extensor muscles in the cat, Exp. Brain Res. 98 (1994) 213–228.

[13] P. Guertin, M.J. Angel, M.C. Perreault, D.A. McCrea, Ankle extensor group I afferents excite extensors throughout the hindlimb during fictive locomotion in the cat, J. Physiol. 487 (Pt 1) (1995) 197–209.

[14] N. Hogan, An organizing principle for a class of voluntary movements, J. Neurosci. 4 (1984) 2745–2754.

[15] N. Hogan, The mechanics of multi-joint posture and movement control, Biol. Cybern. 52 (1985) 315–331.

[16] N. Hogan, E. Bizzi, F.A. Mussa-Ivaldi, T. Flash, Controlling multijoint motor behavior, Exercise Sport Sci. Rev. 15 (1987) 153–190.

[17] J.C. Houk, Regulation of stiffness by skeletomotor reflexes, Annu. Rev. Physiol. 41 (1979) 99–114.

[18] S.G. Massaquoi, J.J. Slotine, The intermediate cerebellum may function as a wave-variable processor, Neurosci. Lett. 215 (1996) 60–64.

[19] G. Niemeyer, Using wave variables in time delayed force reflecting teleoperation, PhD Dissertation, Massachusetts Institute of Tecnology, 1996.

[20] G. Niemeyer, J.J.E. Slotine, Stable adaptive teleoperation, IEEE J. Ocean Eng. 16 (1991) 152–162.

[21] G. Niemeyer, J.J. Slotine, Toward bilateral internet teleoperation, in: Beyond Webcams An Introduction to Online Robots, MIT Press, 2002.

[22] G. Niemeyer, J.J. Slotine, Telemanipulation with time delays, Int. J. Robot. Res. 23 (2004) 873–890.

[23] D.J. Ostry, A.G. Feldman, A critical evaluation of the force control hypothesis in motor control, Exp. Brain Res. 153 (2003) 275–288.

[24] K.G. Pearson, D.F. Collins, Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity, J. Neurophysiol. 70 (1993) 1009–1017.

[25] A. Polit, E. Bizzi, Processes controlling arm movements in monkeys, Science 201 (1978) 1235–1237.

[26] A. Polit, E. Bizzi, Characteristics of motor programs underlying arm movements in monkeys, J. Neurophysiol. 42 (1979) 183–194.

[27] A. Prochazka, D. Gillard, D.J. Bennett, Implications of positive feedback in the control of movement, J. Neurophysiol. 77 (1997) 3237–3251.

[28] A. Prochazka, D. Gillard, D.J. Bennett, Positive force feedback control of muscles, J. Neurophysiol. 77 (1997) 3226–3236.

[29] J.J. Slotine, W. Lohmiller, Modularity evolution, and the binding problem: a view from stability theory, Neural Networks 14 (2001) 137–145.