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Human Motor Control and the Internal Model Principle ⋆

R. Brent Gillespie * **Amir H. Ghasemi** * **Jim Freudenberg** **

* *Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109 USA (e-mail: brentg@umich.edu).*
** *Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109 USA (e-mail: jfr@umich.edu).*

In the motor behavior literature, the observation that humans can learn and adapt to altered limb dynamics is often explained with reference to internal models. Forward internal models enable robust performance even when feedback is intermittent or delayed while inverse models simplify the loop dynamics to manageable form. Internal models of coupled limb/object dynamics, however, do not address the skill with which humans track references or reject disturbances that can be recognized and anticipated. We propose that internal models of reference or disturbance signals create a useful framework for addressing open questions in human motor behavior. We appeal to the Internal Model Principle in control theory, which suggests that a model of the predictable signal (a signal generator) belongs in the controller. When the control loop is already stable, such an internal model will produce perfect tracking or disturbance rejection in steady state. In this paper we apply the Internal Model Principle to hypothesize controllers that elicit cyclic behaviors from systems that feature elastic and inertial energy storage. We also outfit this model with features that describe human neuromuscular dynamics and thereby enable the description of two roles for force feedback: carrying power that couples the human/machine dynamics and carrying information for neural control processing.

1. INTRODUCTION

Humans are very good at eliciting cyclic behaviors from systems that feature elastic and inertial energy storage. Dribbling a basketball, bouncing a ball on a racquet, and juggling are all skills that require energy to be driven back and forth between kinetic and potential forms while dissipated energy is replaced. Humans are evidently able to tune into oscillatory dynamics to identify limit cycle frequencies and to time interactions so as to initiate and stabilize oscillatory behaviors (Stefan et al., 1996; Huang et al., 2007; Ankarali et al., 2014). Even walking and running can be considered dynamic tasks that challenge the human motor system to tune into and appropriately drive the passive dynamics of various gaits (Kuo, 1999). Humans are also quite good at tracking oscillatory targets and when necessary eliminating the effects of oscillatory disturbances. The principles of control harnessed by the human motor system that make such feats possible are of high interest for several reasons. A model that captures human skill in handling oscillatory dynamics could facilitate the design of machines intended for human use and the design of automation systems that share control with humans. Insight into human motor skill might also inform the development of motor skill training programs and motor rehabilitation therapies.

Any control architecture hypothesized as a basis for the human motor system must accommodate delays in feedback signals that are orders of magnitude greater than delays in engineered control systems. Sensory feedback arriving at the central nervous system is delayed by 50-100 ms due primarily to slow neural conduction velocities (Jeannerod, 1998). The transmission of command signals to muscles adds a similar increment to the loop delay. As a result, high gain feedback control, the standard approach for improving response in many engineered systems, is not available to the human motor system. Feedforward control is classically offered as the alternative. However, simple motor behavior experiments indicate that feedback is used for more than simply setting up and tuning feedforward controllers. Corrections are made to rapid targeting movements just as soon as sensory feedback becomes available (Desmurget and Grafton, 2000; Yu et al., 2015). We therefore seek a control architecture that harnesses feedback but also accommodates delay in the feedback loop.

Two rather distinct threads of research and practice have developed in automatic control that can be used to produce potentially fruitful and provocative hypotheses for the human motor system. As it so happens, both of these threads have the words "internal model" in their name. First we have Internal Model Control (IMC), which largely grew out of the process control industry (see, for example (Morari and Zafiriou, 1989)). Second we have the Internal Model Principle that was first proposed by (Francis and Wonham, 1975, 1976). But while Internal Model Control has often been used to generate conjectures about human motor control, the Internal Model Principle remains on the sidelines.

Internal Model Control posits that a model of the process under control can be profitably incorporated into the feedback loop. For example, the Smith Predictor is a type of Internal Model Controller that uses a forward model of the plant to generate a delay-free signal for feedback control. The so-called Internal Model hypothesis in motor behavior, wherein forward

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(Garcia and Morari, 1982; Rivera et al., 1986; Rivera, 1999; Miall R.C. et al., 1993). A forward model of the dynamics of the body and coupled environment has been hypothesized as a means to produce a controller that basically functions as an inverse of the plant (Wolperta and Kawatob, 1998).

In this paper, however, we explore the Internal Model *Principle*, an alternative basis for controller design that is concerned with tracking references and rejecting disturbances whose behaviors can be recognized and characterized. According to the Internal Model Principle (IMP), in order for a feedback system to robustly track persistent reference inputs, or reject persistent disturbances, the controller must itself incorporate a model of the persistent dynamics. The most common use of this idea is the use of integral control to track step commands and reject step disturbances, where each command and disturbance is modeled as the response of an unforced integrator to a nonzero initial condition. The internal model principle is also used in the disk drive industry to reject periodic disturbances and track periodic inputs (Franklin et al., 1994).

In this paper we present a model of the human motor controller that has its underpinning in the Internal Model Principle. We adopt IMP as a framework for exploring human behaviors that involve tracking steady oscillations or rejecting steady oscillatory disturbances. But we are also interested in how IMP might address how humans extract steady oscillatory behavior from resonant systems or underdamped second order dynamics. The limiting case of an *un*damped second order system (an oscillator) is a particularly tractable problem for our purposes, since an oscillator must *not* be driven at its natural frequency to remain stable. In steady state, the oscillator must be uncoupled from the human operator. When uncoupled, the oscillator response only plays the role of an exogenous disturbance, and thereby fits the IMP framework.

Manual control of a mechanical oscillator like a spring-mass system involves a loop closure, like any mechanical contact. Both force and motion variables are involved. With motion designated the input variable to the spring-mass system, the response variable is force. We can consider the force a disturbance input to the control system that is responsible for regulating the input motion of the spring-mass system to zero. Now, the disturbance force acting on the human operator is a particularly interesting matter to consider given that the human does not behave like an ideal motion source. Force feedback is a load under which the human hand will "bend," since the hand has a finite backdrive impedance.

The mechanics of the body, in particular the finite backdrive impedance displayed at the hand, present an additional challenge to the human motor system, perhaps even more fundamental than the challenge presented by sensorimotor delay. Muscle does not function as an ideal motion source (infinitely stiff to loads) nor as an ideal force source (infinitely forgiving to the movement of a load). In engineering terms, the body behaves like an actuator with finite impedance (a backdriveable actuator). To hold position against an oscillating load (or to apply a fixed force to an object that moves in an oscillatory fashion,) the motor control system must anticipate the disturbance load (or the motion) and the response of the body to ensure that responses of the backdrivable body are suppressed. As a result of backdrivability, the user's body and the environment become dynamically coupled at the control interface and biomechanics become part of the closed loop dynamics. Thus the coupled dynamics of the environment and body must be accommodated by any viable control architecture.

Of course to suppress the response of the body to dynamic loads, the option exists to increase the impedance with which position is held or to increase the admittance with which a force is applied. Increasing impedance can be accomplished by co-contracting muscles for example. But these approaches are generally only adopted when the task dynamics is still novel, as they are metabolically expensive strategies (Burdet et al., 2001). Once the dynamics are learned or the pattern of oscillation is recognized and characterized in terms of its waveform and frequency, humans adopt a modest impedance while timing muscle action to the task challenge. We have previously explored the role of force (torque) and visual feedback when human users excite oscillations in a resonant system (Huang et al., 2007). From these studies, we are convinced that the control adopted by the human user accounts for or perhaps even harnesses to advantage the finite impedance with which effort is imposed on the environment by the human body.

In the immediately following sections we compare the McRuer Crossover Model (an example of Internal Model Control) to the Internal Model Principle and offer a simple interpretation of IMC in terms of transmission zeros. We also present results from a simple compensatory tracking experiment with sinusoidal input as evidence for the existence of an internal oscillator that functions as the generator of a signal that cancels the disturbance. Thereafter in section 4 we present a model of the coupled dynamics of backdrivable human operator and a spring-mass system and analyze its stability. In section 5 we present a simulation study in which IMC is used to design a controller that produces steady oscillations in the coupled dynamics.

2. THE MCRUER CROSSOVER MODEL

According to the McRuer Crossover Model, a human operator may be described as a controller $C(s)$ that tailors itself to the plant $P(s)$ such that the loop transfer function $C(s)P(S)$ (see Figure 1) amounts to an integrator and a certain delay within a decade frequency-band centered at the gain crossover frequency ω_c. In symbols,

$$C(s)P(s) = \frac{K_c e^{-\tau_c s}}{s}, \tag{1}$$

where K_c is a gain that effectively sets the crossover frequency ω_c and τ_c is a delay. From a control engineering standpoint, an integrator in the region of crossover is a sound design strategy—it produces a generous 90° phase margin. A portion of that 90° is then taken up by the inescapable sensorimotor loop delay τ_c. Presumably, the human operator uses knowledge of the plant to come up with a controller $C(s)$ that contains an inverse of all parts of the plant but an integrator. From our present perspective, the noteworthy feature is the use of a model of the plant as a basis for the controller. In this sense the McRuer Crossover Model is an Internal Model Controller. Note that the McRuer Crossover Model was not conceived as a means to describe the behavior of the human operator in cases in which the reference signal $r(t)$ or disturbance signal $d(t)$ are recognizable. The McRuer Crossover Model describes only feedback control for the case of random or random-appearing signals $r(t)$ and $d(t)$.

Thus the McRuer Crossover Model cannot account for the observation that delay can be eliminated when the reference or