

The Sensorimotor System of a Martian

An LCNTR Tech Brief

prepared by

Richard B. Wells

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I. Overview

A companion tech brief (Wells, 2007a) introduced the Martian, a simple agent system serving as a platform for investigations of meanings-based, affect-driven unsupervised learning processes. The purpose of using a Martian as an investigation platform is to introduce a biologically homologous agent platform that is complex enough to introduce biologically reasonable constraints on the learning processes without introducing so much complexity of detail in the anatomy of the agent as to render analysis of learning phenomena untenable. This tech brief provides a basic definition of the lower sensorimotor anatomy of the Martian.

A Martian agent follows the general schema outlined by Burke (1986) for the limbic-sensorimotor organization of higher mammalia (including *Homo sapiens*). Figure 1 illustrates Burke's architectonic. This tech brief is primarily concerned with simple models at the level of the spinal cord, the evolving movement function below it, and supraspinal pathway constraints.

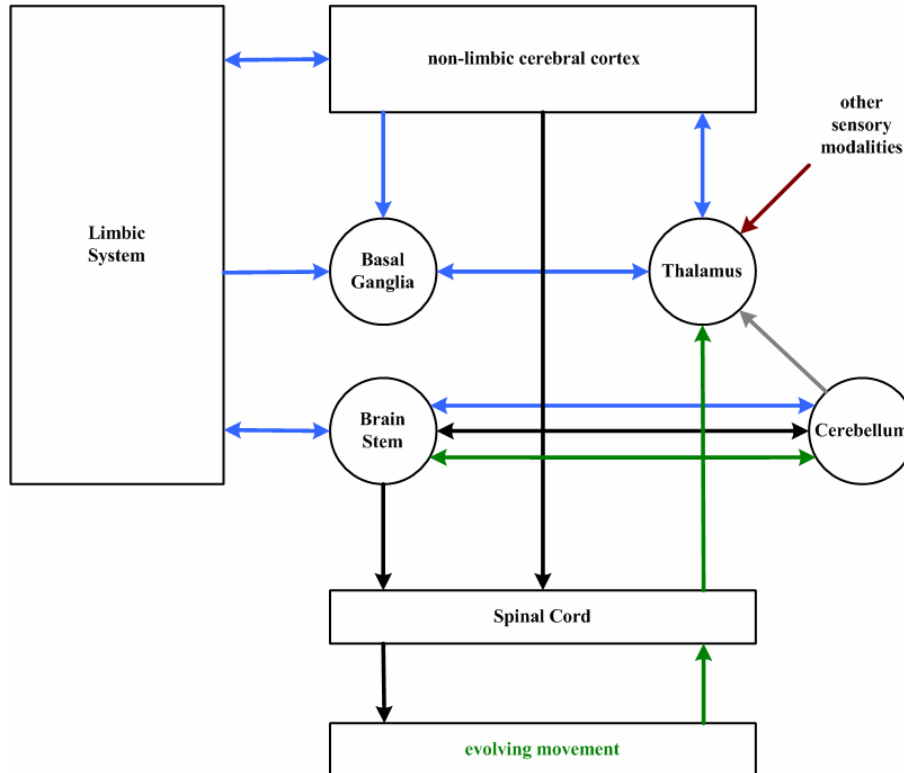


Figure 1: Burke's schematic of the sensorimotor-limbic system.

Although defining the first-order Martian on the basis of the spinal sensorimotor systems appears somewhat overspecialized, this restriction is not as confining as one might think. The most obvious missing part from Burke's architectonic is the sensorimotor systems of the head, which includes visual, auditory, gustatory, and olfactory senses, their related motor systems and the system of cranial nerves which conveys information within this system. However, to the level of detail known about both the cranial system and the spinal sensorimotor system, both systems are surprisingly similar insofar as sensory and motor signal processing schema are concerned. Obviously they are different as well, but these are differences of detail rather than differences in architectural "themes" that show up repeatedly in living mammals.

For example, the relay path links in *all* sensory systems follow a common architectonic (Gardner and Martin, 2000, pp. 425-428). Sensory information begins at the sensory transducer cell (e.g. a pressure or temperature sensing nerve ending in the somatosensory system or a phototransducer cell – rods or cones – in the visual system). Data from various transducers of the same sensory modality converge at contrast-enhancing relay points, most of which follow either a weak or strong form of winner-take-all contrast enhancement, with the weak form being the most common. This signal processing schema at the relay points acts to localize the source of the stimulation. Sensory information arriving at the higher central systems – i.e., the early sensory cortices – form topographic "maps" corresponding to specific body locations. On route to the higher systems, the sensory pathway also puts out collaterals to brainstem and/or cerebellar circuits prior to arrival at the thalamus, by means of which it can be integrated with motor control information.

For example, the optic nerve bundle puts out collaterals to the superior colliculus in the midbrain region of the brainstem (Shepherd, 1994, pg. 375). Ascending somatosensory information reaches the central systems from the spinal cord by means of the spinothalamic tract (mainly temperature and pain data, but also some tactile and joint information) and the lemniscal pathway (for precise and complex information about touch and pressure). Limb position and velocity feedback information from the skeletal musculature travels by way of the spinocerebellar pathway to the cerebellum, from whence it is processed and routed to thalamus and brainstem. The spinothalamic tract gives off collaterals to the brainstem's reticular formation (the ascending reticular system), which is known to be involved with arousal and consciousness. The lemniscal pathway terminates at the margin of the brainstem in the dorsal column nuclei, but likewise gives off collaterals to the reticular formation (Shepherd, 1994, pp. 284-285) as well as projections to hypothalamus, tectum, and pretectum (Sherman and Guillery, 2006, pg. 366).

Similarly, there is a general theme followed by motor pathway efferents in the so-called motor

hierarchy.¹ The brainstem serves both as an integrating center, for information arriving from sensory pathways, the motor cortices of the neocortex, and the cerebellum, and as the source of stereotyped motor action commands. For example, the superficial layer of the superior colliculus, which receives collaterals from the optic nerve bundle, passes this information on to motor cortices of the neocortex, which in turn project to the intermediate and deep layers of the superior colliculus. These, in turn, project to the mesencephalic and pontine reticular formations (both of which are also brainstem formations), which are motor drive centers for the ocular motor system of the eyes (Goldberg, 2000). Descending motor control signals for the skeletal muscles in the spinal neuromuscular system travel by way of the ventral and lateral corticospinal tracts (which originate directly from neocortex), the pontine reticulospinal tract (which originates in the pontine reticular formation of the brainstem), the vestibulospinal tract (which originates in the lateral vestibular nucleus of the brainstem), the medullary reticulospinal tract (which originates in the medullary reticular formation), and the rubrospinal tract (which originates in the red nucleus of the brainstem), (Burke, 1986, pg. 92). Thus, here too various brainstem structures serve as integrating and motor command centers.

At lower levels, just above the motor neurons themselves, the motor system is organized around stereotyped circuits that apparently evolved from neural structures devoted to simple reflex actions and many of which are thought to contain special neural *central pattern generator* circuits (Wells, 2003a, pt. 1). In the case of supraspinal motor systems (i.e., the motor systems in the head), a similar theme is illustrated by the vestibulo-ocular system (Goldberg, 2000), (Goldberg and Hudspeth, 2000), (Shepherd, 1994, pp. 322-327). Voluntary motion is currently thought to be implemented by command pathways originating in the higher brain centers co-opting the basic reflex pathways – in effect, overriding the local sensory pathways for reflex actions and injecting their own “mock-reflex stimuli” signals into the local circuitry. In the case of the spinal neuromuscular system this is called the general reflex afferent (GRA) hypothesis (Lundberg et al., 1987). A similar GRA model for the supraspinal motor systems has yet to be developed.

As stated earlier, all the sensorimotor systems differ in detail at the circuit level, and it is fair to add that a great deal of this detail is not yet known. However, the existence of a general theme in the architectonic of the sensorimotor system makes it reasonable and possible to model these systems in the abstract with *functional proxies*. The advantage in doing so is that this approach permits us to concentrate on interesting aspects of the higher central systems without getting too

¹ Strictly speaking, the term “motor hierarchy” is misleading. The motor system, like the sensory system, contains both serial (hierarchical) and parallel pathways.

bogged down in the details of specific anatomical circuits. This is what we shall do with the Martian agent system.

II. The Outer Sensory System

By the phrase “outer sensory system” we will mean the sensory information originating from sensory transducers that convey information to the agent about how the extra-agent environment affects the agent. The outer sensory system is the formal homologue to the “external” senses, e.g. vision, audition, touch, etc. The simplest case, which we refer to as the first order Martian, is illustrated in figure 2. See the figure caption for the major details of this model structure. Outer sensory information is conveyed through the sensory field window. Each pixel in the rectangular grid represents a non-negative amount of sensory stimulation determined by the environment, which is represented by an immovable background retina grid.

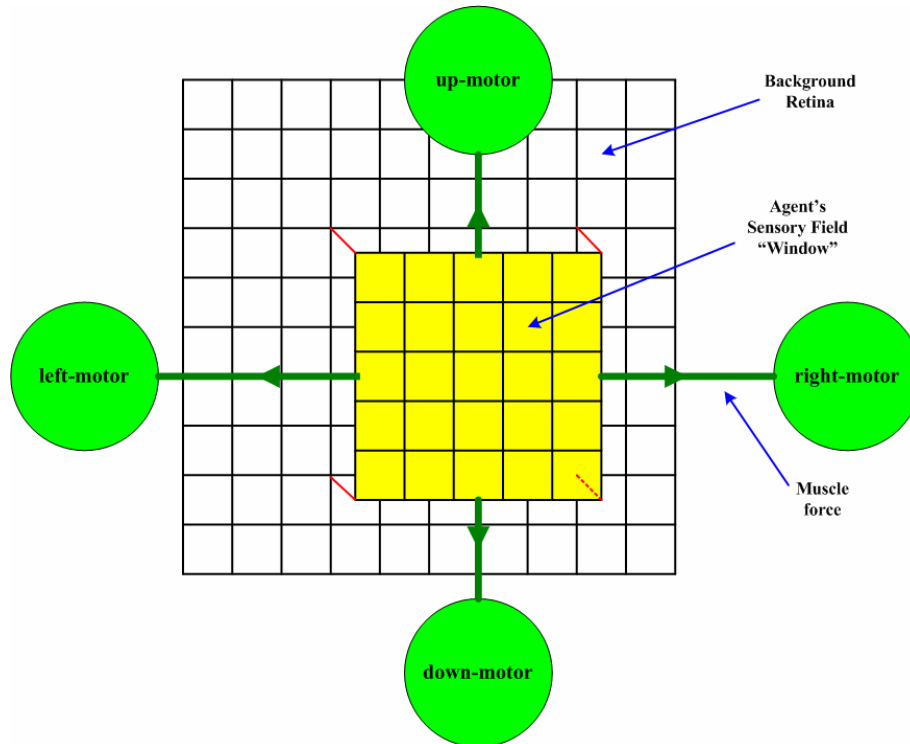


Figure 2: The external sensorimotor system model of the body of a first-order Martian. The Martian receives sensory stimulation through the sensory field window from the background retina grid, which models the external environment. Each pixel in the background retina is characterized by a non-negative number providing the level of stimulation to be experienced when the sensory field window overlays it. If a sensory pixel partially overlaps a background pixel, the amount of stimulation is proportional to the amount of overlapping area relative to the total pixel area. The sensory field window is moved by two pairs of orthogonal, non-interacting motor units. The left/right motor unit translates the window in the horizontal direction. The up/down motor unit translates the window in the vertical direction. The muscle forces generated by a motor unit are arranged as an agonist/antagonist pair (a formal homologue for flexor/extensor muscle pairs). When the motor units are at rest the sensory window is centered upon the background window. Muscles work by contraction, such that activation of, say, the left-motor unit produces a contractile force to the left and simultaneously produces a stretching of the muscle for the right-motor unit. In a first-order Martian the up/down motor unit and the left/right motor unit muscles do not interact, i.e. up/down motion produces no stretch of the left/right muscles. This is done for the sake of maximum simplicity in the first-order agent model.

Because a Martian is an abstract agent model, we assign no physiological significance to what kind of sensory stimulation is being picked up by the sensory window. Multiple sensory modalities in higher-order Martians are introduced by the addition of more grid retina systems with their accompanying motor units. Such additional sensory modalities may or may not be functionally coupled according to whatever phenomena the model is intended to address. The pixels in the background retina are defined to be unit pixels, i.e. one unit of movement equals one pixel width or height.

Each pixel in the sensory field window is represented by one sensory transducer. The amount of sensory stimulation picked up by a transducer is equal to the stimulation number in the background pixel multiplied by the fraction of window pixel area overlapping the background pixel. If a window pixel overlaps more than one background pixel, the total stimulation is the weighted sum of the stimulations from each background pixel.

Each sensory transducer in the sensory window grid sends its stimulus value, p_i , to a first-relay network associated with that pixel, and also to other first-relay networks associated with its four nearest neighbors. The signal to its own relay network is excitatory; the signal to the nearest neighbor relays is inhibitory. This is a functional proxy for the contrast-enhancing relay links found throughout the sensory system. In terms of Burke's model, we can regard this first-relay network as a formal homologue for circuits in the dorsal horn of the spinal cord. Figure 3 illustrates the basic connectivity for one first-relay network. In an $M \times M$ sensory window there will be M^2 first-order relay networks.

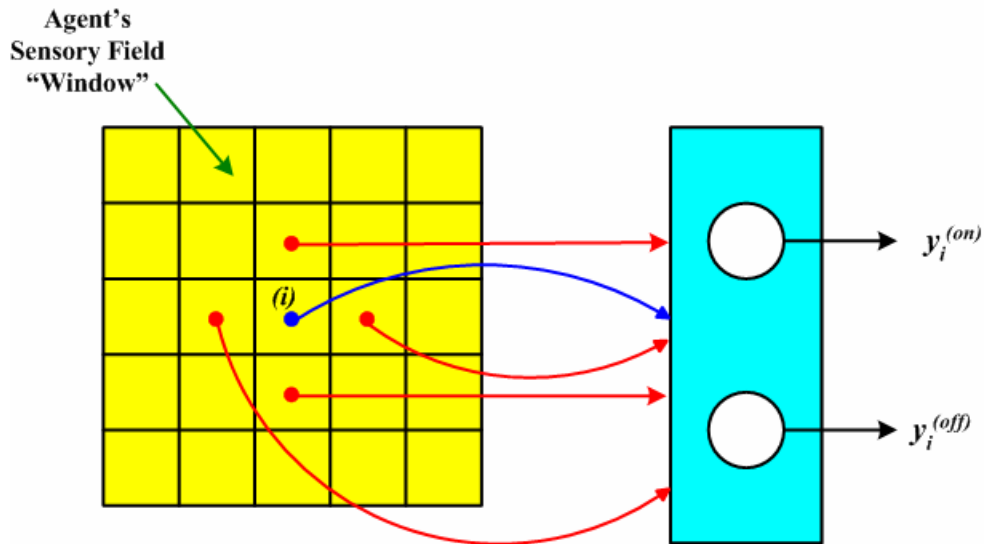


Figure 3: First-order relay link in sensory pathway for pixel i . The relay link produces two outputs, an on-center output and an off-center output. The blue projection is excitatory, the red projection from the four nearest neighbors are inhibitory. The equations for the relay link are given in the text.

Each first-order relay network receives one excitatory projection (shown in blue) from its associated sensory pixel and four inhibitory projections (shown in red) from the four nearest neighbor pixels, $p_{i(1)}$ to $p_{i(4)}$, and produces two output signals, an on-center type output and an off-center type output. Not every sensory pathway in living systems produces both types of sensory signals, but it is known that many do and inclusion of both types allows for investigation of the importance, if any, that off-center sensory data might play in unsupervised learning schemes. Because the model is designed for computer simulation, let integer t denote the present time step in a simulation and $t - 1$ denote the previous time step. Each relay network is defined by six variables,

$$\begin{aligned}
x_i^{(\text{on})}(t) &= p_i(t) \cdot w_i - \sum_j p_{i(j)}(t) \cdot w_{i(j)} \\
x_i^{(\text{off})}(t) &= 1 - p_i(t) \cdot z_i + \sum_j p_{i(j)}(t) \cdot z_{i(j)} \\
s_i^{(\text{on})} &= x_i^{(\text{on})}(t) + (a \cdot (x_i^{(\text{on})}(t-1) - x_i^{(\text{on})}(t))) \\
s_i^{(\text{off})} &= x_i^{(\text{off})}(t) + (b \cdot (x_i^{(\text{off})}(t-1) - x_i^{(\text{off})}(t))) \\
y_i^{(\text{on})} &= h(x_i^{(\text{on})}) \\
y_i^{(\text{off})} &= h(x_i^{(\text{off})})
\end{aligned} \tag{1}$$

where the sums on j are taken over the nearest neighbors of pixel i . The w and z variables are connection weights for the on-center and off-center pathways, respectively. Variables $x_i^{(\text{on/off})}$ are normalized so as not to exceed + 1 in value, and the weight variables are non-negative. Variables a and b are called **post inhibitory rebound factors** and are used to model the post inhibitory rebound effect exhibited by many sensory pathways, e.g. in mammalian retina visual pathways. These variables are non-negative, and setting them to zero removes the post inhibitory rebound (PIR) effect. In many sensory pathways, PIR provides information to the higher level systems about the rate of change of the sensory input. The activation function $h(x)$ is called the **Heaviside extractor function**. It is defined by

$$h(x) = \begin{cases} 0, & x \leq 0 \\ x, & x > 0 \end{cases} . \tag{2}$$

We will define the signal patterns as vectors $\mathbf{Y}^{(\text{on})}$ and $\mathbf{Y}^{(\text{off})}$, the column vectors with elements $y_i^{(\text{on})}$ and $y_i^{(\text{off})}$, respectively. The system of equations (1) produces contrast-enhanced signal patterns such that $y^{(\text{on})}$ values are largest for pixels neighbored by zero-valued pixels and smaller for pixels p_i for which the nearest neighbors have non-zero stimulus values. For the case where w_i is equal to the sum of the $w_{i(j)}$ (and similarly for z_i and $z_{i(j)}$), equal stimulation of p_i and all its nearest neighbors produces a zero-valued signal $x_i^{(\text{on})}$ and a unit value for $x_i^{(\text{off})}$.

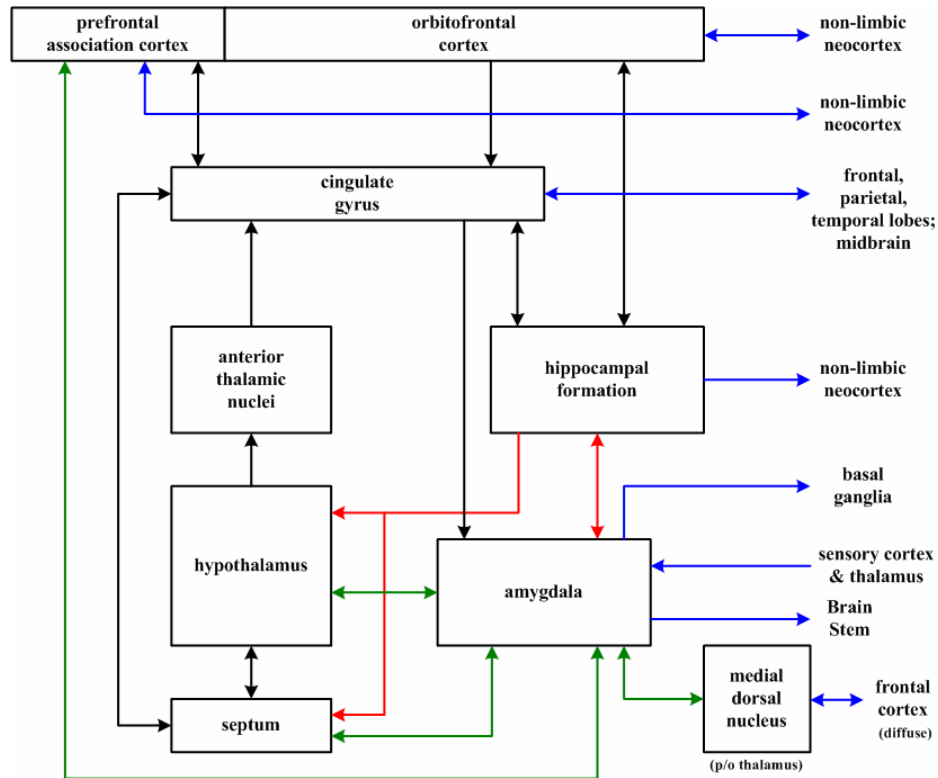


Figure 4: Block diagram level schematic of the principal parts of the limbic system and its major types of afferent and efferent pathways.

A first-order Martian agent assumes the output vectors of the first-order relay network project directly to the thalamus (figure 1) with collateral projections to other non-cortical structures (cerebellum and brainstem). Most sensory path afferents do not make direct projections to the limbic system so far as anatomy has been able to determine. Rather, sensory signal effects registered in the limbic system come in by a variety of cortical, thalamic, and brainstem pathways. Relatively little detail is presently known regarding the signal processing taking place in these indirect pathways. Figure 4 illustrates the organization of the limbic system in more detail. In the absence of detailed knowledge of the signal processing carried out in this system, the limbic system responses to sensory afferents must be modeled phenomenologically. Limbic outputs appear to function primarily in a modulator role, affecting levels of excitability and arousal in various other central systems as well as the endocrine system (which affects musculature as well as other body functions). It is thought that limbic efferents act as “drives” and play a role in *conditioning* the responses of other central systems (Wells, 2007a). In the Martian agent, limbic outputs are represented as non-specific drives, either of an aversive or an attractive nature, and signal organic *preferences* to the non-limbic system. In the first-order Martian these drives are modeled according to Grossberg’s model of conditioning networks, illustrated in figure 5 (Grossberg 1972a, b), (Wells, 2007a).

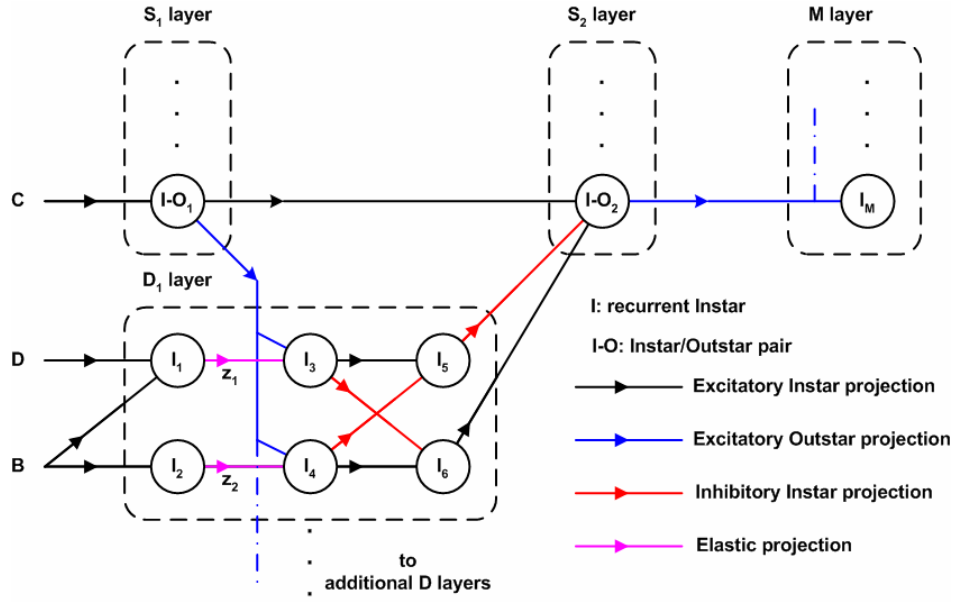


Figure 5: Grossberg’s model of classical conditioning. Inputs D and B represent drive signals, presumed to originate within the limbic system. C represents sensory signals subject to conditioning by dipole networks of the form D₁. S₁ and S₂ represent sensory-processing network layers while M denotes motor control processing networks.

III. The Inner Sensory System

In addition to the outer sensory system and its transducers, the body also contains a large number of transducers devoted to monitoring homeostasis and the condition of the body state. We will call these, collectively, the inner sensory system. From the viewpoint of a signal processing model, the model system for these signals is almost the same as the one defined above for the outer sensory transducers. The principal differences are in the source of the signal and in the fact that, so far as is presently known, these transducer pathways do not generate off-center signals to accompany the on-center signal.

A variety of inner sensory signal types are found in higher mammalia (Wells, 2003a, pt. 1, 2). For the first-order Martian agent, the most important of these are transducers located in muscles and joints that produce ascending afferent signals carrying data on the state of the muscle system back to the cerebellum via the spinocerebellar pathway. These signal sources are the Martian’s homologues to the spindle afferents group Ia and group II, which convey muscle velocity (time rate of change of muscle length) and length variation information, respectively, back to the central systems, and group Ib (arising from the Golgi tendon organs), which convey information on the amount of tension in a muscle (Wells, 2003b).

Because of the shape of the intrafusal muscle fibers in which they are found, these afferents are also known as “bag” and “chain” fibers. For the group II and group Ib sensors, the sensor law is quite simple to the first approximation: the sensor output is modeled as being directly proportional to the amount of stretch (length variation) or tension applied to the muscle. The

relatively good degree of linearity for these sensors is a consequence of the presence of special intrafusal fiber motor neurons, called gamma motor neurons, in the ventral horn of the spinal cord (Wells, 2003c). The group Ia or “primary” spindle afferent, however, is different in that its response shows a pronounced rebound effect, similar to the PIR effect discussed earlier, at the onset and offset of muscle velocity (Wells, 2003c), and the sensor response is also subject to the Heaviside activation function. Thus, its response is approximated by the $x_i^{(on)}$ and $y_i^{(on)}$ expressions in equations (1) with $x_i^{(on)}$ replaced by v_m , the time rate of change of muscle length.²

In addition to feedback of the groups Ia, II, and Ib afferent signals, the cerebellum also receives other sensory feedback signals carrying information comparing the actual stimulus being applied to the main (alpha) motor neurons (which directly drive the extrafusal muscle fibers) to the amount of stimulus commanded by the descending pathways from the brain. These feedback signals are illustrated in figures 23 to 25 in (Wells, 2003a, pt. 4). These signals are used by the cerebellar-brainstem muscle control system and are also thought to play a part in learning motor control.

Finally, the skeletal muscle system employs two types of nociceptors (pain sensors), known as the group III (fast) and group IV (slow) nociceptors (Wells, 2003a, pt. 1). These transducers are associated with tendons and joints and are activated only over a relatively narrow range at the extremes of muscle or joint tension where the onset of tissue damage becomes possible. These transducers are relayed through the spinal cord system to thalamus, brainstem, and cerebellum locations. It is interesting to note that the level of pain actually experienced can be modified by emotional state (especially anxiety), past experience, and the simultaneous activation of other modalities. Thus “pain” per se is a psychological phenomenon rather than a purely physiological response to stimulation of the nociceptors. For the first-order Martian, we assume these transducers become activated when the movement of the sensory window reaches the extreme edges of the background retina grid.

IV. The Motor Model

The Martian requires a dynamical model for the muscle forces applied by the two motor elements of figure 2. A physiological model of muscle dynamics was originally worked out by Hill (1949), but this model results in a fairly complicated if straightforward mathematical model (Wells, 2003d, pt. 1). Considering the purpose for which the Martian agent model is introduced,

² In the absence of the controlling influence of gamma motor neurons, all three sensors show very pronounced nonlinearities in their transfer function expressions. However, this complication need not be dealt with by the Martian because we do not model the muscle fiber system to this level of detail and merely assume that proper gamma motor neuron control is being exercised.

such a complex model does not seem worthwhile, nor could a physiologically accurate model be introduced without also making a number of specifications regarding the explicit musculature to be modeled. Therefore, the Martian employs a simpler motor model using a linearized approximation to Hill's model. The equations are given here for the left/right motor pair in figure 2; expressions for the up/down pair are the same with appropriate changes in variables.

Basic muscle kinetics involve a contractile element (which models the muscle contraction response to motor neuron excitation), a stiffness element (formally a spring which models force due to muscle stretch), a damping element (which models velocity-dependent force during muscle stretch and compression), and a reference muscle length parameter L_0 that represents the amount of muscle stretch when the system is at its undriven state of mechanical equilibrium. Let x denote the horizontal position of the center of the sensory window relative to the center of the background. $x > 0$ will denote displacement to the right of center. Let y_r denote the total excitation for the motor neurons (MN) driving the right muscle and let y_l denote the total MN excitation driving the left muscle. y_r and y_l are both non-negative quantities. The contractile force of the right muscle is approximated as $F_r = Q \cdot y_r$, with the contractile force F_l following the same expression with appropriate substitution of y_l . The constant $Q > 0$ is a proportionality constant representing the contractile element response to motor neuron excitation.

Let each muscle have a spring constant K and a damping coefficient B . Furthermore, let the ratio of spring constant to the movable mass of the window be k and the ratio of the damping coefficient to this mass be b . Denoting the time rate of change of the position x by velocity, v , it is easily shown that the left/right muscle pair dynamics is given by the set of dynamical equations

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -2k & -2b \end{bmatrix} \cdot \begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ q \end{bmatrix} \cdot (y_r - y_l) \quad (3)$$

where q is the ratio of contractile constant Q to the movable mass and a dot over a quantity denotes the time derivative. The muscle tensions, which we will regard as being associated with tendons and monitored by group Ib afferent sensors, are then expressed by

$$\begin{aligned} T_r &= Q \cdot y_r + K \cdot (L_0 - x) - B \cdot v \\ T_l &= Q \cdot y_l + K \cdot (L_0 + x) + B \cdot v \end{aligned} \quad (4)$$

For computer simulation we must approximate (3) by a difference equation. In doing so, we employ an approximation commonly used in control system theory, the step-invariant approximation. Let t denote an integer iteration number in the simulation and let Δt denote the number of milliseconds represented by one simulation time step. Applying the step-invariant

approximation to (3) results in

$$\begin{bmatrix} x(t+1) \\ v(t+1) \end{bmatrix} = \begin{bmatrix} 1 & \Delta t \\ -2\Delta t \cdot k & (1-2\Delta t \cdot b) \end{bmatrix} \cdot \begin{bmatrix} x(t) \\ v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \Delta t \cdot q \end{bmatrix} \cdot (y_r(t) - y_l(t)). \quad (5)$$

Calculation stability for (5) requires the eigenvalues for the matrix term in (5) to have magnitudes less than unity, and physiologically reasonable simulation requires the real part of the eigenvalues to approach +1 (subject to the constraint that the magnitudes be less than 1). Eigenvalue magnitudes in the range of about 0.90 to 0.95 will yield reasonable approximations.

Expressions (4) are unchanged by the discretization operation. To calibrate the onset of activity from the pain nociceptors associated with high muscle tension, the Martian model will assume these nociceptors become active when the magnitude of x is approximately L_0 given the contractile force and velocity are zero. This numerical value is then applied to all values of $T_{r(l)}$ in (4). We will further assume the activity signals from pain nociceptors follow some faster-than-linear function for tension values exceeding this threshold. Pain signals always evoke an aversive drive in the Martian.

V. The Low-level Motor Neuron System

Direct actuation of the motor system is carried out by low level neural circuitry, representing a formal homologue to the motor networks in the ventral horn of the spinal cord. For each motor pair, the Martian uses the simplest possible proxy model for spinal cord control, shown below in figure 6 for the left/right motor pair. The network for the up/down motor pair is the same with the

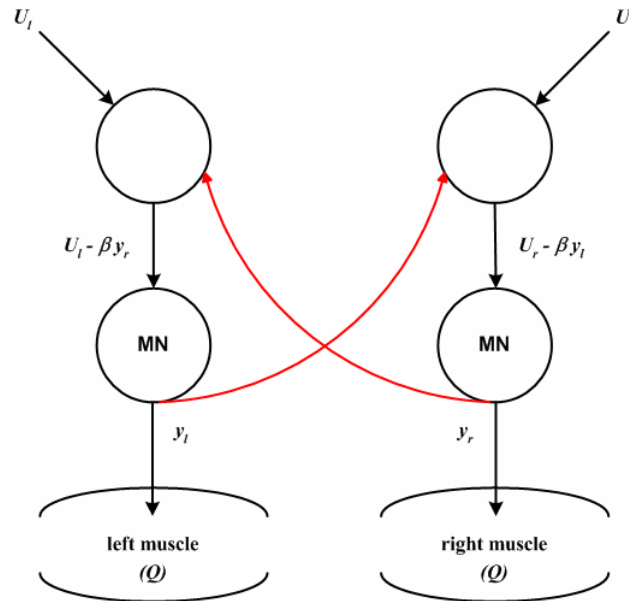


Figure 6: Martian spinal neural network. U_l and U_r are the sum total of descending motor signal excitations. MN denotes a motor neuron network. Other terms are defined in the text.

appropriate changes of variables. The sum total of descending motor activation signals are denoted U_l and U_r . These signals are non-negative. The motor neuron signals sent to the muscle are given by

$$\begin{aligned} y_l(t+1) &= h(U_l(t) - \beta \cdot y_r(t)) \\ y_r(t+1) &= h(U_r(t) - \beta \cdot y_l(t)) \end{aligned} \quad (6)$$

where $\beta > 0$ is a lateral inhibition weight factor and h is the Heaviside extractor activation function.

Conceptually, individual descending motor activation signals are outputs from brainstem and motor cortex networks, schematically represented in minimal form by the M layer of figure 5. Under the thalamus paradigm of Sherman and Guillery (Wells, 2007b), these descending signals or some processed version of them would also have a thalamic pathway back into neocortex by way of high-order thalamic nuclei, possibly mediated by cerebellar and/or brainstem pathways. In principle, therefore, a dynamical space-time signaling process is possible by virtue of the new thalamic paradigm. This view is complementary to an older model proposed by Grossberg (1969, 1970) in which spatio-temporal motor sequencing dynamics were effected by means of what he named an *Outstar avalanche*. It is a question of considerable theoretical interest to what extent spatio-temporal motor control can be adaptively learned by the model system of Sherman and Guillery (Wells, 2007b, figure 6) without or with very little introduction of Outstar avalanche feedforward networks, and the extent to which such a system model spontaneously produces dynamical action sequences fitting the “Mother structure” schemes discovered by Piaget (Wells, 2007b).

VI. Concluding Remark

At the time of this writing, the first Martian agent has not yet been constructed. This tech brief should be viewed as more of a guideline document for principles of Martian agent construction, particularly the first-order Martian. It is no doubt obvious to the reader that this brief along with its two companion tech briefs (Wells, 2007a, b) leaves unspecified a great number of degrees of freedom in the design of the Martian agent. This means not only that many different versions of the Martian agent are possible, but also that one can reasonably expect different versions of Martian to exhibit different affectivity-driven, meanings-based unsupervised learning behaviors. The analysis of the capabilities (or lack thereof) of particular Martian agents can thus reasonably be expected to bring fresh insights to the general learning problem. A question of particularly deep theoretical interest is: Whether behaviorally-realistic sensorimotor performances by a Martian agent as it undergoes its learning process also result in the spontaneous generation of

neural structures that coincide with the mathematical definitions of the three Bourbaki mother structures, i.e., algebraic structuring, order structuring, and topological structuring. If so, then perhaps the Martian project will cast new insight into the long-standing theoretical problem of the putative neural code.

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