

The fuzzy logic of visuomotor control¹

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Abstract: Biological sensorimotor control is characterized by the use of signals from large numbers of sensors, monitoring numerous variables. Among these are the exteroceptive signals from the eyes and ears. Many of the sensory signals are under efferent control, and the motor responses they evoke, whether at a simple reflex level or routed through the higher centres, appear to be task and context dependent. In technology the analysis and management of multiple-input, multiple-output systems clearly exceed the capabilities of classical servo control theory. In this commentary, new types of control system based on conditional logic are discussed in relation to the rules animals use to control movement. It is argued that the concepts of fuzzy logic control provide a useful and "biologically compatible" way of describing sensorimotor behaviour. An example is given of a robotic device under fuzzy control, in which behaviours are selected according to a visual assessment of motor task and context. Each behaviour is associated with a small subset of rules relating specific sensory variables to specific motor actions. The rule-based approach is also discussed in relation to neurophysiological theories regarding the interneuronal control of locomotion, including the recently adduced "parliamentary principle." The analysis and classification of behaviours and rules is seen as a useful preliminary to the future study of interneuronal systems.

Key words: fuzzy logic, behavioural set, reflex control, locomotion.

Résumé : Le contrôle sensori-moteur biologique est caractérisé par l'emploi de signaux provenant d'une multitude de capteurs régulant de multiples variables, incluant les signaux extéroceptifs des yeux et des oreilles. Nombre de ces signaux sensoriels sont sous contrôle efférent, et les réponses motrices qu'ils évoquent, que ce soit à un simple niveau réflexe ou par l'entremise des centres supérieurs, semblent dépendre de la tâche et du contexte. Sur le plan technologique, l'analyse et la gestion de systèmes à entrées et sorties multiples débordent largement la théorie classique du servocontrôle. Dans cet article, de nouveaux types de système de contrôle basés sur la logique conditionnelle sont discutés en fonction des règles utilisées par les animaux pour contrôler le mouvement. On soutient que les concepts de contrôle logique flou s'avèrent un moyen « biologiquement compatible » et utile pour décrire le comportement sensori-moteur. On donne l'exemple d'un dispositif robotisé sous contrôle flou dans lequel les comportements sont choisis relativement à une évaluation visuelle de la tâche motrice et du contexte. Chaque comportement est associé à un petit sous-ensemble de règles associant des variables sensorielles spécifiques à des actions motrices spécifiques. On discute aussi de ce type d'approche en rapport avec les théories neurophysiologiques du contrôle interneuronal de la locomotion, incluant le « modèle parlementaire » (« parliamentary principle ») récemment énoncé. L'analyse et la classification des comportements et règles sont considérées comme un préalable utile à l'étude des systèmes interneuronaux.

Mots clés : logique floue, comportement, contrôle réflexe, locomotion.

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Introduction

Many sensory modalities contribute to the reflex and voluntary control of movement. It is obvious that voluntary control is extremely task and context dependent, but in recent years it has become increasingly apparent that reflex control is too. Reflexes that had previously been thought of as "hard-wired" have now been shown to vary before, during, and after motor acts. This variation is evidently driven by an exteroceptive evaluation of the external environment, by a proprioceptive evaluation of how the task is unfolding, and in some cases by internal "programs" or "schedules," which modulate reflex pathways according to the phase of the movement.

One of the interesting challenges for systems neurophysi-

ologists is to develop analytical schemes to deal with this complexity and variability. Servo theory was the first analytical method to be enlisted, about 40 years ago. In some cases servo models have been extraordinarily successful (e.g., in describing eye movement control). Servo theory also continues to be useful in predicting stability and other relatively simple aspects of the segmental feedback control of limb muscles. However, servo theory becomes unwieldy when applied to multivariate control. Fortunately, the increasing use of multiple sensors in machines has led to the development of new descriptive and analytical tools that can supplement or replace servo control. In this paper, it is argued that the time is ripe to apply some of these tools to the problem of motor control in animals. Indeed, this has already commenced in the practical sphere, with the use of finite state systems in the electrical control of parietic muscles (Popovic 1993). Before we discuss rule-based descriptions of sensorimotor control, it is important to realise that the sensory inputs themselves, and the gain of servo-like responses to them, are under strong control from within the central nervous system (CNS).

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Peripheral and central gain control of sensory feedback

The efferent control of peripheral sensory receptors is now recognised as being the norm rather than the exception. It occurs in visual, auditory, vestibular, taste, and smell modalities as well as in proprioception in invertebrates and vertebrates alike (Prochazka 1989). In mammals, the most numerous proprioceptors, muscle spindles, are under the control of the fusimotor system. In the last few years it has been possible to record from spindle afferent fibres during natural movement. Large changes in stretch sensitivity have been observed in relation to behavioural "set." This task-related fusimotor modulation of sensitivity often appears to stem from a visual evaluation of context and task. Thus an anticipation of difficult terrain, a looming threat, or the need for extreme accuracy in movements may evoke a behavioural set, part of which is evidently routed through the fusimotor system to sensitize muscle spindles (Prochazka 1996).

At this stage there is debate regarding the generality of task-related "fusimotor set." In human neurography experiments, for example, modulation of spindle sensitivity has been sought but generally not found in situations involving increased dependence on proprioception and demands for accuracy (Al-Falahe and Vallbo 1988; Vallbo and Al-Falahe 1990; Aniss et al. 1990). Several reasons have been suggested for this apparent species difference, including the possibility that the "alerting" or "alarm" threshold is lower in cats than in humans (Prochazka et al. 1992). Recordings of spindles have also been obtained in monkeys performing voluntary tasks, but the issue of task-related fusimotor set was not addressed in these studies and it is therefore an open question as to whether fusimotor set occurs in primates (Schieber and Thach 1980, 1985). More data are needed, although the technical challenge of recording from spindle afferents or fusimotor efferents during demanding tasks is formidable, particularly in humans.

On the other hand, there is now evidence in many different animals, including humans, that the synaptic transmission of proprioceptive signals is modulated within the CNS according to task. Thus it has been shown that human short-latency stretch reflexes are reduced in walking compared with standing and in running compared with walking (Capaday and Stein 1987). There is also some evidence that short-latency stretch reflexes are attenuated in difficult tasks (Llewellyn et al. 1990; Nielsen et al. 1994). Some of this attenuation may be due to feedforward mechanisms, including visuomotor preparation, and some may be due to reafference from the moving limbs (Brooke et al. 1993; Cheng et al. 1995; Massion 1992). At first glance, the attenuation of stretch reflexes in motor tasks of increased complexity is somewhat counter-intuitive. Indeed, one might have expected an increased gain to improve automatic load compensation, frequency response, and so on. An attenuation of gain in difficult tasks also seems to contradict the notion of fusimotor set. However, in retrospect, it has been argued that a reduced gain in local segmental reflexes would ensure stability while allowing the fusimotor-sensitized spindle information to be transmitted to the higher centres (Prochazka 1989). The idea is that higher centres "take over" control when flexibility and adaption are required. Simple reflexes might be inappropriate under these circumstances.

Phase-dependent switching: positive force feedback

Changes in central sensorimotor transmission may occur from one phase of a cyclical movement to the next. Twenty years ago it was shown that cutaneous reflexes elicited from the dorsum of the cat's foot change sign in different phases of a movement (Forssberg et al. 1975). In the last few years interest has focussed on the task-dependent reversal of reflexes mediated by load-sensing proprioceptors. In insects as well as in cats, it has been shown that some of these reflexes change from being inhibitory during static posture to excitatory in the stance phase of locomotion (Bässler 1983; Conway et al. 1987; Pearson and Collins 1993). Excitation of load-bearing muscles in proportion to load implies positive feedback, which is normally thought of as being unstable. However, recent analytical studies have shown that at the gains encountered in biological systems and in combination with other modalities of feedback control, positive feedback is not only stable but has certain properties that are well suited for locomotor control (Cruse et al. 1995; Prochazka et al. 1996). For example, after contact with a load, an actuator under positive force feedback control pushes against the load. In locomotion, contact with the ground tends to make a limb "yield" as it bears the weight of the body. With strong positive force feedback (e.g., with an open-loop gain > 1), the limb could in principle develop enough extensor thrust to push the body upwards beyond its position at foot contact: "strutting" gait. The term "affirmative reaction" was coined to describe this property of positive force feedback.

An unproven but intriguing possibility is that positive force feedback might be "switched on" by the CNS in advance of certain types of voluntary movement. For example, in tasks requiring the grasping and holding of objects, the affirmative reaction of positive force feedback would secure a firm initial contact, graded resistance to increased loading, and an automaticity of maintained grip. Prior to contact, the switching on of force feedback would not affect the trajectory of the extremities: it would only take effect upon contact with objects. The hypothesis is currently being tested for human hand grasp in the author's laboratory (Prochazka et al. 1996), using an approach analogous to that of the "foot-in-hole" experiments on cat locomotion (Gorassini et al. 1993).

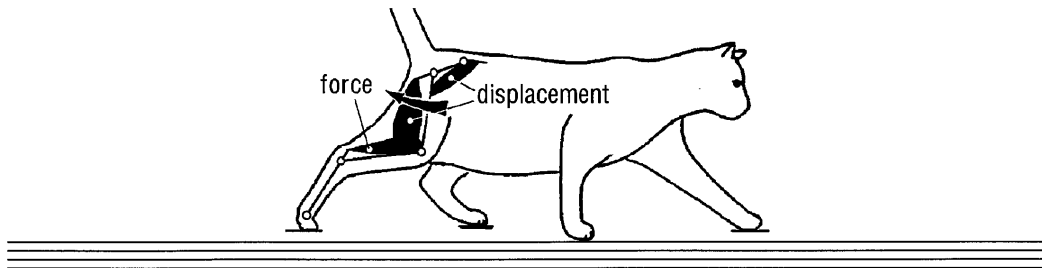
Multivariate control: inference systems and fuzzy logic

For many years, sensorimotor reflexes were thought of in terms of proportional feedback servo control. However, it is now apparent that reflexes can also be described in terms of conditional logic operations, in which the inputs from sensory receptors of many modalities are used to coordinate limb movements in a task- or phase-dependent manner. Servo theory may continue to be useful in analysing certain aspects of control within portions of movements, but it requires an encompassing theory suited to describing switches of strategy (including servo gains) from one portion of a movement to another. In robotic control systems, for which classical servo theory was first developed, there is a growing tendency to use a multiplicity of sensors to monitor and select different aspects of a control task. This has necessitated a new approach to the

Fig. 1. Example of IF–THEN rules governing the initiation of flexion during locomotion in the cat. The rules vary according to behaviour. Thus in slow gait, the transition to swing is promoted by hip extension, whereas in backward gait, the transition occurs when the hip is flexed. The rule for the tripping behaviour is also found in the control strategy of above-knee prostheses in humans, where it is designated a “hazard” state (Popovic et al. 1991).

IF...AND...THEN...rules for three gait behaviours

- 1) **slow gait: IF extensor force is low AND contralateral leg is loaded AND hip is extended THEN flex leg**
- 2) **backward gait: IF extensor force is low AND contralateral limb is loaded AND hip is flexed THEN flex ankle and knee, extend hip**
- 3) **trip: IF extensor force is zero AND hip is flexing AND skin contacts an obstacle THEN lift and place**



analytical management of such systems. The new tools include state space analysis, neural networks, and finite state and inference systems of different types, including fuzzy logic controllers. Fuzzy logic has received little attention in relation to neurophysiology, yet it has some remarkably “biological” characteristics and may provide a powerful approach to understanding sensorimotor control. It should be stated immediately that the goal is not to model the neural motor control machinery but rather to describe the observed behavioural permutations in a systematic way and thereby to determine some of the underlying rules carried out by the CNS.

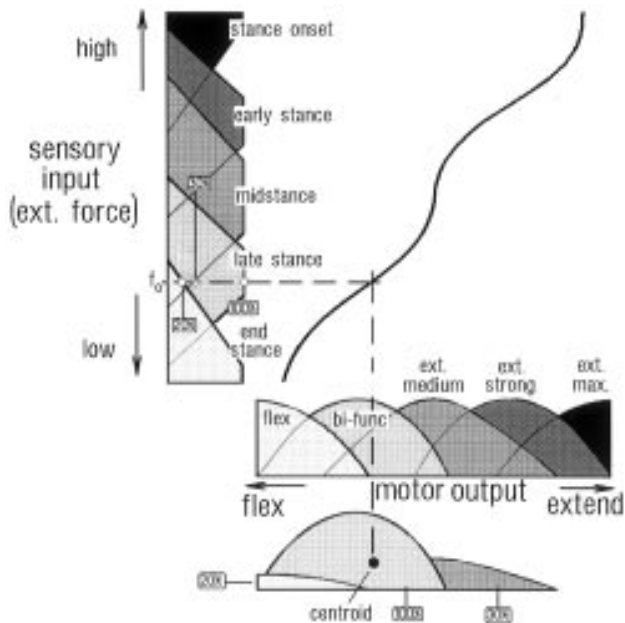
Finite state systems were first devised to control industrial production-line processes. They operate using rules such as the following: IF this sensory state AND that sensory state, THEN perform such-and-such motor action (Popovic et al. 1991; Popovic 1993). The sensory inputs may be viewed as a multidimensional vector: a rule or state is satisfied when the vector lies within a region of vector space “firing” that rule. In inference systems, algorithms are used to automatically rank the efficacy of the available rules in achieving motor goals (Kirkwood et al. 1989). In the last decade, finite state rules have been applied to the artificial control of human movement in active prostheses and functional electrical stimulators. It is significant that finite state control is the essential substrate of these systems, and servo loops are “add-ons” that refine certain aspects of control. This is partly due to the practical constraints on providing more than one or two sensors in prosthetic systems. However, there may be a more fundamental message: motor control in complex systems is as much

about using sensory input to choose between motor alternatives as it is about proportional servo control.

An example of the relevance of IF–THEN rules to biological motor control is shown in Fig. 1. Several rules have now been identified in relation to the transition from stance to swing phase in cat locomotion, as detailed in the figure. Interestingly, similar rules were independently discovered in stick insects, locusts, and lobsters, as well as in the control strategies for above-knee active prostheses (Prochazka 1993).

Fuzzy controllers allow multiple sensory inputs to be weighted and combined according to linguistically recognizable rules, to produce multiple motor outputs (Driankov 1993). Sensor signals are used to evaluate the validity or “truth” of statements such as “the leg is in early swing.” For example, suppose leg extensor force is quite low. The truth of the statement “the leg is in midstance” is medium, the truth of “the leg is in late stance” is high, and the truth of “the leg is at end of stance” is low. The linguistic descriptions of state are imprecise or “fuzzy,” but precision is conferred by so-called “membership functions” (see Fig. 2). These translate the sensory values into numerical “truth” values for each state. Thus in Fig. 2, the horizontal line corresponding to force f_0 intercepts the three overlapping membership functions such that “end of stance” is 20% true, “late stance” is 100% true, and “midstance” is 30% true. Each sensory state and associated membership function are linked to a motor state such as “activate flexors” or “activate bifunctional muscles” and to a corresponding motor membership function. The latter gets scaled by the “truth” value of the corresponding sensory state. Thus

Fig. 2. Fuzzy logic diagram for the contribution of force input to the control of limb muscles in locomotion. The sensory input is divided up into five regions, corresponding to five states: “stance onset,” “early stance,” “midstance,” “late stance,” “end stance,” etc. The truth value of each state is plotted against the sensory input (trapezoidal plots), from 0 to 100%. This allows force input to be translated into truth values of sensory states. For example, at f_0 , the “end stance” membership function is 20%, the “late stance” function is 100%, and the “midstance” is 30%. Each sensory membership function is associated with a motor membership function: end stance = “flex the limb,” late stance = “activate bifunctional muscles” etc. For a particular input value such as f_0 , the motor membership functions get scaled by the truth value of their corresponding sensory state (e.g., 30, 100, and 20% in this example). The motor membership functions are then superimposed (bottom) and the centroid of the composite shape gives the output value (in this case “activate bifunctional muscles”). For each sensory input, there is one or more such control diagram. ext., extend; bi-func, bifunctional.



in Fig. 2, the “flex” motor state is scaled down to 20% of its starting size, the “activate bifunctional muscles” state to 100%, and the “extend medium” state to 30%. The scaled motor membership functions are then superimposed to produce a composite membership function from which a single value of motor output is derived, for example, from the centroid as illustrated schematically at the bottom of Fig. 2.

If this rather involved process is carried out for every possible sensory input value along the ordinate, the wriggly input-output curve of Fig. 2 results. If the process reduces to a fairly simple input-output curve, what was gained by all the intermediary steps involving membership functions? Several things. First, the format allows linguistic expressions of state to be translated into numerically precise sensorimotor relationships. Second, when there are many sensory inputs and many motor outputs, scaled membership functions provide a convenient means of representing and managing the equivalent multidimensional vector space, as is shown in Fig. 3. Unlike neural networks, the operations always remain explicit and understandable in linguistic terms. Third, membership func-

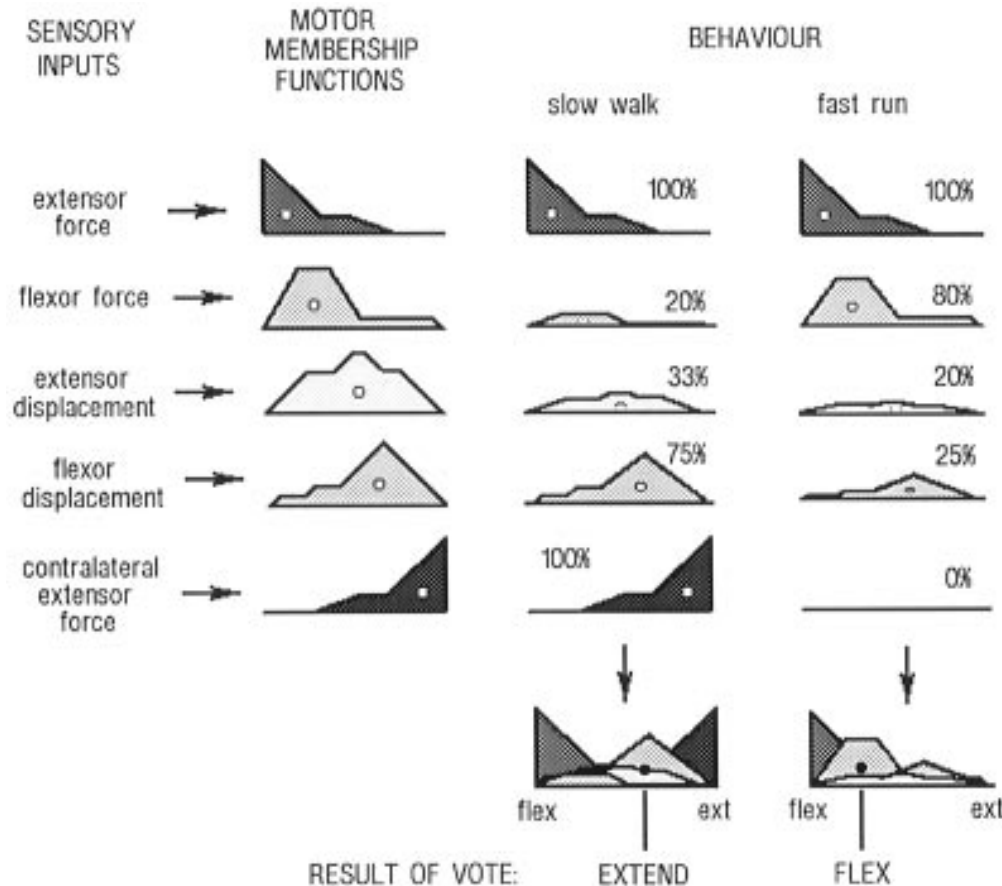
tions may be scaled or deleted to suit different tasks (“behavioural set”). For example, in cats walking on firm ground, sensory input is crucial in the control of the transition from stance to swing phase of gait (Hiebert et al. 1994). However, in the absence of normal ground contact, these transitions can still occur (e.g., in air stepping). In fuzzy logic terms, the rules concerning ground contact are given zero weight and the rules based on central pattern generation are given added weight.

Behaviour and rule selection

The selection of groups of rules to suit specific behavioural tasks is perhaps the most interesting feature of fuzzy control in relation to biological motor function, so the remainder of this article will be devoted to it. To illustrate the process, consider the rule structure of an experimental robotic excavator being developed by Shi et al. (1995). The fuzzy rules of this prototype machine are selected into nine groups associated with nine different behaviours. The behaviours are of the form “floor follower,” “entry-point selector,” “down-digger,” “under-particle follower,” “bucket lifter,” etc. The three or four rules in each behaviour are expressed in finite-state form, e.g., for floor-follower behaviour, rule 1 is if ground reaction force F is negative large (NL), then horizontal forward movement (δy) is positive large (PL) and upward movement (δz) is PL and bucket velocity (BV) is positive medium (PM); i.e., when bucket is forced hard onto floor or a particle is trapped between bucket and floor, move bucket a large increment forward and up at medium velocity. Rule 2 is if F is negative small (NS), then δy is positive small (PS) and δz is zero and BV is PS; i.e., when bucket contacts floor softly, move it forward a small amount. Input from a visual monitoring system is processed by a neural network and combined with other sensor input to provide “situation assessment.” Situations are of the form “the bucket is on a horizontal surface,” “this is a good location to dig,” “there is soft material to be scooped,” etc. An “arbitration mechanism” then decides which of the nine behaviours are appropriate for the current situation(s). A “behaviour fusion strategy” based on the fuzzy inference method is applied to combine the decisions of all activated behaviour programs into a single action. The system constantly monitors the firing strength of the decision rules and retires behaviours or recruits new behaviours according to predetermined thresholds of the firing strengths.

Let us now see if we can use this approach to behaviour selection in our fuzzy model of cat locomotion. Let us assume that we have five sensory inputs, each of which has produced a composite motor membership function such as the one shown at the bottom of Fig. 2. These five motor membership functions appear at the left of Fig. 3, next to their corresponding sensory input modalities. Now consider two related but different behaviours: slow walk and fast run. Assume that the motor membership functions are scaled differently in the two behaviours. For example, in fast run contralateral extensor force is given a zero weight. When the scaled, composite motor membership functions are superimposed, the centroid for slow walk is located closer to the “extend” end of the range and for the fast run it is closer to the “flex” end of the range. Thus the system “votes” for extension in one behaviour and flexion in the other, even though the sensory inputs are identical in the two cases. This example represents real-life

Fig. 3. Rule scaling and selection according to behaviour. Composite motor membership functions corresponding to five sensory inputs are shown on left. Each of these composite membership functions is equivalent to that shown at the bottom of Fig. 2. The composite motor membership functions are now scaled or deleted according to behaviour. Two behaviours are illustrated: slow walk and fast run. In slow walk, flexor force has a low weight, but contralateral extensor force has a high weight. In fast run, the latter is deleted entirely. The motor outcome of the identical sensory information is different in the two behaviours, as a result of the differences in weighting of the motor membership functions. ext, extend.



observations in “foot-in-hole” experiments (Gorassini et al. 1993). The model suggests a reduced reliance on contralateral extensor force signals in fast running, a testable hypothesis.

In this example, the hypothesis would be novel only if the weighting were not anticipated, and could somehow emerge in the course of designing membership functions to fit the empirical observations. “Neuro-fuzzy” controllers use an internal neural net (Fig. 4) that adjusts membership functions to optimize performance criteria (Beuter and Flashner 1991). In theory, a neuro-fuzzy system could therefore generate testable hypotheses regarding specific sensorimotor transformations on the basis of simple models and sets of data on motor behaviour.

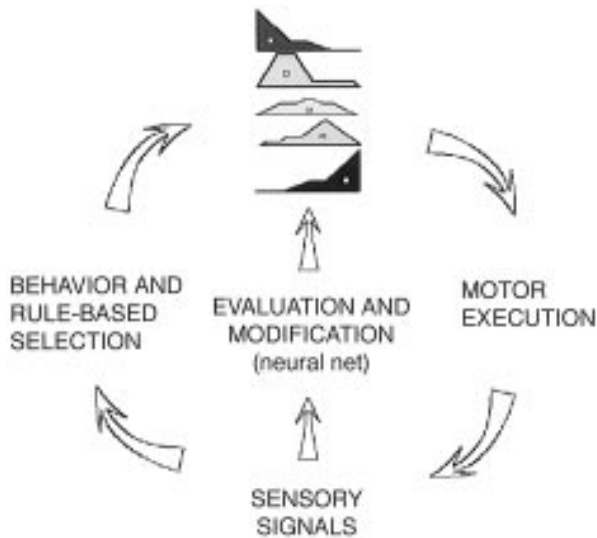
Applicability of fuzzy logic concepts to biological systems

It is clear from the above that rule-based control systems such as fuzzy logic are useful in controlling complex robots. Furthermore, it is possible to describe biological motor control in the format of rule-based systems, which may help in generating testable hypotheses. But will this really help us to understand how the CNS controls movement? To a large extent, this remains to be seen. However, some recent developments indi-

cate that the potential is certainly there. First, conditional logic has become the control strategy of choice in active prosthetic systems. Active prostheses are robotic devices designed to mimic moving limbs as closely as possible on the basis of sensory information. In a general sense the sensorimotor transformations must therefore be similar, although of course the artificial sensors and actuators in the prostheses may differ from biological ones, so it does not necessarily follow that the sensorimotor rules used in the prostheses are identical with those used normally by the CNS. But if the sensors and actuators are broadly similar, there is a good chance that the rules are similar too. Interestingly, there has been a convergence in the choice of sensors and control rules in different designs of above-knee prostheses, and as we have seen, these sensors and rules correspond well to those in recent theories of the natural control of locomotion (Prochazka 1993).

Inference-based controllers, including neuro-fuzzy systems, automatically rank the importance of different sensors. In conjunction with adequate models of the neuromuscular machinery, and a representative rule base, inference “engines” could be helpful in identifying which sensory inputs to the CNS are the most important in certain motor tasks. This in turn would point to the sensorimotor pathways and mechanisms

Fig. 4. Automatic adjustment of membership functions according to optimization of performance criteria. The process involves evaluating prior motor execution, and rescaling membership functions accordingly, in this example using a neural net. In biological systems, the equivalent would be a modification of interneuronal transmission after outcome evaluation by higher centres.



within the CNS that are the most relevant for that motor task. The knowledge to be gained from rule-based models is thus operational rather than mechanistic. It concerns the identification of sensory signals crucial for a task and the linguistic expression of the rules by which these signals are converted into action. This is quite different than neural network models, which perform sensorimotor transformations but do not provide rules or sensory ranking. Neural network models of CNS neuronal circuits are subject to the basic criticism that their structure is unlikely to be comparable with biological neural nets, and that they might mimic natural control, but using quite different mechanisms. An analogous criticism of rule-based models is that the derived rules are unlikely to represent the way the CNS works because the sensors and motor apparatus are inadequately represented. This type of criticism can be countered by better sensory and motor characterization. Another possible criticism, that the CNS is not organized on the basis of rules at all, can also be countered. The rules merely describe in abstract terms the sensorimotor linkages that are important, allowing them to be specified in neural terms later.

There are some remarkable parallels between the basic tenets of fuzzy logic and the “parliamentary principle” recently elucidated by Bässler (1993) in relation to locomotor control. “As in a parliament, the stimulus not only activates the coalition government responsible for the performance of the response but also activates the opposition.” This is equivalent to saying that some membership functions “vote” for extension, while others vote for flexion (Fig. 2). Bässler sees the conditional logic being performed by arrays or modules of interneurons.

The value to neurophysiology of expressing behaviour and sensorimotor transformations in terms of rules and fuzzy logic is likely to be heuristic, i.e., a good understanding of the behaviours and their associated sensorimotor rules will point the

way to a goal-directed search for interneuronal mechanisms. This is a fundamentally different approach than the classical pursuit of anatomical connections without reference to behaviour. In relation to the topic of the symposium, we have seen that vision is crucial in motor set behaviour selection. The rule-based approach is well suited to combine the very different modalities of vision and proprioception into unified models of sensorimotor tasks. In a sense the relevance of rule-based descriptions is obvious: motor behaviour nearly always consists of choices of the form IF this AND that AND that, THEN do such-and-such.

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References

- Al-Falahe, N.A., and Vallbo, A.B. 1988. Role of human fusimotor system in a motor adaptation task. *J. Physiol. (London)*, **401**: 77–95.
- Aniss, A.M., Diener, H.-C., Hore, J., Gandevia, S.C., and Burke, D. 1990. Behavior of human muscle receptors when reliant on proprioceptive feedback during standing. *J. Neurophysiol.* **64**: 661–670.
- Bässler, U. 1983. Neural basis of elementary behavior in stick insects. *Stud. Brain Funct.* **10**: 1–169.
- Bässler, U. 1993. The femur–tibia control system of stick insects—a model system for the study of the neural basis of joint control. *Brain Res. Rev.* **18**: 207–226.
- Beuter, A., and Flashner, H. 1991. Motion control in stepping. *Trends Biol. Cybern.* **2**: 59–78.
- Brooke, J.D., Misiaszek, J.E., and Cheng, J. 1993. Locomotor-like rotation of either hip or knee inhibits soleus H reflexes in humans. *Somatosens. Mot. Res.* **10**: 357–364.
- Capaday, C., and Stein, R.B. 1987. Difference in the amplitude of the human soleus H reflex during walking and running. *J. Physiol. (London)*, **392**: 513–522.
- Cheng, J., Brooke, J.D., Misiaszek, J.E., and Staines, W.R. 1995. The relationship between the kinematics of passive movement, the stretch of extensor muscles of the leg and the change induced in the gain of the soleus H reflex in humans. *Brain Res.* **672**: 89–96.
- Conway, B.A., Hultborn, H., and Kiehn, O. 1987. Proprioceptive input resets central locomotor rhythm in the spinal cat. *Exp. Brain Res.* **68**: 643–656.
- Cruse, H., Bartling, C., and Kindermann, T. 1995. High-pass filtered positive feedback for centralized control of cooperation. *In Advances in artificial life. Lecture notes in computer science. Edited by F. Moran, A. Moreno, J.J. Merelo, and P. Chacon.* Springer, New York. pp. 668–678.
- Driankov, D., Hellendoorn, H., and Reinfrank, M. 1993. An introduction to fuzzy control. Springer, New York.
- Forsberg, H., Grillner, S., and Rossignol, S. 1975. Phase dependent reflex reversal during walking in chronic spinal cats. *Brain Res.* **85**: 103–107.
- Gorassini, M., Prochazka, A., Hiebert, G.W., and Gauthier, M. 1993. Corrective responses to loss of ground support during walking. I. Intact cats. *J. Neurophysiol.* **71**: 603–610.
- Hiebert, G.W., Whelan, P.J., Prochazka, A., and Pearson, K.G. 1994. Contribution of hindlimb flexor muscle afferents to the timing of phase transitions in the cat step cycle. *J. Neurophysiol.* **73**: 416–420.

- Kirkwood, C.A., Andrews, B.J., and Mowforth, P. 1989. Automatic detection of gait events: a case study using inductive learning techniques. *J. Biomed. Eng.* **11**: 511–516.
- Llewellyn, M., Yang, J., and Prochazka, A. 1990. Human H-reflexes are smaller in difficult beam walking than in normal treadmill walking. *Exp. Brain Res.* **83**: 22–28.
- Massion, J. 1992. Movement, posture and equilibrium: interaction and coordination. *Prog. Neurobiol.* **38**: 35–56.
- Nielsen, J., Sinkjaer, T., Toft, E., and Kagamihara, Y. 1994. Segmental reflexes and ankle joint stiffness during co-contraction of antagonistic ankle muscles in man. *Exp. Brain Res.* **102**: 350–358.
- Pearson, K.G., and Collins, D.F. 1993. Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity. *J. Neurophysiol.* **70**: 1009–1017.
- Popovic, D.B. 1993. Finite state model of locomotion for functional electrical stimulation systems. *Prog. Brain Res.* **97**: 397–407.
- Popovic, D., Tomovic, R., and Tepavac, D. 1991. Control aspects of active above-knee prosthesis. *Int. J. Man-Mach. Stud.* **35**: 751–767.
- Prochazka, A. 1989. Sensorimotor gain control: a basic strategy of motor systems? *Prog. Neurobiol.* **33**: 281–307.
- Prochazka, A. 1993. Comparison of natural and artificial control of movement. *IEEE Trans. Rehab. Eng.* **1**: 7–17.
- Prochazka, A. 1996. Proprioceptive feedback and movement regulation. *In* Integration of motor, circulatory, respiratory and metabolic control during exercise. American handbook of physiology. Sect. A. Neural control of movement. *Edited by* L. Rowell and J. Shepard; associate editors J. Smith, J. Dempsey, J. Johnson, P. Wagner, and R. Terjung. Oxford University Press, New York. pp. 89–127.
- Prochazka, A., Gorassini, M., and Taylor, J. 1992. Adaptive control of proprioception. *In* Muscle afferents and spinal control of movement. *Edited by* L. Jami, E. Pierrot-Deseilligny, and D. Zytnicki. Pergamon Press, London. pp. 129–136.
- Prochazka, A., Bennett, D.J., and Gillard, D. 1996. Implications of positive force feedback in the control of movement. *J. Neurophysiol.* In press.
- Schieber, M.H., and Thach, W.T. 1980. Alpha-gamma dissociation during slow tracking movements of the monkey's wrist: preliminary evidence from spinal ganglion recording. *Brain Res.* **202**: 213–216.
- Schieber, M.H., and Thach, W.T. 1985. Trained slow tracking. II. Bidirectional discharge patterns of cerebellar nuclear, motor cortex, and spindle afferent neurons. *J. Neurophysiol.* **54**: 1228–1270.
- Shi, X., Wang, F.-Y., and Lever, P. 1995. Experimental results of robotic excavation using fuzzy behavior control. *IFAC Journal on Control Engineering Practice.* In press.
- Vallbo, A.B., and Al-Falahe, N.A. 1990. Human muscle spindle response in a motor learning task. *J. Physiol. (London)*, **421**: 553–568.