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ROBOTICS CONNECTED TO NEUROBIOLOGY BY TENSOR THEORY OF BRAIN FUNCTION

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Abstract: A theoretical unification of Robotics and Neuroscience is suggested, to be accomplished by applying a common tensor formalism (general coordinate system-free analysis of multidimensional vectors attributed to physical invariants), and a common underlying concept: multidimensional geometry. These formal and conceptual means could be utilized in a general manner since both disciplines concern with comparably complex organisms, each operating with characteristic (usually non-orthogonal) system of coordinates, which are intrinsic to their structure.

The Challenge

Modern brain research and advanced engineering face the challenge of understanding and creating organisms which are comparable both in their complexity and performance. A robotic systems or other cybernetic machine to be endowed with intelligent functions such as coordinated motor action, vision and pattern recognition is not unlike a neocortex-controlled sensorimotor apparatus in the central nervous system. Neurobiology represents what is thus far known about existing intelligent coordinated systems. Robotics will eventually aim at making use of whatever is to be learnt from nature's solutions. Thus, it is desirable both from a theoretical scientific point of view and from the pragmatic practical vantage point of engineering if Neuroscience and Robotics, these hitherto disparate fields of research, could be connected by a common concept and formalism [1,2].

An Attempt of Unification

A recently developed approach, tensor network theory of the central nervous system [3-6], may be useful towards attaining the above goal. Formally, the tensor approach is based on the fact that the brain expresses its function in systems of coordinates that are intrinsic to the organism. While in engineering the choice is ours to apply whatever frames of reference we find convenient, there is no reason to assume that nature's organisms operate in our usual X,Y,Z (orthogonal three-dimensional Cartesian) frames.

This realization necessitates functional representations in terms of transformations within and among general coordinate systems intrinsic to complex organisms, as symbolized in Fig. 1.

Basic Tensorial Distinctions

Development of a general vectorial representation is based on the distinction of covariant, contravariant (and mixed) vectorial expressions. In non-orthogonal frames they have different numerical, operational and transformation properties [7], which relate to basic differences of covariant sensory and contravariant motor vectorial expressions, and the metric-type transformation in between [4]. In these terms, the tensorial sensorimotor scheme can be concisely represented by a three-step transformation (see Fig. 1).

The covariant sensation vector may be transformed into contravariant perception (both expressed in the generally non-orthogonal sensory frame of reference) by a metric tensor of the sensory space.

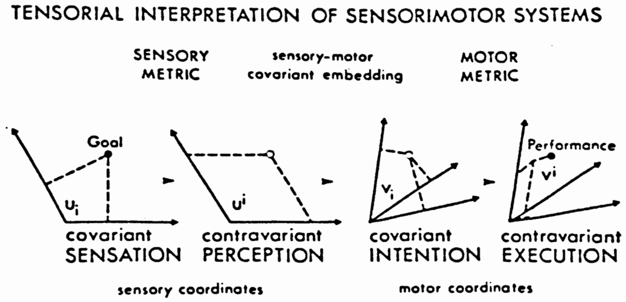

Fig. 1. Transformations from coordinates measured in a general non-orthogonal sensory frame into motor coordinates that are physically assembled in another (also non-orthogonal but overcomplete) frame.

The transfer from sensory frame to motor frame can be performed by an operation called covariant embedding [4,5] by a tensor whose components are the projections of the motor axes into the sensory axes. While covariant embedding enables a transfer from a k to an n dimensional frame (with no restrictions to either k or n); such transfer yields a covariant (intention-type) motor vector whose physical execution would result in an improper physical invariant [4]. Thus, a metric-type covariant to contravariant transformation is also necessary in the motor frame, as the last step of the scheme.

Biological Example: Coordinated Gaze

An example of utilizing intrinsic frames of reference is (as shown in Fig. 1) the set of sensory

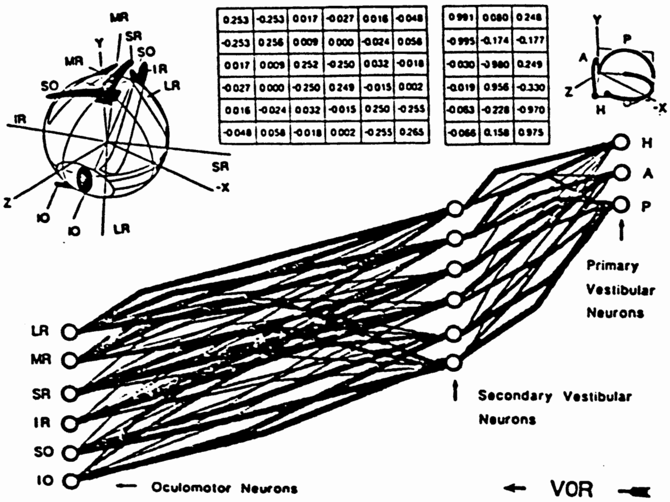

Fig. 2. Brain function, such as the vestibulo-ocular reflex (VOR) is expressed in intrinsic coordinates. Constant gaze-direction is maintained, despite head movements, by neural networks of the CNS, that turn the eye in the frame of reference (which is determined by the eye muscles) to compensate head-movements (as detected in the frame of vestibular semicircular canals). Both frames are intrinsic to the structure.

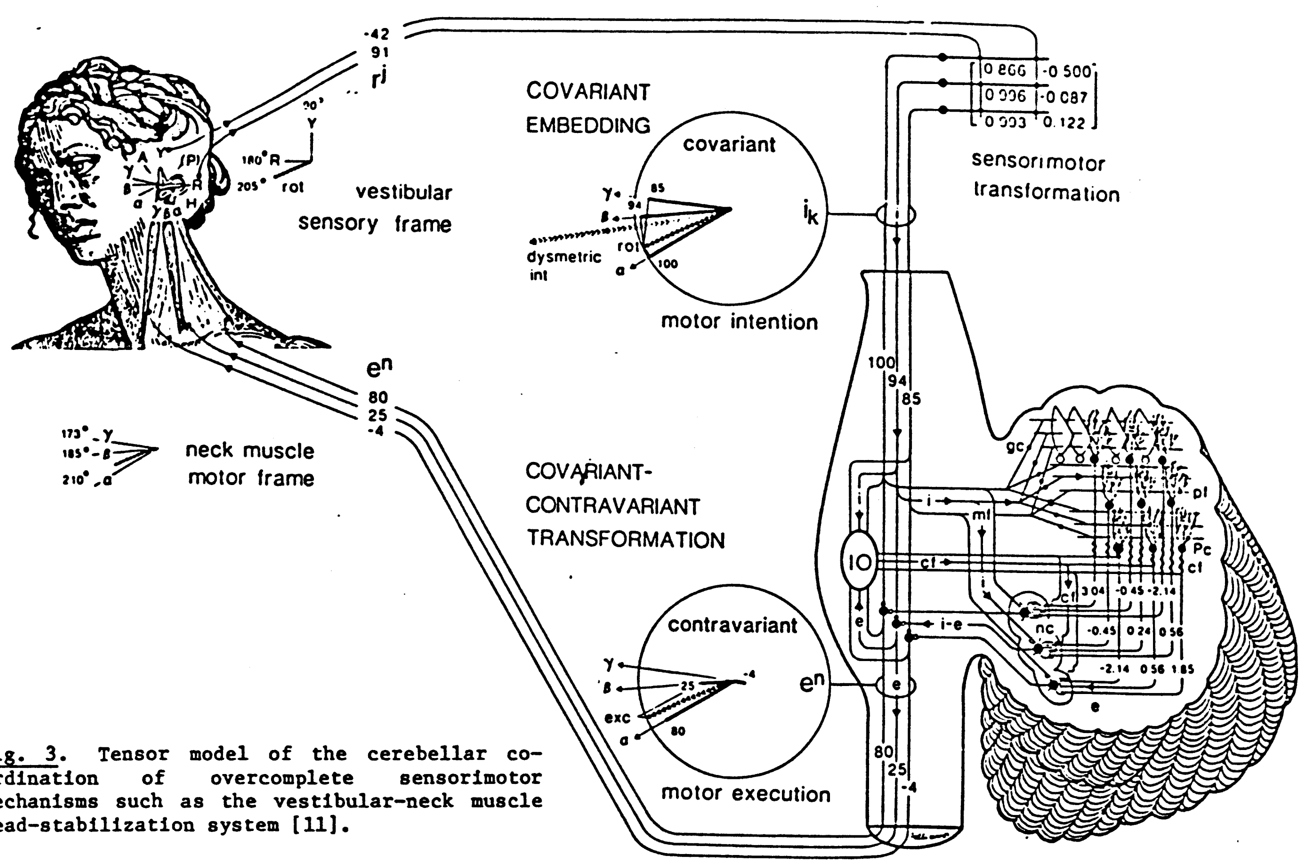

Fig. 3. Tensor model of the cerebellar coordination of overcomplete sensorimotor mechanisms such as the vestibular-neck muscle head-stabilization system [11].

vestibular coordinates (A,H,P) that measure a passive head movement and the corresponding non-orthogonal motor muscle coordinates (LR,MR,SR,IR,SO,IO) by which an active compensatory gaze-movement is generated [8,9,10]. This function is implemented through a neuronal network that performs the transformations necessary to convert the covariant (sensory-type) vector, which consists of orthogonal projection-components of the physical invariant to the axes of the frame, into the contravariant (motor-type) vector, which consists of physically executable parallelogram-components.

Coordination by Cerebellum

Some aspects of a tensorial interpretation of CNS morphology are fairly obvious. For instance, fundamental operations shown in Fig. 1. may be implemented in the CNS in more or less concise forms. If some transformation tensors are contracted (eg. the first two combined and the remaining third left separate); a two-network "three-neuron arc" results (as in Figs. 1,2). In turn, if some transformations are implemented in the CNS by more than one network, a more than three-step scheme would emerge.

Other morphological aspects are more substantial. For example, the theoretical requirement of a transformation of the covariant motor intention vectors into contravariant motor execution vectors led to the hypothesis that the neuronal network of the cerebellum acts as a metric tensor-type coordinator [4].

Beyond yielding a biological model of the cerebellum as an intention-execution transformer, the tensor-approach directly relates to some control problems of coordination of multi-jointed, kinematically redundant manipulators [12]. Therefore, the tensorial elaboration of a cerebellum-model (see in [5,11] and Fig. 3) could be parallelled by obtaining a US patent ("sensorimotor coordinator"; #4,450,530) based on the tensor-hypothesis of the function of cerebellum. The mathematical elaboration of the coordination-scheme [13] is based on the Moore-Penrose generalized inverse [14] of the covariant metric tensor of the motor frame, since in case of kinematic redundancy (overcompleteness) the inverse is not uniquely determined.

The tensorial coordination-paradigm is shown in Fig. 3. as applied to the head-stabilization system consisting of an intrinsic vestibular sensory and neck muscle motor frames. The head-movement vector (expressed in vestibular coordinates) is converted into intention-type covariant motor vector (expressed in neck-muscle coordinates) by covariant embedding. This transfer can be performed from k to n dimensions (from two to three dimensions in the shown case). Then, the cerebellar neuronal network, acting as a covariant-to-contravariant metric-type transformer, converts these intention-components (which would add into a dysmetric performance) into executable physical components. The Moore-Penrose generalized inverse of the covariant metric of the motor frame is not implemented as a single throughput of one matrix. The cerebellum is a later addition in evolution, providing the e=i-(i-e) execution vector through supplementary bypasses (by a transfer of intentions via the cerebellar nuclei and through the cortico-nuclear network, where the numerical components of the Moore-Penrose generalized inverse are shown).

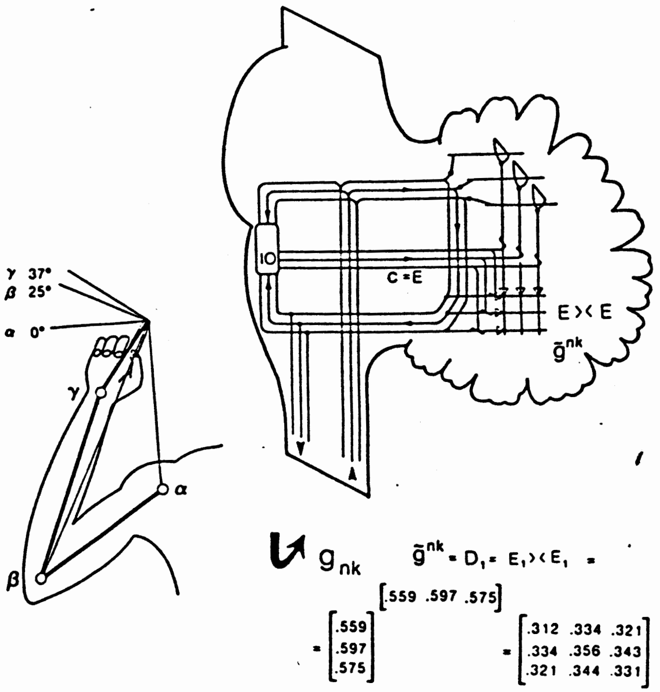

Fig. 4. The principle of emergence of neuronal networks for coordinated limb control by metaorganization [6]. The process is based on finding the proprioception - motor execution eigenvectors and imprinting the Moore-Penrose generalized inverse in the form of spectral representation by the dyads of eigenvectors.

Applications of Tensorial Sensorimotor Scheme

The tensorial scheme of overcomplete transformations in general intrinsic frames of reference is the starting point for developments into several directions.

Elaboration of Sensorimotor Models: First, the conceptual model is developed into quantitative interpretation of existing sensorimotor systems such as vestibulo-ocular [8,9,10] and vestibulo-collic reflexes [11,15], which are highly complex mechanisms (the latter consisting of 6 semicircular canals and 30 neck muscles).

Further Conceptual Development of Theory: The cerebellar coordination-scheme is suitable for addressing the important question of how neuronal networks (eg. acting as metric tensors) emerge in the CNS. As shown in Fig. 4, the principle of metaorganization [6] of such metric networks is based on finding the covariant-contravariant eigenvectors of the motor frame by reverberation of the proprioception - execution signals. When such eigenvectors are detected by the inferior olive, which serves as a comparator of incoming and outgoing vectors, the climbing fiber vectors can build in the cerebellar cortico-nuclear circuit a metric-type transformer from the cumulative dyadic (outer) vector products of the eigenvectors.

Applications in Biotechnology

Since neurophysical schemes as above hold not only for coordination of living motor systems, but also of man-made organisms, applications can be developed in the fields of biomedical physics and engineering (for medical rehabilitation) and the physics and engineering of mechanical and electronic systems (for robotics).

"Electronic Nervous System": As for medical rehabilitation, two applications are immediately obvious. From Fig. 4. it is apparent that the basic tensorial scheme also applies to the motor control of multijoint limbs other than the intact human limb. One potential field of application, therefore, is prosthetics. While the mechanical sophistication of "cybernetic limb protheses" is outstanding [16], the control paradigms that are available for operating them in a coordinated manner are detached from those principles that the CNS is using for the control of existing limbs. This gap could be filled by supplementing protheses with an "artificial brain"; an electronic cerebellum. The other need of potential application in medical rehabilitation is providing "electronic brains" for patients with intact musculature, but have lost neuronal control on them (paralytic victims of various diseases, physical trauma and stroke; such as paraplegics). In such cases an artificial electronic activation of muscles (by external stimulation) is already possible. However, most research projects in this field await a breakthrough for developing suitable paradigms for a coordinated multidimensional control of such motor apparatus with highly complex intrinsic systems of coordinates.

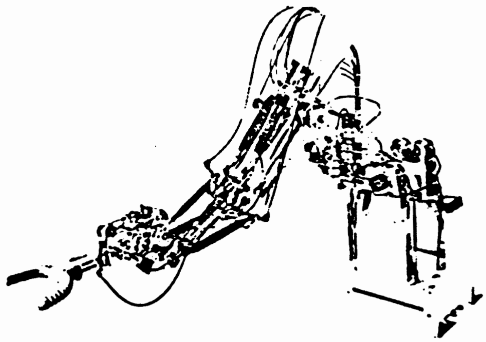

Fig. 5. Robotic arm, working with "artificial, pneumatic rubber-muscles" (Bridgestone Corp. and Hitachi Ltd.). This "antropomorhic" instrument, which uses rubber actuators in pairs, enables a delicate assembly task by soft-touch. However, the use of non-conventional intrinsic system of coordinates (especially if it is overcomplete) presents a problem of developing suitable control paradigms. CNS uses a cerebellum for coordinated control in similar instruments.

Brain-like Robot Controllers: As for robotics, it should be mentioned that the use of a general theory in engineering (such as tensor analysis which can represent vectorial operations in any system of coordinates) is a controversial one. Almost half a century ago Kron [17] initiated such an approach of "general engineering" (a contradiction in terms, since engineering is aimed at simplicity embodied in a particular apparatus). His efforts remained heroic, mostly because he was so much ahead of his time. Half a century ago neither the need was self-evident, nor the means were available for dealing with complex systems with intrinsic coordinates.

Tensor network theory of the CNS (which is akin to Kron's pioneering efforts [17,18]) may face a kinder fate. At least, there are three sources of hope. First, this approach originates with neuroscience (a basic research) and is directed towards engineering (an applied science). Not only is this a more natural trend, from the general towards the specific, but biology teaches us that evolution selects general solutions that are manifested in many specific varieties (eg. general cerebellar coordination is accomplished by different particulars in various species). Thus, finding the underlying general principles of operating in any system of coordinates may provide the key for a whole class of specific solutions. Second, looking at biological mechanisms such as neck- or limb-muscles arranged in highly complicated fashions, not only the need of dealing with complex intrinsic systems of coordinates is obvious, [16] but already there is direct experimental evidence [19] that limbs are activated in a manner that supports the tensor hypothesis. Third, and perhaps most important, we have come to possess almost unlimited means of dealing with complex systems: computers. By these instruments (either in their computer of microprocessor-form) rather sophisticated control paradigms can be programmed in a general vectorial language and numerically implemented in the intrinsic coordinates of a specific apparatus.

An implementation, at a practical utilization level (a formal and conceptual merge of neuroscience and robotics) can be envisioned as follows. Once a theoretical scheme (such as the coordination-paradigm) is made available, a software system needs to be developed, leading to a high-level special-purpose compiler. Such software, beyond being a convenient language for tensor network models of parts of the CNS, could be utilized in robot-controller computers. Such a truly "brain-like machine" may eg. coordinate electronic signals that either activate existing muscles, or "rubber muscles" of actuators in cybernetic prostheses [16] as well as in advanced, obviously "anthropomorphic" robots (such as shown in Fig. 5).

Tensorial Geometrical Processors for Intelligence

To outline further utilizations, one wishes to emphasize the following fact. The usual choice of convenient three-dimensional orthogonal systems of coordinates is even more artificial in brain-like machines that are built to perform more sophisticated acvities than motor execution. To resemble any biological apparatus, sensory processing (eg. computer vision) ought to be developed in general coordinates; eg. in tensorial formalism that can accomodate highly non-conventional frames of reference. It is even more likely that cognitive brain functions (such as intelligence) not only may not use trivial systems of coordinates, but may exploit geometrical properties of non-Riemannian multidimensional functional manifolds. The tensor approach conceptually focuses on the functional geometry of the multidimensional representation within the brain of the external reality. Thus, with the help of common formalism of tensor transformations in general systems of coordinates, and with the common concept of intelligent systems operating as geometrical processors the rapproachment of Robotics and Neuroscience may be greatly facilitated for substantial benefit of both.

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