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Tools and Computational Machinery for Movement

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Abstract

This paper is a discussion of computational tools and circuits that deal with the internal and external worlds of the human body. The information processing avenues in the central nervous system (CNS) are an important part of the development.

All sensory channels and the vision system are involved. It clarifies the role of the sensory system in internal coordinate systems and for all activities of the CNS. It includes the inherent redundancy aspects of the motor system as well. The visual system is involved in sports such as soccer and basketball and for being aware of and paying attention to both the internal world and the external reality surrounding the athlete.

Keywords: visual processing, computational tools, learning, redundancy, stacks, interrupts, imagination

1. Introduction

One way to perform a particular movement or maneuver is to observe and imitate the action of another human. The process may also involve learning. There are four operations: visual observation, perception, storage, and reproduction of movement. Observation involves the retinal mechanism and vision. Perception involves visual processing. Storage involves memory. Reproduction of the maneuver involves the transmission of the stored movement to both the cerebellum and the musculoskeletal system. In this paper, we consider several computational structures and two alternative coordinate systems for this purpose.

One way to achieve a long-range understanding of the CNS and all its functions is to identify smaller and more limited CNS processes (Angevine & Cotman, 1981; Mountcastle, 1980). These processes should be described in terms of their inputs and outputs. They should be amenable to computational machinery to describe them and simulate them initially with standard computer packages and programs and, later, possibly with neural and neurologically oriented elements as functional units. If events can be represented or related to neural oscillators, a large number of events can be considered that work by inhibition, excitement, and working together in groups. Some simpler efforts and endeavors can be cited.

The interruption of one movement by some action and resumption of the original motion, the imagination of motion rehearsed without physical execution, and mental control of movements are standard CNS events. The role and involvement of the vision and vestibular systems are part of such smaller CNS endeavors. The involvement of the motor cortex in voluntary movement (Angevine & Cotman, 1981, figure 9.1), is the abstract map of how the sensory system can provide a set of variables. Joint angle sensors are involved (Mountcastle, 1980). The motor cortex should point to ways of producing a movement by combining the individual function or action of a group of segments as in athletic efforts.

A motion such as a three-dimensional dance of a single dancer or a group of dancers points to some of the attributes of retinal and visual processing. How the motion is observed, processed visually, stored for recollection, and extracted for later physical repetition is not well understood at this time. In sports such as soccer (Marchiori & Vecchi, 2020), the role of the visual system is essential in assessing the environment for the best delivery of the ball, shooting it, or holding onto it. The visual survey of the field and physical efforts to keep the ball under full control are two simultaneous activities that divide the athlete’s attention and concentration. While the implementation of many of the CNS neural processors are analytically defined, and can perhaps be described by artificial neural networks, knowledge about chemical and physical CNS processors (visual, chemical and electrical) is scant. Further, the distribution of the mental resources between visual efforts to the field and physical efforts to manipulate the ball are new challenges in athletics, psychology, and understanding mechanisms of division and manipulation of internal human resources.

Conversion of standard engineering programs to neurological functioning (Hemami & Utkin, 2019) has additional degrees of difficulty and challenge: frequency modulation of amplitudes, the amplification and/or attenuation of neural signals, and lack of negative numbers are other challenges.

CNS memory structures and their natural implementation will have a great deal to do with the CNS processing. A realistic model of the combination and inclusion of memory structures is beyond this paper.

In order to develop an adequate and physiologically accurate model of the CNS and the cerebellum, one needs accurate information about the streams of input and output to and from the cerebellum. Factual data and accurate information about streams of data and data and commands flowing from the cerebral inputs to the cerebellum are needed (Ghez, 1991). As an example, consider the case of a damaged cerebellum where a multi-joint parallel effort cannot be undertaken. The CNS seems to recognize the difficulty and rearranges the inputs such that the task takes place as a sequence of single-segment actions. The issue is not only that the human movement system appears to be redundantly designed, but this kind of redundancy does not fit any of the available definitions of redundancy.

Certain deficiencies, injuries, and genetic defects are detectable by the CNS and mechanisms of compensation are available (Terman & Wang, 1995). Besides, the CNS processes are a combination of electrical and chemical processes. The CNS does not have standard arithmetic processing with positive and negative numbers, and most of the signal intensities are frequency modulated rather than amplitude modulated (as in the technology of today.) One way to develop a coordinate system in humans is by trial and error, learning, and the use of stacks. The discussions and the implementation of the routines employed here are in standard engineering routines and mathematical formulations. To assemble and process a large amount of data, use is made of four kinds of synchronous stacks: first-in-first-out (FIFO), last-in-first-out LIFO), combined-in-combined-out (CICO), and multi-dimensional stacks.

To understand stacks better, four movements are considered:

- Interruption of an action or movement, and multiple interruptions based on the high priority of the current action,
- Reversing a movement in time,
- Design of signals, and
- Design of oscillators.

It is shown how stacks can be useful in understanding memory, creative mental processes, and mechanisms of imagination. In what follows, examples of CNS processing patterns are considered in Section 2. Visual processing and visual pattern processing and applications are addressed in Section 3. Internal coordinate systems are presented by examples in Section 4. Computational issues (joint sensors) are presented in Section 5. Discussion and conclusions are presented in Section 6.

2. CNS Processing Patterns

To gain better understanding of internal processing of the CNS, several processes are briefly discussed. The human CNS has many processing routines of different speed, complexity, neural detail, and applications. A number of different processors are cited here: interruption of movement, multi-interruptions (interruption of an interrupted movement a number of times by higher-priority interrupts,) reversing a motion in time, imagination machinery, and creativity (construction of a multi-object scene or decomposition of a multi-object image) (Ethan, 2018). Some are briefly addressed here. There is need for determining and being aware of where the body is relative to the external world and where the limbs are relative to the body.

2.1 *Interruption*

Interruption of a movement of is a complex issue. The complexity of the interruption process depends on the difficulty of the task. As an example, consider a person carrying a pot of coffee in his hand. If an internal or external interrupt is issued, the system has to come to a stable equilibrium point with zero velocities for the person and the pot. Carrying out the latter requirements may demand the execution of a completely new motion. Further, all the positions and velocities at the time of interruption should be stored for the resumption of the original motion later. Therefore, implied in the interrupt command are two motions of safe disengagement from the first motion and, later, bringing the system to positions and velocities for further execution of the first movement. Stacks are very convenient for storage of all the states (position and velocity) involved in safe interruptions. The relations between position and velocity variables (or states) are also important in motions and jumping in the air (Kupferman, 1991). The learning process is very challenging and complex.

A simple case of a multi-interrupt system in a simple computer is illustrated here. Under every register of the computer a simple stack is installed. When a request for computer service arrives, one of two options is adopted. If the request is of a higher priority than the current program, the interruption is initiated. This means all register contents are pushed into the stacks and the registers are loaded with the state of the new program to perform the new higher-priority program. The service is the execution of a software program for a higher priority. If a higher-priority case arrives, the processing stops, and all the registers are pushed down in the LIFO stack. Now, all the registers are free for the higher-priority program. After the higher-priority program is finished, the stacks are popped one position and the previous program resumes execution. Many priority levels could be involved and deep LIFO stacks can handle it.

2.2 Reversing the Trajectory in Time

The idea of replaying events in reverse could explain the synchronization of internal action with external events.

Consider a function of time f (T) stored in a computer as f (kT) where T is the unit of time, and k is the duration of the function. In this application, the successive values of k and f (kT) are sequentially entered in a stack. The stack works as a mapping for the function. When the motion is reversed, the stack becomes a LIFO and the states are sequentially read out and fed to a new stack that implements the reversed function.

Foster and Wilson (Foster & Wilson, 2006) found that while rats rested after running a maze, their brains replayed the movements in reverse. The idea of replaying events in reverse cold explain the synchronization of internal action with external events.

2.3 Signal Design

Suppose three functions of time are available in three stacks: $stackp$, $stackq$ and $stackr$. Specific portions of these stacks could be moved to a new stack to generate a new signal. This process allows the design of many signals for learning, phantasy, imagination, etc.

Define a new stack that takes portion ab, cd, and ef from the above three stacks and combines them into a new function of time. Let us use j for joining the three segments. This operation is given by Eq. 1

$$s\ mstack = stackp\ (a,b)\ j\ stackq\ (c,d)\ j\ stackr\ (e,f) \tag{Eq. 1}$$

Thus, a mechanism is available for all desirable functions of time. Any function could also be reversed in time by popping it out of the stack.

A second example is the design of arbitrary oscillations with a desired shape and frequency. The desired shape is stored in a stack with the right sampling, (i.e. with the right frequency.) This signal is read out of the stack and all read values are output to a transmission line for further transm isson. Actually, this may be one of the ways the CNS generates periodic signals.

Thus, use of LIFO structures in imagination and creative brain processes is literally infinite. A more complex example is imagining a street and modifying the shape and color of the buildings sequentially – one after another or in groups. LIFOs may also be involved in the process of learning sports and many skills, such as parallel parking. A general class of CNS processes deals with the situation here the internal and external events have to be related and connected.

An external cue or alarm could involve associative learning (Kandel, Schwartz & Jessell, 1991, Chapter 65). Triggering an alarm can initiate running away, hiding, seeking protection, confronting the danger, or many other strategies. The devotion of time is also involved in mechanisms of attention or preparation for a movement or in a motor set (Evarts, Shinoda & Wise, 1984; Brooks, 1986).

2.4 Design of Observed Signals

The human observer sees a sequence of images (Szturm, & Fallang, 1998; Iqbal, & Roy, 2009). These images are sampled, visually processed by the retina, and stored in a brain x-y plane. These planes could be the elements of a two-dimensional stack. The x axis of the stack (say, to the right) is horizontal and the y-axis is vertical (upward.) A sequence of images is recorded and pushed onto the stack, in the stack, and stored along the longitudinal dimension of the stack. This FIFO stack is two-dimensional: N by N and, at every position, the value of the intensity of the image is stored. For the time being, we assume the image is black and white with different intensities. One neural processing operation can be that these images are transmitted sequentially to memory for further processing or storage. Another mental processing operation is to translate one image in position. Let the coordinate of one position in the stack’s current page be [xp, yp].

It is desired to move this point horizontally to a new position(xn,yn)

$$xn = x(p+3)$$

$$yn = yp \qquad \text{(Eq. 2)}$$

The translated image is transported to the next page or plate of the stack. If the translation command is issued to all plates, a sequence of translated images is generated. By programming both x and y, an arbitrary sequence of translations in some desired direction can take place, while the shape of the image does not change. This effort corresponds to mental artistic creativity to change, create, or transfer images to a sheet of paper, canvas, etc. This same structure can be envisioned for moving an object, image, or drawing in one's head as a form of imagination. A more complex operation is to rotate the image about a particular point and specify the amount of angular rotation – in one step or a repeated number of times.

Another example is the detection of specific features in an image, such as circles of a particular size or corners of different angular extent. Eccles (Eccles, 1997, page 115) has discussed how a column of neurons can dominate by self-excitement and inhibition of the surrounding columns. A mechanism for implementing this dominance is presented here. Alternatively, one could use neural circuits and structures as proposed by Eccles (Eccles, 1997, Figure 3.3).

Consider the following discrete-time version of version of the translation of the image. Suppose one plate in the stack is considered and a particular feature is detected in the cell $q_{i,j}$. The intensity of the content of the cell is $\delta_{i,j}$. The objective is to amplify the content a Times and suppress the content of the eight neighboring cells to zero. The nine equations below describe the operation of suppressing the surround (SS). The difference equations of the process are given by Eq. 4.

$$q_{i,j}(k + 1) = \quad a\ qi,\ j(k)$$

$$\underline{q_{(i-1),j}\ (k + 1) = 0)}$$

$$q_{(i+1),j}\ (k + 1) = 0$$

$$q_{i,(j-1}(k + 1) = 0)$$

$$q_{i,(j+1)}(k + 1) = 0$$

$$q_{(i-1),(j-1)}(k + 1) = 0$$

$$q_{(i-1),(j+1)}(k + 1) = 0)$$

$$q_{(i+1),(j+1)}(k + 1) = 0\ )$$

$$q_{(i+1),(j-1)}(k + 1) = 0) \qquad \text{(Eq. 3)}$$

To mentally create a horizontal line, one uses the same structure as before

$$q_{(i+1),j}\ (k + 1) = q_{i,j}(k) \qquad \text{(Eq. 4)}$$

All other eight surrounding values are zero. A repeated number of this operation extends the line. The line could be drawn vertically. A 90-degree corner could be created by running the horizontal line sequence twice and following it by two vertical movement commands:

$$qi,(j+1(k+1)=qi,j(k). \qquad \text{(Eq. 5)}$$

Through this process one could create geometric structures made of lines, corners, etc. With neural models, one could create angles of arbitrary size. The importance of this surround suppression operation (SSO) is that now one has two mechanisms: a fast process and a slow process. It can be a relatively fast process for images. The flow of the images through the FIFO stack is the slow process. More information about the processing and experimental efforts for sensory processing and commands can be found in Kuffler and Nicholls (Kuffler & Nicholls, 1976, Chapter 15) Mental amplification, attenuation and rotation of planar images are interesting examples of brain processing not to be treated here. To clarify the structure of this fast local processing, a number of simple (i.e., planar) visual images and mental activities can be cited:

- The boundary and the slope of the boundary of the image are tracked and recorded for remembering, storing, or reproducing the image of the observed object,
- to translate an observed object to a new location in the same plane,
- to rotate an image around a certain point,
- to chop a specified part of an image,
- to magnify or shrink an image,
- to transform an observed image into a newly (mentally) defined image or picture, and
- to create and execute the addition of artistic or other features to the image

Many more examples can be added here. Most of such simple mental processes can be programmed in discrete time planar state spaces and verified by programming. The challenge here is the verification of the process in natural systems and designing the neural CNS equivalent processor. Production of images of any kind can be handled by stacks with the structure of processing in time along the longitudinal axis and other geometric and shape-related commands along the current plate or plane in the stack. This double mechanism can be used to mentally imagine and design still or moving figures, as will be shown below.

This process of a slow three-dimensional stack and a multi-layer fast-processing local operator in every plane is a very convenient way to model many CNS processes and be able to simulate them with conventional current computer structures and programs. In the CNS models, the clock rates can be controlled by mechanisms of attention and how important the immediate issues, portrayed in the stack, are to the CNS. The most important difference between computer stacks and the natural stack models, as envisioned here, is that the clock rates are not rigid and the mental processes can be controlled to be fast or slow, depending on what the CNS is trying to do. This points to a serial integration of one or several secondary computer schemes and structures imbedded in a first computational structure. A number of CNS applications of three-dimensional stacks with second-level local processing are introduced here as models of different routines and processes of the CNS;

- Development of kinematic models of movement
- Body-based coordinate system
- Image construction in creative mental work
- Mechanisms of attention
- Imagination
- Memory

Many more CNS processes can be cited. Here some attributes of each of the above six items are described to clarify the processes The most important difference between computer stacks and the natural mental stack models is that the clock rates are not rigid and the mental processes can be controlled to be fast or slow, depending on what the CNS is trying to do.

We can introduce another level of computational capability in the visual stack. If the image is moving, detection of time-varying parameters and storing them for future CNS use is another area where different stack qualities and processes are useful (Tomovic, Popovic & Stein, 1991). As an example, link image of a human in motion. The movement to be observed is the body and the right leg remaining vertical and the right thigh moving from the vertical position to a horizontal position in one second. The objective may be to extract the trajectory: horizontal angle of the thigh rising in one second from zero to 90 degrees.

The computed or measured angle α and zero values for the angle of the body and the right leg can be stored in another stack for future reference and use (either to imagine the motion or as input to the musculoskeletal system in order to perform this motion.) A similar strategy can be proposed to extract the motion of the lower extremity in the frontal plane. These two movements were observed visually. Rotation of the body and head about the vertical axis (yaw) is easier in self-observation (Kane & Levinson, 1985) because the vestibular system is sensitive to rotational acceleration and, by integration, has access to rotational velocity and position of the head in ICS. In other words, the vestibular system provides the states of the head in the inertial coordinate system. The extraction of the states of a moving or dancing human being from visual observations and recognition of the visually observed patterns is a future effort for understanding neurophysiological pattern recognition of three-dimensional patterns. The natural process is not well understood. One possible direction is to divide the observed image into individual three-dimensional objects and combine Fourier descriptors (Humphrey, 2009) and visual processing to estimate the trajectories of the segments of the image in ICS coordinates. This is a worthwhile effort for future research. The question of how all simple motions thus observed are stored and combined for more complex motions and how learning improves the procedure also remain important issues for future research.

Alternative processing may depend not on the whole image of the thigh but on the upper boundary curve of the retinal image. The initial processing of the retinal image is considered here from a bright black-and-white image. The initial processing of the cone signals (Thach, 1980, Figure 9.1) is by the ganglion cells that are the principal output neurons of the retina (Thach, 1980, page 187). Different ganglion sizes appear to modulate the sensory signal according to its intensity: smaller ganglion cells oscillate at lower frequencies and larger ganglion cells oscillate at higher ones. These signals project onto the lateral geniculate nucleus (LGN) of the thalamus. From the thalamus, these signals are guided to the neocortex (Thach, 1980, Figure 11.1, page 247). The neocortex destination is area 17 (Thach, 1980, Figure 11.2). One may speculate that the two-level stack processing introduced earlier may be a natural candidate for the processing of the reticular formation. Several other examples of retinal processing and the stack tools for the processing are presented here. The important thing to remember is that all imaging, recording and uses are measured, calibrated, and applied relative to the internal coordinate systems the body uses rather than external coordinate systems such as Euler angles, etc. Therefore, all processing of planar two-dimensional images have to be related to the human body and its internal coordinate systems rather than other external coordinate systems. For a physical example, consider the process of parallel parking a car. The four corners of the car are either visually available or are mentally estimated to be at certain distances from the position of the driver. The position of the basketball hoop is recorded relative to the position of the player who throws the ball. The position of a painting on a wall is related to the brain image of the wall in the person’s head.

2.5 Processing of Lines

The observed line may be stationary (as in buildings) or a fast-moving line or object. A point (or cell) on the fovea captures the energy or image of the object, and it responds with a high output. At the same time it inhibits all the cells around the excited cell as discussed before. This whole effort is pushed into a stack (the next layer of cells.) The light or object image hits the next cell on the retina, and the process repeats. Now, the stack has two layers.

This process is repeated until the line or object is not in sight of the eye. If the whole stack is projected on one plane, the image of the line forms by all the excited cells on this plane. If it is decided to move this image and record it in permanent memory other actions are needed. Eccles (Eccles, 1997, page 187) refers to these images as engrams that are also used for retrieval of information.

The same process could be applied to a stack with cells that are sensitive to velocity of the image. The cell that is sensitive to the image velocity gets excited and all the neighboring cells are inhibited. The storage and pushing the image in a stack are similar to the previous case. Here, it is possible to have images of objects that move on a closed trajectory, such as an ellipse, circle, etc.

3. Connected Rigid Bodies

Connected rigid bodies with constraints can be used to model robotic, humanoid and bipedal locomotion systems. Further, the equations of motion can be reduced and modified to correspond to a variety of human-like movements, such as jumping in the air, coordinated motion on the ground or on ice, responding to a variety of disturbances, and maintaining balance. Humans perform such tasks and others efficiently and smoothly by selective attention to the task at hand, involving the appropriate components of the neuro-- system, the brain, and the sensory system. Evart (Evarts, Shinoda & Wise, 1984) has referred to the phenomenon mentioned here as the attention set The musculoskeletal system can be segmented into two disjointed components: one carries out the task, and the second one supports the execution of the task. The support may take many forms. The second component may firmly attach itself to an inertial coordinate system to support the task. It may attach itself to the first component, or it may take on a facilitatory maneuver to help the task. Many examples can be cited in sports: tennis, soccer, basketball, etc.

From a philosophical point of view, the above methodology is very important in human efforts: degrees of freedom are added to ease the execution of a task. As learning takes place and the task is executable, the added degrees of freedom are removed. The best explanation and execution of this philosophical point of view is discussed and implemented by Kane and Levinson (Kane & Levinson, 1985, Chapter 7) in the computation are constraint forces. Degrees of freedom are added to a constrained system to make the computation of constraint forces possible. After the forces are computed, the constraints are applied to the process to derive the force equations.

A similar human effort is in sports. Suppose a soccer ball is shot by a winger into the penalty area. The ball is moving fast across the goal at about five feet above the ground. The player (striker) is running toward the goal, tracks the ball visually, and aims to intercept the ball with his head and drive it to the goal. For simplicity, let us assume there are no defenders for the striker to deal with physically. The striker must use his feet to propel his body and head as one rigid object colliding with the ball and change the velocity of the ball in the direction of the goal. The feet are used to propel the body (Kandel, Schwartz, & Jessell, 1991). The vestibular system constructs the three angular position and angular velocities (states of the head) relative to the coordinate system of the external world (the soccer field.) The equations of one rigid body on the ground are repeated here for comparison. Let vectors of force G and H be, respectively, the gravity vector and the vector of external forces. Let Λ be the supporting ground force. The equations of motion of the single rigid body are given in Humphrey, 2009.

Suppose the neck is held rigidly such that the angles and angular velocities of the one-segment rigid body trunk are the same as those of the head. Let this vector of angles be Θt. Now, consider a second rigid body (as one of the four extremities) attached to the first rigid body. The position of the second rigid body (i.e. Θe) can be described by three joint angles that measure, respectively, the difference between the angles of the two segmentations of ICS and JA-Based Coordinates.

Still a third system of estimating the states involved in joint angle computation may be the spindle system, normally thought of being used only in muscular control but that may be involved in CNS derivation and computation of segment states (Thach, 1980). In the ICS-based system, the states are hard to measure, but the computations are relatively straight forward. In the JA-based system, it is easy to measure the joint angles as states, but the computations are more complex. Perhaps the CNS uses other state coordinate systems and states that are yet to be discovered.

One possible candidate is the trunk, with ICS coordinates as measured by the vestibular and vision systems. The extremities are related to the trunk by joint angles that may be needed for some other movements for directing a ball in soccer or basketball.

4. Action, in Soccer and Basketball

The example here is a special movement of the upper or lower human extremity. The lower extremity is lifted in the air and rotated in space (the foot or toes moving in a circular trajectory.) In soccer, the trunk is used in translation to give the ball a high velocity. The head is used for directing the ball toward the goal. There are other variations of such a strike. The strike of German forward player Mario Goetze in the World Cup Final of 2014 match between Germany and Argentina is a good example. A basketball player may decide to launch a long-distance three-point shot or dribble to the goal area (i.e., release the ball or pass the ball.) The launching effort is understood in terms of Evart’s platform effort: The body is used as a stable platform from which the arms launch the ball. The visual system is essential in determining trajectories of the ball, the player, and other players.

Three areas are essential for the future:

- storage of desirable motions,
- creation of efferent signals to perform the motions, and
- the involvement of the cerebellum.

The joint angles may have to be computed from all the remaining sensory inputs. Another related area is when a motion is observed and its major characteristics are processed visually and stored in memory for later recall. The recall is either to remember or to repeat the motion. The visual three-dimensional pattern recognition involved in this effort is worth exploration. In the motor system, timed events may be constructed in real time or made, alternatively, available in short-term memory (STM). They may be sequenced to construct longer output events. Coordination with external events, storage, recall, delaying or advancing in time, synchronizing, time scaling, and inverting events in time are examples of CNS processing.

5. Computational Machinery

A basic model of human movement can be represented and possibly simulated by a computer system. This model is far below what human abilities and capabilities are (Foster, & Wilson, 2006), but it points to certain structures that are helpful in postulation of gross feedback and feedforward paths. It also identifies certain directions for future research in all aspects of human neurophysiological and neuropsychological structures. The major advantage is in imitation of human movement by a multi-link physical model, a cerebellar structure, and a brain model where all paths of signals, all processing, and all disabilities of the model are under control and can be imitated by simulation. The behavior of the artificial model can be compared with the physical human model. When the model is physically and neurologically accurate, accurate information becomes available about the CNS. When the model is not adequate, additional research is called for.

5.1 Musculoskeletal Component

The first computer can represent the musculoskeletal dynamics of almost all movements by conventional state-space representations, and special mechanical state space. In the musculoskeletal computer, as discussed before, the major states are the memory elements that represent position and angular velocities of all the body segments represented by Euler or Bryant angles.

5.2 Cerebellar Component

The second computer represents implementation of the cerebellum as an intermediary device between the CNS computer and the musculoskeletal computer in some of its better-defined functions. The cerebellum computer implements (Ethan, 2018) higher efforts of the CNS in providing desired trajectories of movement to be executed and in monitoring and modifying the efforts. As an example, consider the simultaneous movement of several joints. The cerebellum is equipped with structure and function to implement activation of many muscles to implement the motion in parallel. The vector of forces for all the linkages or the vector of torques for all angles becomes available. Therefore, under normal and healthy cerebellum operation, the movements are executed in parallel. When the cerebellum does not function, alternative functioning of the cerebellum, issued by CNS commands, takes place and the movement of the multi-link is carried out slowly (serially and one segment at a time.) This element of redundancy and serial design must be integrated in the CNS computer.

5.3 Central Component

The central computer (i.e., the CNS) does not get involved in the detailed execution and implementation of movements. All such efforts are relegated to the cerebellum but are monitored by the CNS. When the cerebellum fails, the function is observed by the CNS computer and the movement proceeds serially and slowly.

In this regard, a major attribute of the CNS is that it appears to be redundantly designed so that certain deficiencies, injuries, and genetic defects of the cerebellum are detectable by the CNS and certain mechanisms of compensation are available [8,9]. The chemical processes of the body (nutrition, growth and learning) are not considered here. Efforts have been undertaken to design parallel circuits that perform parallel distributed processing (called pdp). A second effort, along the same lines, has been called recurrent network (Foster & Wilson, 2006). The past standard approach to system theory, control and communication in engineering has been to concentrate on minimally structured systems. No systematic and mathematically based design methodologies exist for mathematical, logical, or abstract formulation, design, and implementation of redundant systems. However, one needs a redundant and over-designed system to be able to adequately represent the natural system.

Based on experiments and existing theories, the third computer (i.e., the CNS) unit is modified here as follows. One of the major attributes of the third computer is that it is equipped with all instructions, hardware, and behavioral capacities of the second computer. When the movement is not carried out as desired, the CNS attempts to undertake the same effort with its own instructions, functions, subroutines, etc. The CNS computer cannot implement the parallel processing that is not functional due to cerebellar deficiency. It must carry out the movement in series. This fact calls for a special design of the cerebellar computer as embedded in the CNS computer. The computer needs instructions for carrying out the movement differently than when the cerebellar machinery was healthy. The CNS needs a processor status word (PSW) that guides the program to the parallel or serial execution. With the above philosophy of design, the three computers are briefly presented below. All three rely on standard state-space representations.

In the musculoskeletal computer the major states are the memory elements that represent position angles and angular velocities of all the body segments represented by Euler or Bryant angles.

For the cerebellum computer, three classes of central inputs are assumed.

- The vector of the desired trajectories and gains of the musculoskeletal system,
- sequence of central instructions that have to be executed, and
- the sensed positions, velocities and tactile forces.

The desired gains amplify the difference between the forward and feedback (observed and sensed trajectories of movement.) These gains are either constants or learned and programmed functions of time. They are coordinated with the forward trajectories.

The state-space representation allows a single loop for implementation in hardware: a synchronous sequential network in the front loop with all feed-forward connections and a read-only-memory structure in the feedback path that can accommodate the complete set of register transfer controls. The input to the computer controller is the instruction register (IR). The binary outputs of the ROM change the content of the register when the input is one and does not change it when the input is zero. In the physical cerebellum, Purkinje cells inhibit register changes and their disinhibition allows the register content to change depending on what the replacement is.

The third computer that represents the CNS functions has a special structure, namely that a second cerebellum computer is part of this computer. In other words, the total system is redundant in this sense (i.e., when the system’s cerebellum computer is defective, injured or disabled, this deficiency is discovered and detected by the

CNS computer and its embedded cerebellar portion becomes active and tries, perhaps at a slower speed, to remedy the situation.)

This ability for the higher part of the system to be able to independently compensate for some non-functioning part of the neural system has not been verified in previous experimental and theoretical studies and merits attention. The main three functions of the CNS computer are:

- identification of the desired movement to be carried through and digital construction of this motion,
- monitoring the performance of the other two computers and detection of failures, injuries or malfunction, and
- implementation of the cerebellar computer inside the CNS computer in a serial rather than parallel fashion.

This last function implies that the segment movements are prioritized according to how close the limb (or segment) is next to the body and how the feedbacks and feed-forwards are combined to account for and imitate what the cerebellum does. The Purkinje cells, in a healthy cerebellum inhibit alternative paths.

Since the alternative (serial execution) is possible and feasible and exists for the healthy person to carry out the segmental movements as he wishes, this may introduce neural structures in the higher CNS that allow this flexibility and provide sufficient control for it.

Two of the better-known cerebellar functions and their computer implementations are presented in this section. A cerebellar disfunction is also considered. The significance of the disfunction is that the CNS monitors the behavior of the cerebellum as far as performance is concerned. If the cerebellum does not deliver the desired movement, the CNS (based on its redundant design) implements a simpler version of the motion. The cerebellar implementation in parallel and the redundant CNS compensation is implemented in series. The redundancy is considered in some detail. It is assumed, for simplicity, that

- all three computers are synchronized by one clock, (i.e., run by the same clock,)
- amplitudes of all signals are proportional to intensity,
- the register transfer controls are binary (one changes the content of the register and zero does not,)
- Purkinje signals are used to disable register transfers in the cerebellar computer,
- priorities are allowed so any higher priority (according to the wish of the person) can interrupt the current movement and execute a priority movement before going back to the previous movement.

A further challenge would be to convert the amplitude intensities to frequency intensities and to disable the register transfer by inhibition of the signal paths by Purkinje inhibition.

A number of simpler timing events (Ethan, 2018; Hemami, 2022) are described here: conditional reflex, interception, synchronization, and priority movements. The objective is to illustrate the flexibility and range of application of stacks.

In conditional reflexes, an alarm is sounded and, after a fixed period of time (T1), an avoidable action is taken, such as blowing a puff of air onto a rabbit's eye . The alarm starts a time counter (i.e., a pulse propagates down a LIFO stack. When the puff of air is sensed, the pushing stops and the stack simultaneously pops the two signals (the alarm signal and the action – neural and muscular – signal (T2)) that closed the eyes. When the action signal reached the top of the stack, the alarm pulse's position signal $(T1 - T2)$ in the stack points to the time interval after the alarm when the rabbit should start to close its eyes. This means the stack is a natural mechanism to subtract T2 from T1 without having negative numbers in the CNS.

A second example is the synchronization of an internal event, such as moving the hand to a proper position in space and time in catching a falling ball. If this operation is feasible and doable, a similar LIFO stack process can facilitate the learning and timing involved.

A third case is the synchronization of many events, each taking a different interval of time to perform. The requirement is that all events should end at the same time. The stack here is larger (one signal per event.) An example is to move one's eyelids, lips, fingers, and toes at the same time and in synchrony with a musical beat. The involved muscles are at different physical distances from the CNS and consequently have different time delays in their path. Two solutions can be envisioned here. One is to add a complementary delay to each signal to make all delays the same. Alternatively, one may use transmission-line structure, such as in the reticular formation, to extract the signals with larger delays earlier and the signals with little delay later. A more computationally clear picture is to use a FIFO stack as a tool. All these efforts may also involve learning [43], but the learning involved should be addressed separately.

A fourth example here is the interruption of a movement by the person and serving or performing a higher-priority movement. After the priority movement is completed, the original movement resumes. All the variables that are important for the resumption of the original movement are pushed into a LIFO stack. These variables serve two purposes: They are needed to return the limb to its original position and then resume the original movement. Exactly how the CNS carries out the intermediate motion of the limb to its interrupted state is not known. Once the CNS is ready to proceed with the execution of the original motion, the stack has to be popped to reset the initial states to resume the original motion. The operation of the stacks is simple to describe for simpler movements, as in the conditional response.

5.4 Redundancy

To articulate the theoretical redundancy of the cerebella control, it is important to articulate the structure and function of the musculoskeletal computer. Here, it is assumed that a multi-link three-dimensional system with a sufficient number of muscles (i.e., force generators) at every joint is available. All segments are represented by Bryant angles of roll, pitch and yaw. How the CNS may use the visual and vestibular systems for the state variables (angles and angular velocities in the body coordinate system) is not addressed here.

The system is equipped with state feedback (angular positions and angular velocities) at every joint. It also senses gravity, which must be compensated for. The objective of the control is to drive the system from an initial stationary position to a final stationary position while all the trajectories are specific functions of time specified by the CNS computer. For simplicity, it is assumed that all gains needed for this purpose are constant and available from the CNS computer or available as constants.

Two alternative strategies are explored here: a normal fast system executed by the cerebellar computer and a slower serial system. The serial system is implemented by the CNS computer when it detects a malfunction of the cerebellar system due to injury or malfunction.

All segments start from a stationary position and end up at a stationary position. The cerebellar computer generates the forces to the multi-joint system. A simple example of this would be the process of standing up. Standing on one leg would require balance and stability.

5.4.1 Slow Sequential Movement

In this implementation, all segments are held rigidly next to one another as if the whole multi-segment was one rigid body. The implementation is the same as before for the first segment; however, it may need larger feedback and feedforward gains to implement the point to point movement. All controls and inputs are provided by the CNS computer and disabled from the cerebellar computer. The first movement stops when the first segment has reached its final position. The second step starts now when the first segment remains stationary, the second segment moves to its desirable position (Kupferman, 1991), and all segments beyond the second one remain stationary relative to the second segment. This process repeats sequentially until all segments are finally in their destination.

The implementation of this sequential movement requires learning what gains are necessary to keep all joints that are expected not to move stationary and move the one that is required to move mobile. Gravity has to be located in every one of these intermediate geometries. If one of the observed cerebellar injuries causes the movement one segment at a time. With the present model, moving one segment at a time precisely would be very challenging and difficult. It would be desirable to have such movements recorded and see whether it is possible to imitate the sequences precisely by the three computer systems. It also appears that individuals without the cerebellum (Kupferman, 1991) learn to perform standard everyday movements with no obvious difficulty.

Another challenge in this regard is the supervision and monitoring of the other two computers by the CNS computer. The monitoring is a realistic challenge for any multiple computer system where additional computers have been added for vision, vestibular, psychological, and chemical.

5.4.2 Priority Interruption of Movement, Thought or Emotion

For a motion to be interrupted, all states and addresses to the ongoing internal movements have to be stored. The purpose of this storage is to continue the movement after the priority movement is completed. Sometimes interrupt within interrupt is also desirable. A LIFO stack where all the important states are pushed and then popped at the time of restarting the original movement is the candidate for the storage. When and if the second movement is interrupted, another push is necessary. The number of necessary interruptions determines the pushing stages. When a movement is finished, a popping state is required to access all the states of the next suppressed movement to be executed.

The same structures are necessary for mental rather than physical processes where different thoughts or mental solutions are desirable. One goes through instinctual analysis and mental contemplation. The mental exercise or emotional sequence to be monitored and studied will require similar stack structure and processing. The neurological component for this exercise may be in the hippocampus. The speeds of the physical and emotional processes are different and, depending on the situation, may be physically very fast or emotionally and mentally very slow. Slowly contemplating consequences of different courses of thought, behavior or action are examples of mental activities that may require the hippocampus machinery.

The same structures may be involved in mental learning by trial and error and may help in the development of frustration tolerance.

6. Discussion and Conclusions

Stacks are one good candidate for this purpose. These stacks have flexible variable-speed (clock rate) and faster-speed rates for the layers of neural processing under every planar or three-dimensional sheet or plane of the stack. This “double-stack” manipulation and processing in real and imagined time can create many natural, observed, mentally created, and artistic mental pursuits, and may also contain elements of all possible memory-related operations of the brain. As stated, one set of challenges relate to physical and mathematical models of natural neural systems. Another is the natural growth of the neural systems. With more research in the dynamics of growth of natural systems, one could add properties of physical growth to the dynamics of stacks and bring them one major step closer to behavior of natural systems.

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