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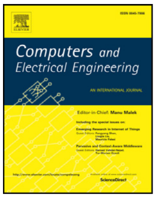

Human and robotic movement in the air[☆]

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ABSTRACT

The long-range objective is to help the development of computational tools for all human movement on the ground and in the air. Movements that can be neurally and physiologically observed and measured contribute to unlocking the mysteries of the central nervous system (CNS). Medicine, science and engineering have successfully adopted minimal and reduced systems to understand the complexities of the human system and to offer effective solutions. The coordinate systems and the state variables the CNS utilizes are not well known. Movement in the air poses problems of dynamics, control, stability, coordination, maneuverability, landing and signal processing. Awareness of the states of the implement and how the CNS estimates these states from the available contact with it in the air is one challenge. It is assumed the head and the torso are held as one rigid body such that the angular velocities and accelerations, measured by the vestibular system, are the same as those of the torso. The vision system is not considered.

1. Introduction

A variety of relatively simple human movements have been analyzed by standard engineering approaches in the past. Two major issues are the choice of state variables and how the trajectories of segments are articulated. The angles between the segments may be observed as state variable constraints. These angles are used as feedback in neural circuits that define the kinematic trajectories [1]. For walking, a massless leg is actuated by knee torques and a lumped torso mass is centered above the knee [2]. A preliminary somersault motion is considered in [3]. The athlete or robot is supposed to reach specific well-defined position states. All three above models can be implemented in a robot. None provide physiological or neural elements.

Biomechanics principles [4,5] can enhance the models: determining the angular momentum [6], energy transformations in impacts [7] and the role of contact [8] and the rotational non-holonomic constraints [9] as in the rolling motion of the tibia on the femur. Non-analytical methods [10] have been proposed in order to understand physiology and neural structures. Computational methods have been used [11] to understand the complex neural processes.

The role of the vestibular machinery is discussed in measuring acceleration [12], the cerebellar machinery [13], acceleration feedback [14], and a robot with many acceleration sensors [15]. The involvement of the CNS and central mechanisms are discussed in trajectory generation [16] and in cortical projections on muscles [17]. The reverse process of sensing and controlling the net pressure on the fingers that touch and hold objects in different positions is discussed below.

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A reduction strategy, based on observation of human movement, is one relevant issue for motion in the air. Controllability is another issue because the multi-rigid body is not completely controllable in the air. It must be assumed that the head and the torso are held as one rigid body such that the angular velocities and accelerations, measured by the vestibular system, are the same as those of the torso. A more general point of view of the vestibular sensory systems is presented in [15]. Other holonomic constraints [18] may be induced in order to reduce the dimensionality of the system and, therefore, make it controllable in the air.

For simpler airborne motions, such as simple diving, somersault, motion on a trampoline, high jump and vault jump, a three-segment system consisting of legs together, a torso, and hands together seems to be adequate for the mathematical analysis of the airborne phase. As stated above, the movement in the air is an under-actuated system that is not amenable to standard control mechanisms of feedback and stability because there is no ground support and no ankle moments of force. Therefore, initial positions and velocities are important for leading to a controllable trajectory in the air.

For jumps, the takeoff interval requires three phases:

- assume starting state position with zero velocities,
- apply forces (or inputs) to initiate trajectories for takeoff, and
- taking off the ground with proper position and velocity state (ground support forces having been diminished to zero.)

For landing, two strategies are applicable to minimize impact. In a sliding strategy, the contact velocity is tangent to the surface of contact. If the velocity at landing has a vertical component to the surface, the body must be deformable and not be one solid object [7]. The knee, leg and foot in human athletic landing absorb kinetic energy after impact and dissipate it slowly afterwards. An example of athletic landing is given in [19]. Smooth walking without impact is discussed in [20]. Athletic activities with skis, bicycles, and skates require proper surfaces for takeoff and landing. Also, the central nervous system (CNS) may signal moment-of-inertia change, so the hands and the skis can be used to change the moments of inertia[14]. The CNS also uses the forces and velocities of contact and possibly the vision system to estimate the positions and velocities of the appendages. This issue merits further exploration. Simulation models clarify how energies of impact are absorbed [14], how observed angles can be used to guide simulations [21] and how mathematical models of inertia can be confirmed [6]. Two important issues are how the athlete senses positions and velocities of the whole body and how these quantities enable the athlete to be aware of his position in the world beyond his body. The vestibular system measures translational and rotational accelerations and, by integration derives the velocity and position of the head in space. The vestibular and the vision system allow the CNS to be aware of the head's angles of roll, pitch and yaw - the so-called Euler angles. It appears the CNS is aware of positions and velocities of all segments of the body in space. If this hypothesis is correct, a state space can be defined for the whole body [22]. In this state space, all states are available in parallel at the same time.

The availability of this state space requires that the CNS compute the state variable of the neck segment, connected to the head, from its sensors between the head and the neck segment, and, by iteration, the state variables of the next segment (and so forth.) This is a sequential computational process to arrive at the positions and velocities of all segments of the body. An equivalent, but less complicated, process can be imagined. If every rigid segment of the body had sensory organs such as ears and their supporting vestibular system [15], all state variables of the whole body would be available at the same time. It appears as if the CNS is able to construct or estimate all these state variables with its own processing through control, communication and processing of its own internal and sensory information - a cybernetic system of the human movement system [11].

Muscular and neural models can be added to the skeleton [14]. Fast movements and how to control them are modeled in [11,23]. However, there are no methods to establish a one-to-one correspondence between these conceptual issues and the CNS structure. From a more general point of view, the individual events in a human maneuver may be internally timed by the CNS. Internally timed events are involved in motor learning[24], natural reflexes [17], and tight input-output coupling [25]. It has been argued that the stereotyped signals the brain uses are symbols that do not resemble in any way the external world they represent ([26], chapter 1); however, here the internally timed events are dictated and necessitated by external events. Different CNS processing may be involved in the control. Doeringer and Hogan [27] have considered the issues of central serial processing in human movement. A single trajectory of force or motion [28] can be stored in a tapped delay line [29], compatible with the structure of short-term memory [30]. When the clocking of the delay line is sped up, the movement duration is shorter. With a slower clock rate, the signal is expanded in time, i.e., it is slowed down. Alternatively, Fourier transform can show that an expansion in the time domain corresponds to a frequency domain compression. Therefore, roughly, when a signal is generated in a simulation diagram, systematic increases in the gains of the simulation diagram correspond to a compression in time; reduction of the gains amounts to an expansion in time [31].

A different kind of timing occurs when the CNS has to relate internal decisions to external events. Timing [32–34] is also involved in dancing, catching a ball, etc. The latter could involve associative learning. For this purpose, patterns may have to be recalled simultaneously from storage or from pattern generators [35]. A neural pattern generator is created from coupled nonlinear oscillators [31].

The control of neuronal excitability is discussed in [36]. A model of the basal ganglia for controlling the gain of efferent kinematic signals is provided in [37]. Linear filters and more general artificial and neural networks are presented in [38]. Constrained and desired restricted patterns are alternative schemes to generate patterns[39]. The task may involve coordination or synchronization of a large number of discrete time events. The computations for pairwise coordination may not be efficient or quick enough for the CNS. Relation of movement to perception [16] and action patterns are examples of such large events. It is stated on page 989 of the latter reference that, ”each species has a repertory of fixed action patterns generated by central programs.” Presumably, the shaping and timing of these patterns are learned. The learning issues are even more complex and require further knowledge about the processes involved as stated in the latter reference.

More recent findings for perception are covered in [13]. Describing and processing complex actions are covered in [40]. Some neurological studies have related neural signals to standard exponential engineering signals, but the applications remain obscure. The transient outward current in the bag cell neuron is shown to contain one exponential function of time (with time constant of 76 milliseconds) and, under the influence of cyclic AMP (cyclic adenocine 0), to contain a second exponential of a much faster decay and, hence, a rationale for a second-order system. Neurotransmitters change the shape of an action potential [35], suggesting the possibility of filtering and processing mechanisms that are implicit (in this case, the narrowing of the action potential pulse in the dorsal root ganglion of a chick.) Whether these exponential functions of time are relevant to learning, movement, or stability is a challenge to all disciplines involved.

A second class of patterns is involved in voluntary movements, elicited maneuvers [12,41], or slipping and sliding [42,43]. How these patterns are learned, generated, stored, recalled and accessed by demand is very difficult to model and to verify.

The point of the above discussion is that the CNS mechanisms proposed here may not be what the CNS does. To understand what the CNS really does is a most difficult task to explore. State space theory [44] and interconnected systems [45] are the tools we understand. A virtual musculoskeletal system is considered in [46], and a model suitable for simulation has been formulated [47,48].

Studies of fingers, the palm of the hand, and forearm (needed in holding other objects) are carried out in [49]. Mathematical investigations of the arm and the kinematic issues are addressed, respectively, in Raikova [50] and Williams et al. [51]. Engineering muscle models are discussed in [52]. More physiologically accurate moment arms of the muscles are presented in [53], and musculo-tendon lengths are investigated in [54]. The underlying control effort appears to centrally reduce or increase the dimensionality of the system to accommodate controllability. This is relevant to all human jumps in the air where the system is completely controllable before takeoff and setting up all desirable initial states is feasible. The resulting trajectories should help controllability in the air. Human movement in the air can be roughly classified in terms of the difficulty of the maneuver. Ordinary human jumping (as in reaching an object and jumping over obstacles, small streams, etc.) is not considered to be too difficult for mathematical analysis.

Athletic activities such as broad jump, high jump, somersault, diving maneuvers, etc., are examples of motion with no implement. Throwing a ball, hitting a bar, hanging from a bar, or rotation around the bar are relatively simple aerial movements. Jumping with implements such as bicycles, skis, motorcycles, etc., is more challenging. The major issue is the function of the CNS.

Simple movements with no implements are addressed in Section 2. Movement with simple implements or objects is addressed in Section 3. Movement with a bicycle model is discussed in Section 4. Discussion and conclusions follow in Section 5.

2. Simple movements

Simple movement can be described by low dimensional mathematical systems and are, consequently, easy to simulate by computers.

Four simple movements are considered here : back somersault, simple dive, high jump and pole vault.

2.1. Back somersault

The back somersault maneuver can be thought of as four sub-maneuvers, one after the other: the takeoff phase, climbing in the air, descending, and contact phase with the ground [14].

The dynamics and control of the takeoff phase are not considered because a physiologically meaningful and adequate model of the foot is necessary for the takeoff. A one-link foot has been previously used for jumping up [55]. We assume that the system is capable of setting all initial conditions (positions and velocities) and imposing any necessary constraints. The descent and landing phases are addressed in [14].

Suppose the motion is limited to the sagittal plane. So, we can imagine a planar three-link system. Suppose the hip and shoulder joints are locked. The system reduces to a single rigid body with initial position of, say, zero degrees and a particular angular velocity. The translational initial conditions are the horizontal and vertical velocities, along with the position of the center of gravity of the rigid body. The initial conditions prescribed above are not independent of one another. After 180 degrees of rotation in the air, the whole body should have lifted sufficiently in the air so that the head would be safely clear of the ground.

2.2. Simple dive

Let angle θ be the rotation angle of the rigid body, x and y the coordinates of the center of gravity, and b_i:

$i = 1, 2, 3$

be the linear friction coefficient vector of the air. These coefficients guarantee stability of the simulated system. However, how real divers stabilize their motion in the air is not clear. What mechanisms of the vestibular and cerebellar system are involved in negative velocity and possibly rotational and translational acceleration feedback are not known. The same argument can be extended to the movement of the eyeballs in the head. The mechanisms of feedback for stability are alluded to but have not been established or measured in the vision system. Eq. (1) summarizes the dynamics of the system for the lifting airborne phase for one planar pendulum:

$$\begin{aligned} J\ddot{\theta} &= -b_1\dot{\theta} \\ m\ddot{x} &= -b_2\dot{x} \\ m\ddot{y} &= -b_3\dot{y} - mg \end{aligned} \tag{1}$$

Assume a diving robot with two external force generators attached to its hip in the sagittal plane. It jumps from a non-bouncing diving board. The final condition is a desirable height h for the center of gravity when the diver is vertical with the head at a pitch angle of 90 degrees. This means the eyes are looking at the water:

$$\theta_f = \pi/2$$

when starting a straight descent downward. We assume there is a fixed torque generator τ, similar to gravity, which slows the rotational velocity to zero at the same time as the vertical velocity goes to zero. The frictions can be managed and are ignored here. The equations become

$$\begin{aligned} J\ddot{\theta} &= -\tau \\ m\ddot{y} &= -mg \end{aligned} \tag{2}$$

These equations can be integrated twice with respect to time. Let the initial velocities be respectively v_0 and ω_0

$$\begin{aligned} J\dot{\theta} &= -\tau t + J\omega_0 \\ \dot{y} &= -gt + v_0 \\ J\theta &= -0.5(\tau)(t)^2 + J\omega_0 t \\ y &= -0.5\ gt^2 + v_0 t \end{aligned} \tag{3}$$

From the above equations, the velocities are ramp-shaped and the trajectories are parabolas. At the terminal time (t_f), we would like both translational and rotational velocities to be zero, the desired vertical height to be y_f, and the desired angle to be θ_f. From the final vertical position, we derive the terminal time, and t_f gives us the initial vertical velocity. Finally, from the terminal time, terminal rotational velocity and terminal rotational angle, one can solve for τ and ω_0.

The important part of the above analysis is the dual role of the vestibular system in sensing translational and rotational accelerations:

- Torques caused by gravity forces acting on the body parts have to be sensed and compensated for.
- To move body parts relative to one another and change moments of inertia, rotational accelerations have to be sensed and perhaps integrated to derive angular velocities.

The vestibular system provides, through the otolith organs, the gravity constant (g), which the cerebellum scales to derive τ and transmit to the muscle in the sagittal plane. These muscles can generate a torque that acts between the body and the legs. Such a body-generated torque acts on the body and the lower extremity in opposite directions. In humans, the path of these forces is from the otolith to the cerebellum, then to the spinal cord and finally to the proper muscles. The produced (τ) is between two segments of the body: arms and body or thighs and body. One would need a two- or three-segment model to incorporate such torques. The rotational accelerations are needed to control moments of inertia [14,15].

2.3. High jump

In high jump, the initial condition (before takeoff) is from running and not from a stationary position. The important issue is to convert the horizontal translational velocity to a vertical translational velocity such that the whole body of the athlete rises opposed by gravity that eventually reduces the vertical velocity of the center of mass to zero. The four phases of the movement are

- direct horizontal translational velocity to vertical velocity,
- bring the body to a stationary horizontal position slightly above the horizontal rope,
- roll over the rope, and
- fall safely to the mat.

The transfer of horizontal to vertical velocity can be done by impulsive forces of contact with the ground while the jumper is on the ground. The transfer also could be done by transforming the kinetic energy to muscular forces where the energy is first stored[7]. This energy is then recovered in directing the muscular forces to produce a vertical velocity. Other mechanisms, including combinations of the above two schemes, could be involved. A still more efficient way may be to rotate the whole body upside down while moving upward and rotate the whole body 180 degrees such that the body is in a vertical standing posture.

2.4. Pole vault

The pole vault study is important because the whole musculoskeletal hand structure is utilized, formed in special geometry and used to induce the desired human maneuver. The same complexity and detail is also demanded from hands when external appendages are controlled and manipulated in the air. Additional tasks of the CNS are to use the forces of constraint between the athlete's body and the appendage to estimate the position angles, velocities and the position of the appendage relative to the body. The vision system may also be involved. The scientific effort here may take a long time and involve many disciplines.

The pole vault jump is a sequence of four movements.

- The first movement is running on the ground to accumulate sufficient kinetic energy.
- The second movement starts when the end of the pole vault makes fixed contact with the ground. All the kinetic energy of the runner and the pole propel the runner on a circular motion about the fixed end of the pole. The runner lifts in the air with a circular movement (a constrained rotational movement.) The pole may also bend and store some of the kinetic energy.
- The third movement starts before the pole is vertical and the body rotates over the horizontal bar that defines the height of the jump.
- The fourth movement a safe falling on the mat.

The vertical accumulation of height needs energy that comes from a constrained motion about the pole end on the ground, the change of direction of the velocity from horizontal to vertical could possibly take place by transformation and redirection of velocities, as in a gear-actuated mechanism. Or, it could involve all three mechanisms of force, energy and velocity. Nonholonomic control could also be applied. A still more efficient way is to use a flexible pole that stores energy until the body is halfway up to its final vertical elevation. Then the pole delivers the stored energy back for raising the body further upward. At the final vertical position, the pole is straight. The whole body also starts to rotate around its center of gravity. This rotation stops when the body has turned 360 degrees and has cleared the bar.

3. Movement with implements

3.1. Simple objects

Throwing or kicking a ball is relatively simple. In throwing a ball, the body is used as a momentary stable stationary platform to launch the ball. The arms are used for trajectory control and imposition of initial rotation and translation velocities to the ball. The ball is held by the player in basketball. In soccer [56,57], an arriving ball sets up prediction processes in the player to activate the kicking process in order to impose translation and rotational velocities to the ball [57]. The strike is carried on by the feet or the head but not by hands. Another challenge with the soccer situation is that the platform, i.e., the rest of the body, has to be set optimally for the strike before the ball arrives [58].

Motion on a swing or fixed bar are aerial movements that are simpler than striking a soccer ball. The challenging aspect of the swing motion is how to use the body to transfer more energy to the swing and amplify its range. This subject has been previously studied under parametric amplification, oscillation, and attenuation [59]. To reduce the swing amplitude, the body has to reverse the process and absorb energy from the swing.

Hanging from and rotating the body as one rigid body in motion about a fixed elevated bar is another example. Similar energy transfer mechanisms are used to elevate the body through a periodic movement with successively larger amplitudes and finally stabilize the rigid body above the bar. Challenging issues here are the motion of the hand, fingers, and feet; their synchronicity and timing; and the CNS processing and coordination of all necessary steps with their inherent transmission delays in the CNS and up and down the spinal cord [58].

Even though the implement is simple, the body of the athlete has to be modeled as a multi-segment rigid-body system for encompassing all the CNS mechanisms involved in control. A simple model would involve the arms as single rigid bodies connected to the bar and the rest of the body as a third rigid body. This model is previously formulated in some detail [8]. Three holonomic constraints connect each of the two bodies to the bar. Three additional holonomic constraints describe the equality of the Euler angles of the two segments. Finally, two additional non-holonomic constraints describe that the rotational motion of each arm is along the fixed pitch axes of the bar. This model completely ignores the movement and control of the wrists, hands, and fingers in their complex interaction with the bar and how the cerebellum [60] and other central mechanisms are involved in the control.

As stated above, the physical and neurophysical issues can be very challenging. However, a very simple way to formulate the constraints is sketched here based on [61] and a five-link biped model. All equations and variables are given in the reference. Consider a five-link " handstand". The hands are modeled as points of support on the ground. The two forearms are analogous to legs. The two upper arms are analogous to the thighs and the body is the fifth rigid body. The holonomic connection constraints can be derived similar to those of the five-link biped model (the coordinates of the two contact points with the ground are the holonomic constraints.)

Now the same handstand model can be applied to an athlete model on and around the bar. The two contact points with the bar represent the complex action of the hands that connect the athlete to the bar. The athlete can rotate around the bar or even take steps with the hands to move along the bar.

3.2. Movement with a bicycle model

Humans move and seemingly control very complex machinery in the air. One of the many important questions is whether the CNS tracks and estimates the state of the appendage for control purposes, maneuvers, stable landing, etc. Simpler appendages may facilitate engineering and experimental analysis and answers to the above question. For this reason, we consider the simplest model of a man-bicycle system ([9], Chapter 5, Fig. 5.9.3). In this model, the man is minimally modeled as a five-link system: body and head as one rigid body, the upper extremities as two rigid bodies to hold the handle bar, and the lower extremities as two rigid bodies to hold the bicycle between them.

The bicycle is modeled as two symmetric ”cross-shaped” rigid bodies. The first cross is the handle bar and everything else that moves with the handle bar, including a non-rotating wheel. The second cross involves the rest of the bicycle, composed of a horizontal bar and a vertical bar. The two bars are connected together (three holonomic constraints) and two non-holonomic constraints that provide one rotational degree of freedom between the two crosses.

The two systems are coupled together as follows: The hands hold the handle bar and the wrists’ rotations allow two motions of the bicycle: pitch and yaw. The yaw motion of the bicycle’s body (cross 2) is allowed by first using pitch motion to free cross 2 from the control of the lower extremities and (indirectly) swing cross 2 to the right (positive yaw) or to the left (negative yaw).

A more desirable and physically realistic model would consist of a complex model of the rider and a similar more physically acceptable model of the skis, bicycle, motorcycle, etc. The two systems, formulated in state space, have to be embedded [62] in a larger state space. In this state space, problems of the controllability and observability of the combined man-machine system have to be studied. The whole system must be controllable with the muscular inputs of the rider. The whole system must be observable through the contact and constraint forces that are available to the rider. The role of the vision system in all this analysis would be a very challenging scientific issue.

The constraints appearing in the equations of the system are more complex than the standard holonomic and non-holonomic constraints studied in mathematics and mechanics. Computer computations and simulations are indispensable because the systems are large and elaborate. Adaptation to such unpredicted surfaces, primarily due to inputs from the visual system, is another dimension of future efforts. Constrained movement on curved sliding surfaces, slopes and more complex paths and twisting trajectories are hard and demanding future neuroscience efforts. Learning to navigate on such surfaces and possibly suffering pain and injury are other admirable human efforts.

4. Control and processing tools

In order to verify the concepts discussed above, a flying robot is to be designed with a compatible appendage. Both the robot and the appendage are subjected to maneuvers in the air, as discussed above, and possibly on sliding surfaces on the ground before launching in the air or in preparation for landing. Their performance must be observed and recorded. Gyroscopes are needed to measure and record inertial angles of roll, pitch and yaw. The robot hands and how they hold the appendage may be the difficult part of the design. Possibly force and movement slippage sensors are needed to estimate the position and velocities of the appendage in space. It is possible that the system fails without a vision component.

To imagine the role of the vision system, consider the case of ordinary parallel parking of an automobile. The driver must be aware of where the four corners of the automobile are at all times. There is no neural or other physical sensor helping the driver. It seems as if the CNS is capable of imbedding itself in a large container the size of the car. These subjects, covered in psychology [63] under attention and perception, merit further consideration. The involvement of the vision system [64] and its processing, in turn, relies heavily on the vestibular processing [65].

The required vision system and the processing of the large number of the muscle tissues of the fingers and the palm of the hands may require processing of arrays of data. The size of the robot here is small enough to warrant study of a number of different arrays and their functions. Several specific functions are suitable candidates for this effort: interruption of a task by a higher priority task, reversing the trajectory of a task or movement in time, synchronization of movements of parts of the body that are at different neural distances from the CNS, and learning machinery. Computer structures for such arrays are the standard last-in-first-out (LIFO) stacks, first-in-first-out (FIFO) stacks, and combinations of the two under control.

Depending on the application, these stacks can be of one to three dimensions and a dimension of time for all of them. The one-dimensional arrays are useful in reversing a function of time, as in reversing the direction of a motion. If the motion is jumping in the air, the reverse motion in time can be imagined or fancied but cannot be physically implemented. The stack may represent a memory of activities in the past that are ushered from storage [16] or are creative movements that are imagined but not performed [60]. These stack contents can be advanced in time, reversed in time or partially or totally implemented in physical activity of the body. Whether the same stack is used for creative work, recalling memory contents, etc., is not known at this time. For simple movements in the air, the lower dimensionality of the situation and physical interpretation help the design of the stacks and possibly their location in the CNS. Similarly, interruption of an activity by a higher priority event and resuming the previous activity after completion of the higher priority event are easier to visualize and implement by circuits associated with the cerebellum than by dreams, creativity or remembering of past stored events.

These processing tools that serve the functions of the cerebellum are briefly discussed here with the objective of being able to program these processes in the computer. The actual measurement and confirmation of the models and procedures are postponed for future research. The latter effort requires collaborative efforts of different disciplines.

In general. a stream of parallel and serial instructions are issued from the CNS as input to the cerebellar control and communication machinery. A large body of parallel sensory data is a second torrent of inputs. The instructions have to be decoded and identified in terms of two classes: algebraic, such as addition, comparison, multiplication, etc.; and differential, involving timing processes stored as LIFOs or FIFOs, accessible delays (AD) and delay-compensation schemes (DCS) by accessing a signal earlier in the CNS. An example of this is to model the reticular formation [16] as a time delay line and extract a signal before it has propagated down the delay line. Moving the lips, the fingers and toes simultaneously to the same rhythm requires compensation for delays inherent in the afferent paths.

One other major challenge is to convert all the standard amplitude-modulated signals to frequency-modulated signals in the CNS so comparisons and verifications can be objectively studied. Temporary storage and other time-related processes such as integration in time (of accelerations in the vestibular system) or actual construction of predictors are examples of the latter processing.

All the instructions have to be decoded, i.e., rendered in terms of parallel and serial operations of primitive ”operations” or ”register transfers.” The execution of a task or subtask may be assigned to some other component of the CNS. Gains may be programmed in the basal ganglia. Hemami and Moussavi [37] Processes may be reversed in time in the hippocampus because the hippocampus is involved in memory storage.

5. Conclusions

In searching for CNS principles and foundations for movement in the air, functions of the components of the midbrain have to be understood, and their computational and theoretical bases have to be developed and verified. Some possible directions are outlined here that involve cooperation, collaboration, and communication for several scientific disciplines. The use of the two computers, as sketched above, is one of the challenges. At some point, all inputs and outputs of the cerebellum, at least in some simpler forms of life, have to be identifiable and uniquely coded. These efforts may better define mathematical models of the central nervous system.

Declaration of Competing Interest

None.

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Supplementary material

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