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Attractor as a common framework for converging sensorimotor behaviors of a mobile robot.

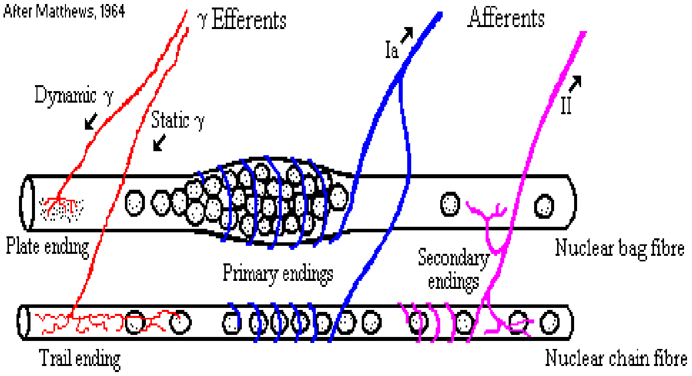
During early stages of vertebrate's development, fetus is confined to a very limited space forcing it into characteristic fetal position - limbs are brought in front of developing eyes and chin is forced toward the chest.

- When relaxed in a gravity-free environment, an adult human also "collapses" into similar fetal position.
- Human binocular vision system had evolved to optically converge our eyes onto a point in front of our nose. This point also coincides with the area to which our hands move subconsciously while in fetal position.
- Our vision system is attention driven - under most conditions only elements of the visual scene that coincide with the point of ocular convergence warrant our attention. However, a transition in the visual scene that we otherwise are not "focused" on may trigger visual attention switch by performing saccade to a moving object.

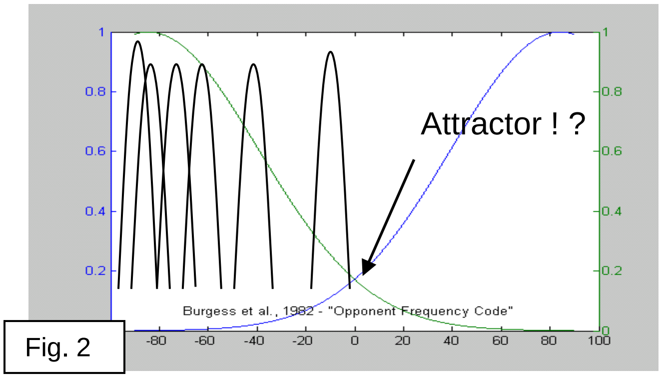

Fig.1

It is understood that visual perception in mammals and birds is possible only with moving eyes. Mechanisms underlying neuromuscular aspects of oculomotor functions are similar to mechanisms that control skeletal muscles.

Joint-Neuromuscular interface:
- Efferents: α- and γ-Motor Neurons
- Muscle Afferents: II and Ia - slow and fast responses
- Tendon Afferents: Ib – overstretch protection
- Joint Receptors (ligaments): Type I, II, III, and IV



Responses of Type I, II and III joint receptors are obeying the "Opponent Frequency Code" behavior described by Burgess et al. in 1982. Activity of receptors in opposing joint ligaments is such that they fire at highest rate when the corresponding ligament is stretched the most. Sigmoidal function extrapolates the firing rate of a stretched ligament in response to corresponding joint's position. The total firing rate from ligaments in antagonistic receptors is minimal when the corresponding joint is in its middle position. When the joint moves one way from the middle point – firing from the opposing ligament dominates, when the joint moves the other way – firing from another ligament dominates. Such mirror symmetry produces equilibrium in the middle position. I call this equilibrium point an Attractor.



Attractor ! ?

Burgess et al., 1982 - "Opponent Frequency Code"

Fig. 2

*Conjecture-1***:** to minimize brain stimulation and required energy expenditure during gestation the developing positional receptors in ligaments migrate away from the most comfortable position. At some point during fetal development receptors “freeze” in place forming attractors. Attractor is the point in joint’s operational space where brain stimulation is minimized. This may explain the results obtained by Burgess et al.

Attractor - Technical implementation

Traditional approach to motion control - Fig. 3: Linear input-output characteristic (transfer function) has no preferred point resulting in stability problem that must be addressed with introduction of control loop utilizing often complex algorithm.

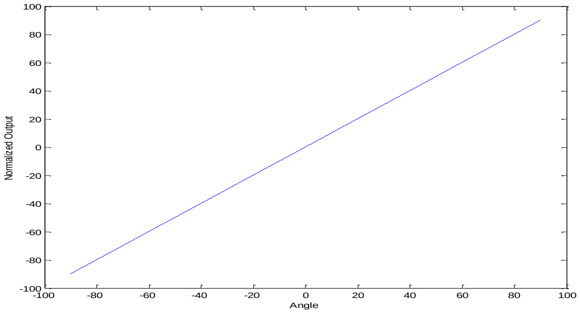


Fig. 3

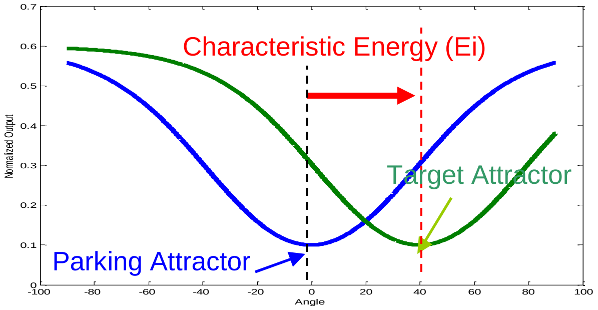


Fig.4

Fig. 4 explains an Attractor-based approach to motion control where operational space of a system is represented as a continuum of potential energy wells – attractors; the figure shows only a subset of two out of continuum of attractor points – zero energy Parking Attractor and one arbitrarily selected Target Attractor. Parking Attractor is special as in absence of input stimuli (fetal position) the system collapses into it – thus Intrinsic Stability. The system is defined as having zero energy when at Parking Attractor; the Characteristic Energy of the system increases as it moves farther away from its Parking Attractor. Complex self-converging behavior may be achieved if Characteristic Energy of one degree of freedom is communicated to the adjacent degrees of freedom. Neural feedback and feedforward loops work to minimize the total energy of a complex system, like an arm or a leg.

Fig. 5 explains how an Intrinsically Stable Neuromorphic Motion Controller leads to introduction of *first-degree* attractor. Two antagonistic channels – Flexor and Extensor – actuate the degree of freedom via two motors Mf and Me. Magnetic field flux measurements are being used for both position and force sensing.

- 2D angular position sensing: A permanent magnet M is rigidly attached to rotational degree of freedom DF. As DF rotates, two Hall-Effect transducers - He and Hf measure magnetic fluxes θf and θe produced by M as a function of the DF angular displacements in relation to corresponding sensors. Positional sensors’ outputs are mirrored sigmoid functions – Inserts 2a and 2b.
- Torque sensors Tf and Te are built into corresponding “tendons.” Fig. 5a explains torque sensing mechanism. “Tendons” pulled by corresponding motors are attached to corresponding magnets that induce magnetic flux through associated Hall Effect sensors. Resultant force applied to spherical camera assembly is the superposition of all forces applied by tendons. Each tendon force is translated into compression of corresponding spring, results in deflection of attached magnet and thus reflected in change in magnetic flux. Fig. 5a shows two antagonistic and intrinsic to spherical camera torque sensors, in this case spherical camera rotates until forces applied by to antagonistic motors pulling on corresponding “tendons” come to balance.

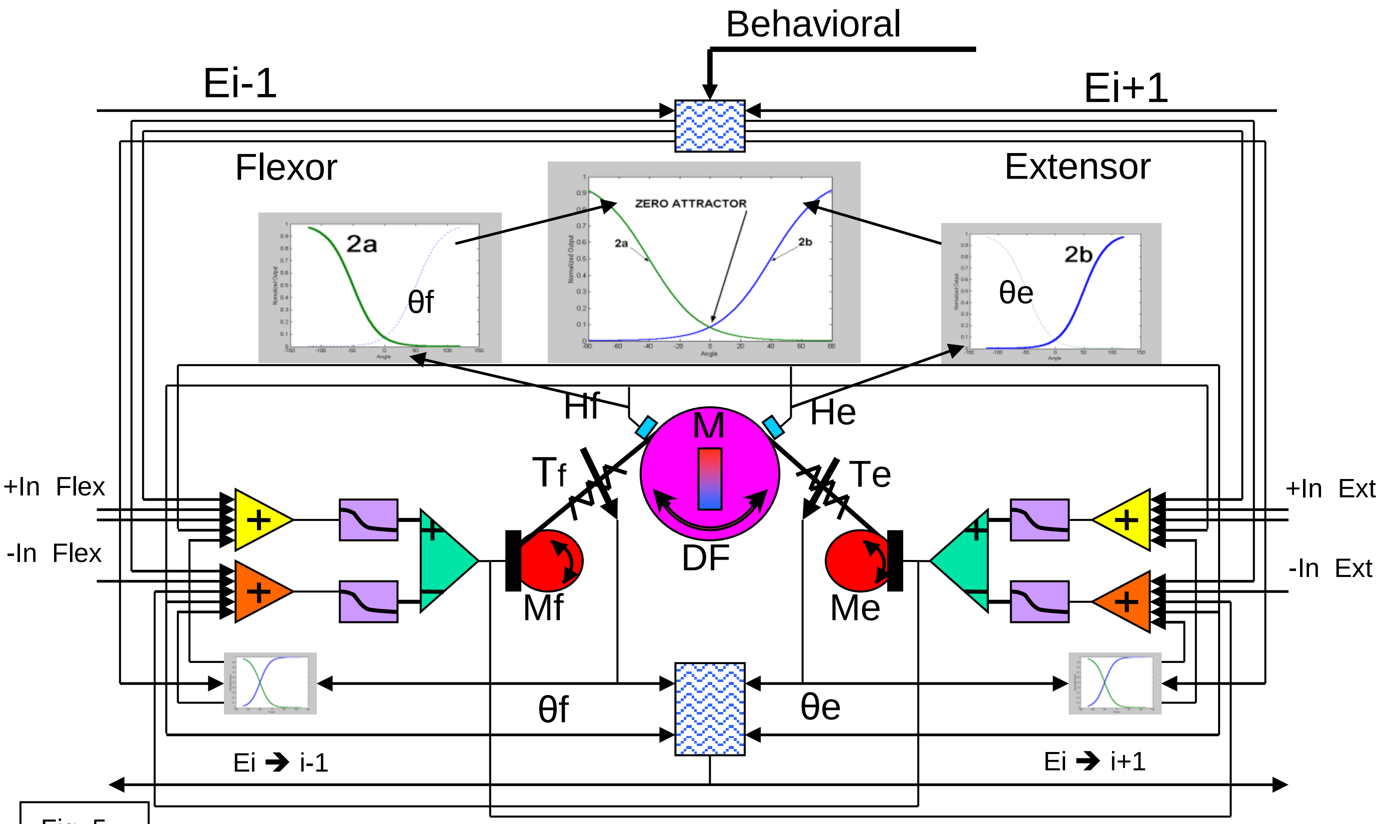


Fig. 5

Ei = k(θf* Tf - θe* Te)

Three primary feedback loops form motion controller's flexor and extensor channels – 1) ipsilateral torque and 2) contralateral positional sensors are applied to the summing nodes of output amplifiers after being appropriately scaled and filtered, while 3) ipsilateral positional sensor output is applied to the subtracting node of the corresponding amplifies. These feedbacks produce Attractor-driven behavior. Several auxiliary loops are involved in fine tuning the dynamics behavior of the system.

Characteristic Energy of a First-Degree Attractor:

$$E_i = k(\theta f^* \, Tf - \theta e^* \, Te) \qquad [1]$$

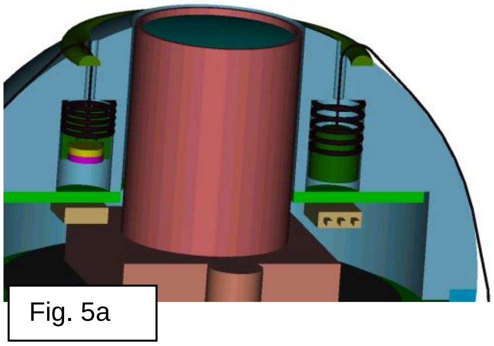


Fig. 5a

Daisy chaining multiple neuromorphic motion controllers in a way when characteristic energy [1] of each controller is shared with its neighbors results in linked system that minimizes total characteristic energy of a complex mechanical system while producing smooth motion of all linked degrees of freedom. This is achieved by feeding Ei output (bottom of Fig.5) from one controller into inputs (top of Fig.5) of i-1 and i+1 controllers resulting in all degrees of freedom responding to change of target attractor of an end-point (wrist) degree of freedom.

This leads to introduction of a *second-degree attractor* that governs the behavior of complex subsystems, i.e. binocular vision system, a robotic or prosthetic arm, leg, etc.

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Attractor and vertebrates' vision

There are two clearly defined systems in higher vertebrates visual processing:
1. Volitional and
2. Reflexive loops

Volitional loop is driven by image flows from foveae and foveolas via midget cones pathways feeding parvocellular layers of LGN, while retinal peripheral areas drive the reflexive loop via LGNs' magnocellular layers. Some dedicated fibers from retinae directly feed the Superior Colliculus as well. SC integrates visual and proprioceptory information and drive oculomotor nuclei. In addition to retinal ganglion cells, SC receives afferents from extraocular and neck muscles, while Inferior Colliculus integrates auditory and neck muscles afferents. Proximity of SC and IC to each other suggests importance of these structures to audio-visual correlation and cueing - http://www.neuronix.net/sitebuildercontent/sitebuilderfiles/OculoAudioSys_Rev.pdf.

The objective is to implement a retinomorphic image processing with motion- and direction- sensitive periphery to trigger a rapid saccade onto the moving area of the image. The resulting saccade brings area of potential interest into the foveae where high spatial sensitivity ensures further vision processing.

Parking attractor of the left camera is biased to the right, while parking attractor of the right camera is biased to the left (Fig. 6) resulting in intersection of optical axis in front of the "nose", i.e. second-degree attractor or Mechanical Parking Attractor of vision system. Furthermore, optical axis of the left and right cameras intersect corresponding imaging arrays at their centers – foveae. This leads to highly correlated foveal projections only when both cameras converge on the same area of a physical object.

Fig. 6 explains how Intelligent Binocular Vision System exploits property of the Intrinsically Stable Neuromorphic Motion Controller for visual object locking and tracking:
Fig. 6a - When the visual system is "awaken" or powered up, both left and right cameras are converged at the point in 3D space which is associated with the binocular vision system's Parking Attractor. If there is no physical object present at this point, images projected into the left and right foveae are uncorrelated. The left-right foveal image de-correlation initiates divergent camera motions in horizontal plane until image of any object within the visual scene is projected on both foveae.

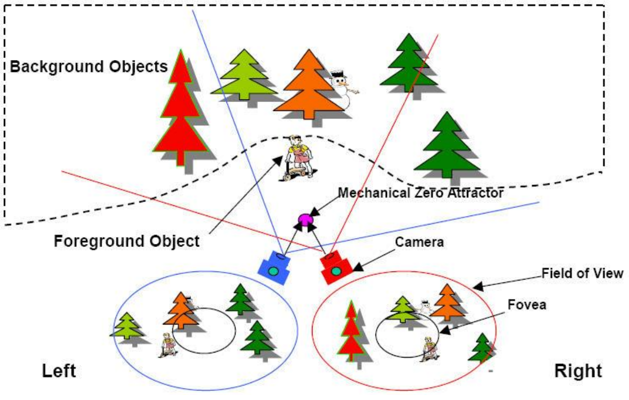


Fig 6a

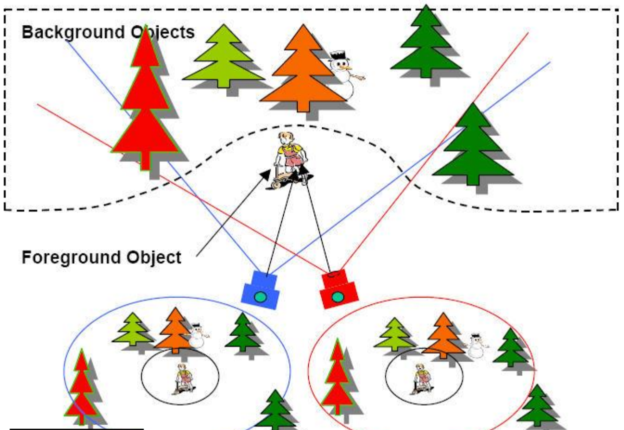


Fig 6b

Fig. 6b - Binocular retinomorphic Image processor initiates search to achieve highest degree of correlation between two foveae. When correlation between left and right foveae is achieved, both cameras are locked on a physical object – vision system attractor point. From this time on, cameras may move from one physical object to another or along the contour of an object while always staying locked. Following objects' boundaries while maintaining foveal correlation allows scene triangulation, depth extraction, and 3D scene reconstruction.

Attractor and manipulation

A neuromorphic motion controller (NC) - Fig. 5 is associated with each degree of freedom of a mechanical system – for example an arm consisting of a wrist, an elbow, and a shoulder - Fig. 7. All NCs are daisy chained in such way that residual energy Ei of each degree of freedom is communicated to the adjacent NCs. This hierarchical arrangement provides smooth motion of the entire system and is configured to minimize energy expenditure while improving dexterity. For example:

- When the entire system is in hand parking attractor position – all joints are also in their corresponding parking attractors.
- A new Offset Attractor is created when the wrist (or a gripper) is assigned a target position. Because of both – feedback and feedforward connections between the manipulator's NCs, all degrees of freedom are coming into motion until the wrist (gripper) reaches the Target Attractor. The system is again at the local minimum energy
- When the target Offset Attractor is outside of the operational space of the manipulator, the residual energy of the entire manipulator system is communicated to the locomotion system that brings the platform within the reaching distance of the manipulator.
- The entire process may be visually guided.

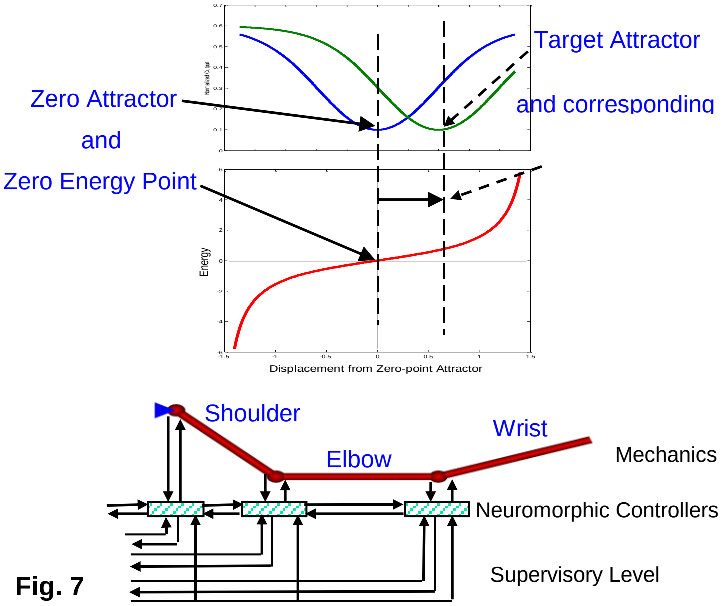


Fig. 7

Fig.7a shows rendering of an arm's elbow joint. Two antagonistic motors actuate rotational degree of freedom via two tendons routed through spring-loaded rocking motor mounts. Motor mounts have permanent magnets built into them with Hall-based torque sensors stationary positioned on arm's structural beam. Two positional Hall effect sensors measure angular displacement of an elbow. Spring loaded rocking arm motions result in force measurements via magnetic flux change as corresponding spring compresses,

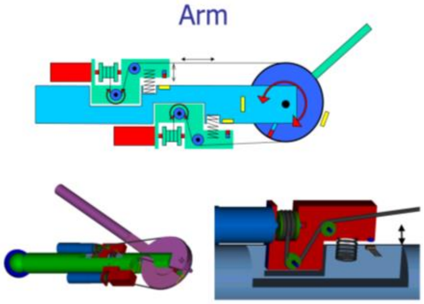


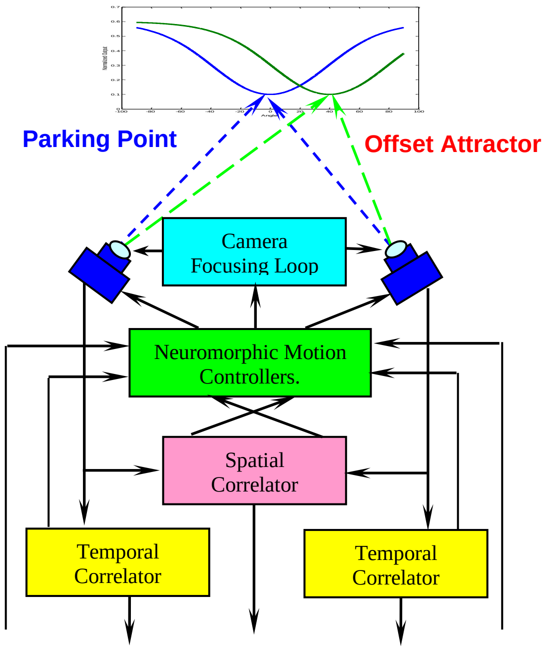
Fig. 7a

Self-converging saccade-capable binocular vision system, prototype

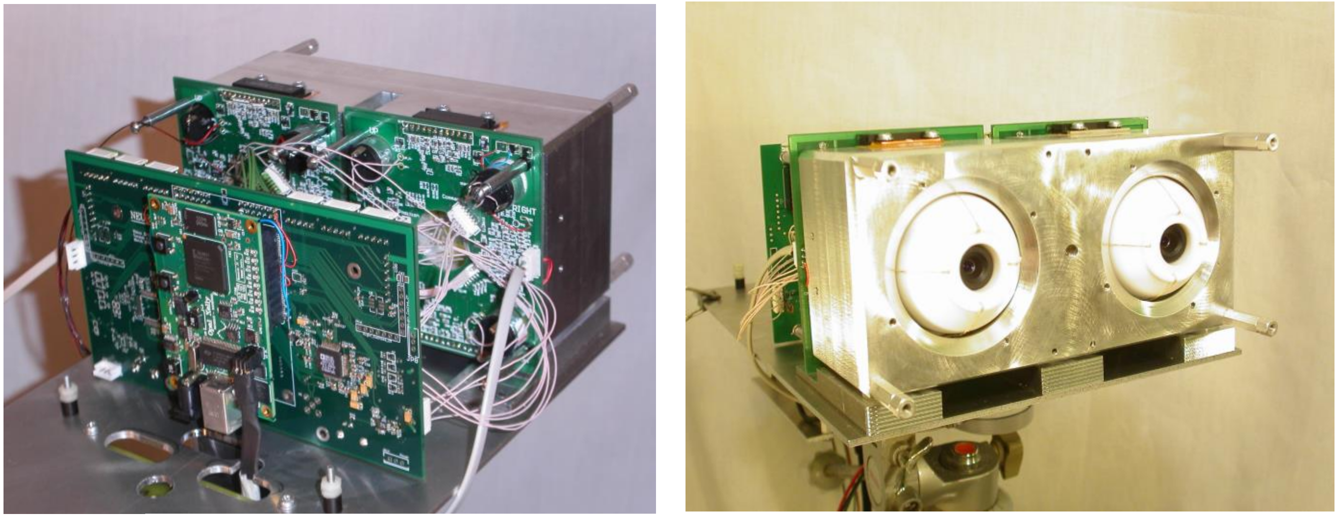
This is the example of a second-degree-attractor-driven system. First-degree attractors govern dynamics of the left and right cameras in such way that Parking Attractor of the left camera is slightly shifted to the right and the right camera attractor is shifted to the left. In this way, the intersection point of optical axis of both cameras are in the medial plane in front of the binocular system – its Parking Point. A physical object may or may not be present at the Parking Point. In the latter case the elements of the background visual scene projected on the left and right sensors will be completely uncorrelated.

The Neuromorphic Motion Controller of the binocular system forces cameras to converge on an object of visual attention and warrants that their optical axes never diverge. This remains true even when higher levels of vision-processing hierarchy request smooth pursuit of a moving object or rapid saccades from one object to another. Additionally, due to very low inertia and fast response of the mechanical system, optical convergence is immune to relative camera-object motions and vibrations. Image stabilization on foveae reduces image smear improving image quality. It also allows increased integration time improving low light sensitivity.

Current development relies on FPGA-based image processing. However, FPGA algorithms are developed in a way that allows future use of retinomorphic image sensors with focal plane processing in analog silicon. Spatial correlator ensures camera locking on an object of interest, while temporal correlator detects objects' motions within field of view to continuously adjust location of binocular system second-degree attractor.



Second Degree Attractor – Self-convergind Saccade-capable Binocular Vision System



Saccade-capable self-converging binocular system. Rear and front views.

A QuickTime video of an electromecanical prototype can be found here www.neuronix.net/neuronix/id15.html.

Third-degree attractor governs the converging behavior of a complex system of subsystems, i.e. robot, manipulation, locomotion including path planning and collision avoidance, vision- and manipulation-equipped wheelchair for quadriplegic assistance.

Sequence of events leading to the converging sensory-motor behavior of a robot:

Initial condition - eyes, head, and hands are in their respective Parking Attractors – "fetal position", Fig 8a.

Visual cue is within parking attractors of eyes, head, and hands - an object appears near the eyes parking attractor where hands can easily rich it as it is also near the hands parking attractor - Fig.8b, and 8c. This is an infant-level response to grab toys in front.

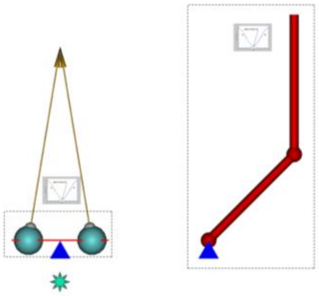


Fig. 8a

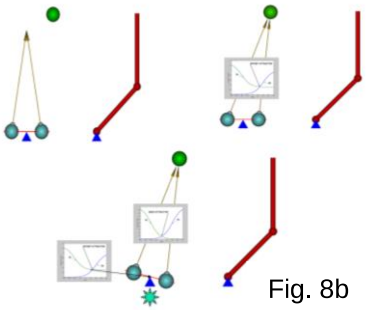


Fig. 8b

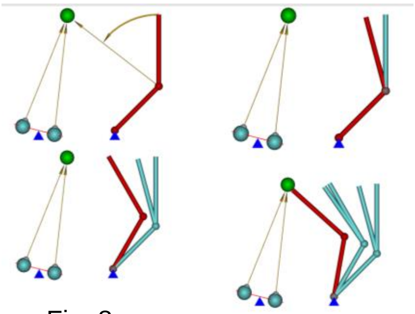


Fig. 8c

Visual cue is away from Parking Visual Attractor - the Characteristic Energy associated with eyes Offset (Target) Attractor is communicated to the neck muscles to turn the head in direction of visual cue; this reduces the energy of eyes' offset attractor within head system by bringing the cue into vision system medial plane; however, at the same time this leads to increasing the characteristic energy of head in body coordinate system. If needed, the head energy is communicated to the locomotive system to turn the body in direction of cue, minimizing head's energy in the body coordinate system. Now the cue is right in front of the robot, but may still be out of reach of hands. If manipulation is required, the robot's body is brought in motion along the line of sight until cue (object of interest) comes within grasping distance from hands. As the result, the target attractor (object of interest) is brought into the area with minimal characteristic energy of eyes, hands, and head - this is the point where an object can be easily manipulated. This is a toddler-level response.

The above mechanism creates the environment for a system converging behavior governed by an Attractor-based mechanism.

More complex sensory-motor responses require involvement of the higher level cognitive functions.

Technology Integration Platform is optimized for research of different implementation aspects of volitional and reflexive loops based on attractor concept and by using intrincically stable neuromorphic motion controller on all levels of robot's behavior. Volitional loop inhibits reflexive behavior for as long as "importance" of sensory input is below dynamically adaptable threashold that warrants motor action of high energy demand functions.