

A Robotic Optical Circuit that Generates a 3D-visual Image: Solution to the inverse optics problem for robotic visual seeing by reverse engineering the neurophysiology of the modalities of the retinal receptors

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Abstract: A robotic optical circuit that generates a 3D-visual sensation and is based on Wheatstone's stereoscope may be obtained by reverse engineering the neurophysiology (central connections) associated with the modalities of the retinal receptors. The optical circuit, called the Neuronal Correlate of a Modality (NCM)-circuit may be used to solve the inverse optics problem for visual "seeing:" How does the robotic controller convert two 2-dimensional camera images into a single 3-dimensional sensation of an image that is a high fidelity representation of the objects that gave rise to the two images. In addition the NCM-circuit may be used to solve the neurobiological visual binding and recombination problem and shed light on the neurophysiological function of the LGN and striate cortex.

1. INTRODUCTION:

The design of a robotic optical circuit that generates a 3D-visual image is based on two discoveries; the discovery of the Wheatstone stereoscope [1] and the discovery of the itch-scratch robotic system [2], [3] (see <http://www.mcon.org/refpublications.html>).

The Wheatstone stereoscope converts binocular vision, consisting of two 2D-images into a 3D-image that corresponds to the 3D-objects that gave rise to the two 2D-images. Steven Pinker [4] writes "Wheatstone proved that the brain turns trigonometry into consciousness when he designed the 3D-picture stereogram" [4].

The itch-scratch robotic system [2], [3] is designed by reverse engineering the psychophysical sensations¹ correlated with the connectivity of the itch-type receptors (pressure transducers), and described as modalities of the itch receptors. The connectivity of the receptors and the central connections associated with them may be viewed as a neuronal circuit in the brain, defined as the biological Neuronal Correlate of a Modality (NCM). The reverse engineered NCM-circuit is the sensation-generating Mechanism (SgM) that generates the itch-type sensation² defined by the modality of the pressure transducers (reverse engineered itch-type mechanoreceptors) [5](see <http://www.mcon.org/refpublications.html>)

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2. METHOD

The design procedure for reverse engineering the central connections of the visual-NCM was defined but not implemented [2], [3] and presented at the IEEE-IJCNN-WCCI-Vancouver conference, and the ICONIP-2006 Hong Kong Conference. The design procedure was described as follows:

1. The modalities and central connections of the visual receptors must give rise to a sensory form of "Self"-location and identification data ("self" knowledge) in a coordinate frame defined by the visual receptors and located within the controller.

2. The coordinate frame defined by the visual receptors must be consistent with, and calibrated with the coordinate frame defined by the itch-modalities of mechanoreceptors.

In order to proceed with the reverse engineered design of a visual NCM-circuit, it is necessary to expand the law of specific nerve energy to collective groups of receptors that are activated simultaneously. In the field of psychophysics, The law of specific nerve energy [6], [7] applied to the modalities of the individual visual receptors, explains the subjective sensation of pinpoints of light, and small patches of visual colors correlated with the L, M, and S cones [8]. However, groups and patterns of receptors must be activated simultaneously, in order to generate a visual experience of "seeing" the shape, form, and color generated by the pattern. Thus the law of specific nerve energy must be expanded to a collection of receptors that are activated simultaneously. The law of collective nerve energy consists of the sum of the specific activations that adhere to the law of specific nerve energy. In the following sections the subjective experience of a collective sensation is defined to be the collective modality of groups of biological receptors that are activated simultaneously. Furthermore, the collective sensation is assumed to be corre-

¹ Psychophysics: Psychophysics is often regarded as a sub-discipline of psychology dealing with the relationship between physical stimuli and their subjective correlates. The modern study of sensation began in the 19th century with the pioneering work of E.H. Weber [19] and G. Fechner [20] in sensory psychophysics. Despite the diversity of sensations we experience, all sensory systems convey four basic types of information when stimulated, modality, location, intensity and timing. These four attributes of a stimulus yield sensation. An early insight into the neuronal basis of sensation came in 1826 when Johanne Müller advanced his "laws of specific sense energies." The specificity of response in receptors underlies the "labeled line code," the most important coding mechanism for stimulus modality [8].

² Psychophysical illusions: The subjective experience of "seeing" is an "illusion" (image in the brain) that is generally assumed to be a high fidelity representation of "real world objects" that gives rise to that "illusion." When the "image" is not a representation of "real world objects," psychiatrists and psychologists look for malfunction in the visual system and in the brain. The design of a visual NCM-circuit, based on the central connections in the brain, gives the psychiatrist an additional analytic tool that may be applied to the analysis of physiological structure and possible malfunctions in the central connections.

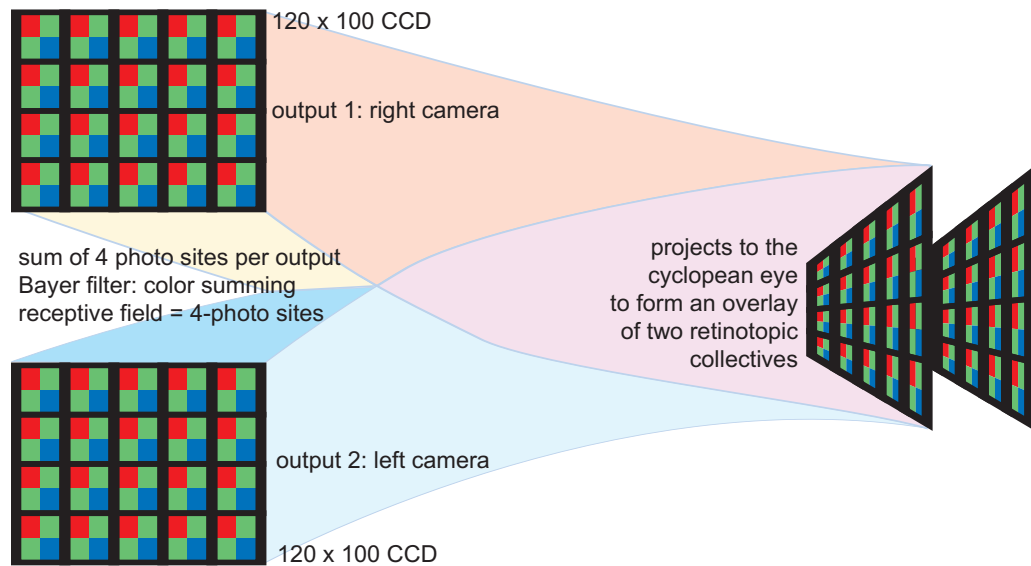


Figure 1 For binocular vision, the collective modalities of the right and left camera project onto an overlay of two superposed retinotopic collectives. The right and left CCD-images then form a single overlay which is called the cyclopean eye of the system.

lated with the collective receptors, the collective afferent axons, and the central connections in the brain activated by the collective set of axons.

The biological visual Sensation-generating Mechanism (SgM) is a NCM-circuit that depends on all the collective modalities present in the retinal system. In the following sections the implementation of the Rosen and Rosen [2], [3] design procedure for a visual NCM-circuit is divided into 3-sections: 2.1) The reverse engineered design of the superposed binocular collective modality layers, the “cyclopean eye” in the brain, 2.2) The connectivity of the reverse engineered biological NCM-circuit, and 2.3) The calibration of the “cyclopean” image with the coordinate frame defined by the itch-modalities of mechanoreceptors [2], [3].

2.1 The Reverse Engineered Design of the superposed collective Modality Layers: The cyclopean eye in the brain and within the controller.

The eyes are reverse engineered by 50-millimeter focal length camera lens’ and the retinas of the eyes are replaced by two 35-millimeter color detecting Charge Coupled Devices (CCD)-arrays located in the film-region of the camera. Figure 1 shows the 2-CCD-arrays covered with a Bayer pattern of filters. Four photo sites, may be combined to form one color-hue receptive field. The resolution of the color image is less than that of a comparable monochrome image, obtained by taking the output of each photo-site, without combining the colors [9], [10]. In figure 1, the collective modalities of the right and left camera CCD-array project onto an overlay of two neural networks. Each neural network maintains the retinotopic organization pattern of the CCD-array. The superposition and correspondence of the two overlays into a single neural network system is defined to be the “cyclopean eye” of the robotic system. This optical system reverse engineers a biological “cyclopean eye” that has been observed in the LGNs and striate cortex.

2.1.1 The Design of the Input Circuit

The first step for the design of a binocular robotic optical system is to project the collective modalities of the right and left CCD-camera array onto a single overlay of two superposed retinotopic collectives. The right and left CCD images then form a single overlay, shown in figure 1, which is designated as the cyclopean eye of the system. This projection is based on the biological neurophysiological standard model for vision [11]. In that model, collective modalities from the right and left eye, originating in the retinas, are projected through the optic nerves, to the optic chiasm and are superposed in the LGN-layers. The right eye and left eye superposed LGN layers are aligned to one another so as to reflect the total retinotopic organization of the retina. The set of overlaid collective layers in the brain have been referred to as the “cyclopean eye” of the system [4], [12]. In Figures 1, the overlaid “cyclopean eye” is made up of overlaid arrays of visual receiving neurons located within the controller, that form a neural network that is part of the part of the input circuit to the “self” receiving neurons of the NCM-circuit.

2.1.2 The Optical Apparatus for 3D-viewing.

How does binocular vision, consisting of two 2D-surfaces, generate a 3D- image that corresponds to the 3D-objects that gave rise to that image? This problem is often referred to as the correspondence problem. This problem was first described by David Marr [13] as the correspondence between the visual image in the brain and the real external world that gave rise to that image. It is a problem of identifying and detecting an object’s shape-depth and substance from its projection on the retinas of both eyes. This problem is part of the inverse optics problem and is often referred to as an “ill posed” problem, since it is not amenable to a unique solution³ [14]. The description of the reverse engineered design of a biological 3D-SgM is based on Sir Charles Wheatstone [1], [15] discovery of optical apparatus that can generate 3D-visual sensations.

The apparatus for 3D-viewing was discovered by Charles

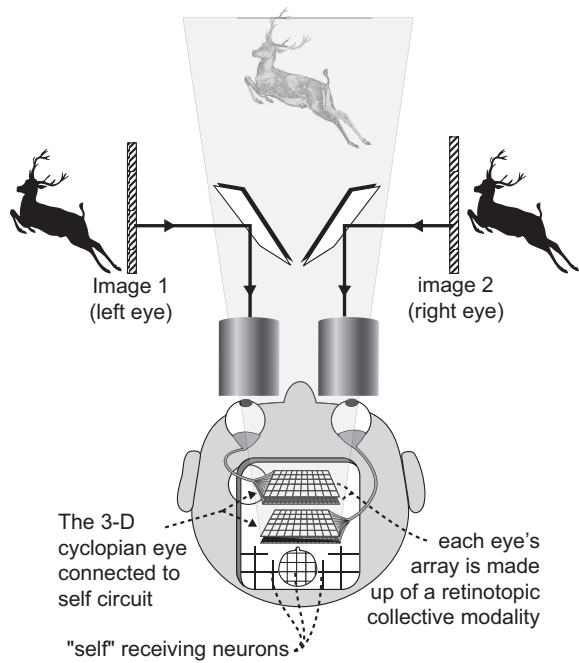


Figure 2 The Wheatstone stereoscope and the 3D-sensation generating mechanism.

Wheatstone in 1838 by the invention of the 3D-picture stereoscope [1]. To generate a 3D- image, two cameras obtain two 2D-pictures with the difference in views coming from binocular parallax. The picture obtained by the left camera corresponds to the image of the left eye, whereas the picture obtained by the right camera, corresponds to the image of the right eye. The images the left and right camera must be presented to the left and right eye, in order to produce the sensation of a 3D-image. Figure 2 presents the design of a Wheatstone stereoscope that is outfitted with a 2- tube viewing systems that constrain the view of the left eye to the picture obtained by the left camera and the view of the right eye to the picture obtained by the right camera. An illustration, presented at the bottom of Figure 2, shows the SgM in the brain of an observer that “turns trigonometry into consciousness” [4]. The illustration of the brain of the observer is based on the assumption that there exists a collective set of receptors similar to the overlaid collectives observed in the LGN and striate cortex. In Figure 2, the two overlaid collectives that have 3D-sensation correlated with the them, are labeled in the figure as the “visual receiving neurons of the Cyclopean eye.” From a biological perspective, the ability to perceive 3D-depth due to the distance between a person’s two eyes is called stereopsis. Stereopsis is the perception of depth produced by binocular retinal disparity. Stereopsis is one of

3 Constraint satisfaction: The biological solution to an “ill-poised” problem: Constraint satisfaction in a biological system is implemented by constantly learning to calibrate the “seen” image with the depth, distance and size of the objects giving rise to that image. Constraint satisfaction may also be implemented in a constraint network designed for stereoscopic vision [14]. In the biological system, constraint satisfaction is implemented by the Darwinian search engine, which monitors and searches the total world space for objects that represent environmental contingencies (those observations that affect Darwinian survival). The biological search engine is designed to focus attention on environmental contingencies and identify and respond to them.

more than 10-visual-depth cues that is used by the biological system to solve the visual correspondence problem³.

Figure 3 illustrates the use of Wheatstone’s principle for 3D-video production. In Figure 3 two prisms are adjusted by rotation so that the left (red) and right (green) pictures are superposed. When the pictures are properly superposed the central portions of the fields of view correspond to one another, however the right peripheral portion of the FOV is unique to the right eye whereas the left peripheral portion of the FOV is unique to the left eye.

The two superposed images are projected onto a projection screen shown in Figure 3. The screen contains all the data necessary to generate the sensation of a 3D-image. In order to abstract the 3D-data from the screen, the projection screen is viewed with filtered glasses, with a green filter over one eye and a red filter over the other. The filtered lenses separate the two images for presentation to the overlaid collectives of the 3D Cyclopean eye.

Charles Wheatstone [15] working in the field of psychophysics, also studied the characteristics of 3D sensations and the design of the 3D-Cyclopean eye (visual collectives and their modalities). In a variation of the stereoscope, an instrument that Wheatstone called the “pseudoscope,” prisms and mirrors are so arranged that the right eye sees the left eye’s view and vice versa. In this case the observer perceives a 3-dimensional figure, which Wheatstone called the “converse” of the original.

The significance of Wheatstone’s pseudoscope is that it gives information about the superposition of the overlaid right and left eye images on the biological 3D-Cyclopean eye (The layers in the LGN and striate Cortex). The information is illustrated by noting in Figure 3 that a) the superposed images on the projection screen must be properly aligned in order to be a SgM. b) Any change in the screen’s superposed images is reflected in the overlaid alignment and superposition of the images on the 3D-cyclopean eye (in the brain). And c) the 3D-sensation of depth may be studied, as Wheatstone has done, as a function of changes in the superposed images on the pro-

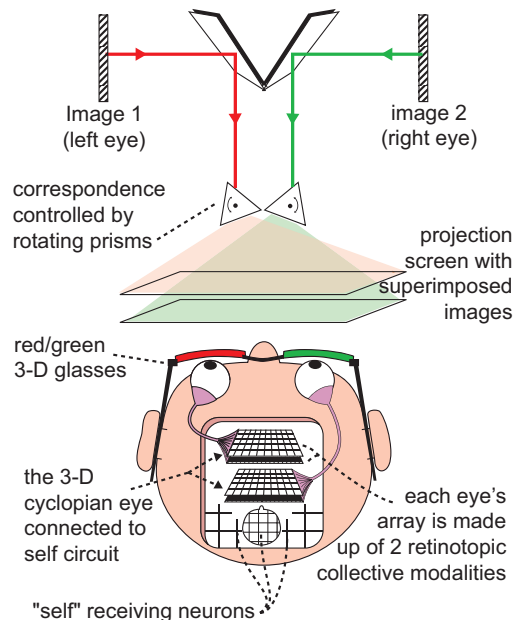


Figure 3 The basic principle for 3D-video viewing.

jection screen².

2.1.3 The Physical Requirements for Generating the Sensation of a 3D-image from the Binocular Disparity of Two 2D-images.

Figures 2 and 3 illustrate the physical requirements that must be satisfied in order to generate a 3D-image from the binocular disparity of two 2D-images.

1. Binocular disparity recording is required: The two retinal receivers, or two CCD arrays of the two cameras must be separated from one another (disparity distance), and they must simultaneously record the same image viewed from the disparity perspective.

2. The images must be superposed and aligned so that the central portions of the FOVs correspond to one another, the right peripheral portion of the FOV is unique to the right retinal receiver (CCD-array) and the left peripheral portion of the FOV is unique to the left retinal receiver (CCD-array). Note that this occurs on the projection screen shown in Figure 3 for 3D-video production, and also in the brain with the formation of a biological 3D-Cyclopean eye

3. In order for stereopsis to occur the Cyclopean images of the right and left eye must be presented separately (shown as red and green images in Figure 3) to the receiving homunculus in the brain.

The physiological structure of the 3D-Cyclopean eye must adhere to the physical requirements enumerated above in order to generate stereopsis.

2.1.4 Correspondence-Matching the images of the right and left Camera. Engineering the biological Cyclopean eye. An adaptation for 3D-viewing.

Correspondence matching of the images of the right and left camera, within the cyclopean eye in the controller, is achieved by reverse engineering the biological convergence and accommodation reflex associated with the Rectus and Ciliary eye muscles. Figure 4 is an illustration of the reverse engineered biological convergence and accommodation reflex. The convergence reflex may be reverse engineered by a mechanical auto-focus constraint that couples the rotary motion of the two cameras so that they always converge at a near or far point located on the midline between the cameras. The accommodation reflex is reverse engineered by relying on the camera's depth of field (lens aperture and focal length) to generate focused images in the near and far points on the midline. The "Cyclopean eye," shown in figure 4 as the superposition of receiving neurons from two eyes, imitates the superposition of layers in the LGNs and in the striate cortex.

2.2 The Connectivity of the Reverse Engineered Biological NCM:

The design of the reverse engineered 3D-Cyclopean eye follows closely the biological pathways and central connections associated with the retinal collective modalities. The pathways for 3D-viewing are illustrated in figure 5 and described for the biological visual system by A. J. Parker [16] in an article titled "From binocular disparity to the perception of stereoscopic depth." The connectivity of the reverse engineered Cyclopean eye to the "self" location and identification itch-scratch-homunculus is identical to the connectivity of additional mechanoreceptors to the itch-scratch homunculus [2], [3]. The receiving neurons in the superposed layers of the Cyclopean eye, must be connected to, and presented to the

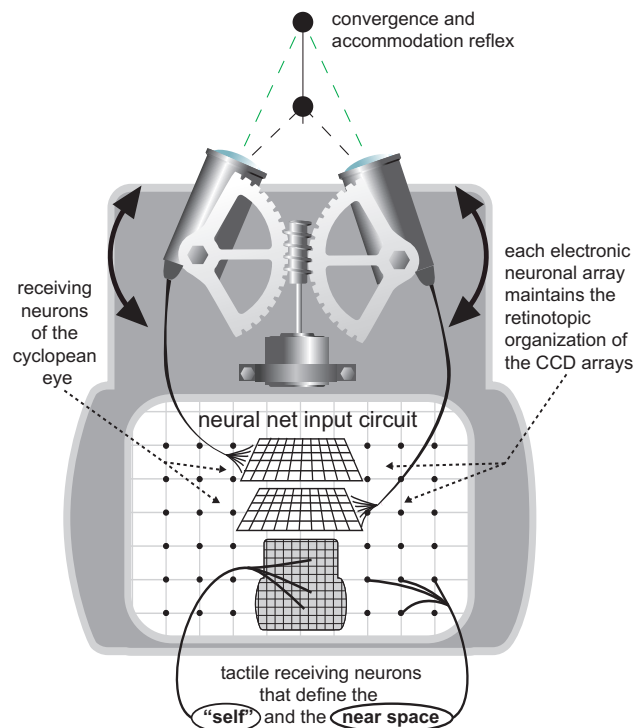


Figure 4 Correspondence-matching of the images of the right and left cameras by reverse engineering the convergence and accommodation reflex associated with the rectus and ciliary eye muscles. A solution to the neural net input circuit has been published by Rosen and Rosen [2].

configured input circuit (self identification and location homunculus) so that the two images maintain their separate retinotopic organizations and are properly superposed on one

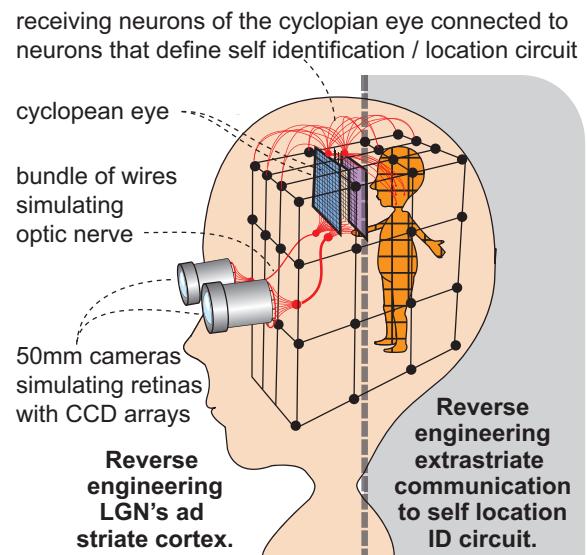


Figure 5 The binocular system is connected to the receiving neurons of the cyclopean eye. The cyclopean eye, consisting of a superposition of collective modalities, is connected to the "self identification and location"-circuit. The cyclopean eye reverse engineers the neurophysiology of the LGNs and striate cortex. The interconnections between the cyclopean eye and the "self location and identification"-circuit reverse engineers then extra-striate communication in the brain.

another. The connectivity of the Cyclopean eye to the self identification and location homunculus and thence to the sensorimotor control circuit, thus forms a NCM-collective modality circuit that is a 3D-SgM [2], [3], [5]. The NCM-sensory motor control circuit must control the itch-scratch trajectories of motion of the itch-robotic system in order to calibrate the FOV-visual coordinate frame (generated as a 3D-image), with the measure of the near space defined by the training procedure applied to the itch-scratch robotic system [2], [3].

2.3 The Calibration Problem

The problem is one of calibrating the 3D-coordinate space defined by the tactile sensors, with the 3D-illusion defined by the Cyclopean eye. It is a problem of scaling the FOV-illusion (the 3D-sensation) so that it corresponds to the scale size measured by the tactile receiving neurons in the near space.

This calibration can only be performed in the near space region where the measured scale size of the tactile sensors is common with the FOV-region of the 3D-sensation. Figure 6 shows the calibration region where the tactile space is common with the 3D-sensation space. Once the calibration is performed in the near space region, the regions beyond the near space, defined by stereopsis, is calibrated by the depth perception produced by binocular retinal disparity that is related to the calibration performed in the near space.

2.3.1 The Measure of Depth-Distance

The visual NCM-circuit does not calculate the “trigonometry” of the corresponding images. It learns by performing itch-scratch type actions identical to those described by Rosen and Rosen [2], [3] for the itch-robot with the addition of various sized obstacles placed along the itch-scratch trajectory that are viewed by the visual system. The learning/training, performed in the nodal map module and sequence stepper module [2], [3], is a repetitive procedure that relates the convergent position of the two cameras, the motor-muscle position of the flailing limbs, and the relative image sizes and positions on the retina, with the tactile (touch-feel) object depth-distance and size. It is a process of “teaching” a neural network the “correct” size of an obstacle, located along the itch-scratch trajectory, so that the pre-planned, obstacle avoiding trajectory, actually does avoid the obstacle.

The relative data that is available in the FOV-space consists of the convergent position of the Rectus eye muscle and the relative size and position of the objects imaged on the retinas of both eyes. Calibration and learning takes place in the near-space regions where the flailing limbs yield proprioceptive-position data and the image of the flailing limbs is within the FOV of the visual system (the flailing limbs are “seen” by the visual system). Figure 6 shows the positions of the tactile receiving neurons in the near space (location defined by flailing limbs) and the “seen”-FOV of the 3D-Cyclopean eye.

The calibration of the size and depth distance of the pencil (Figure 6) takes place between the tactile receiving neurons in the near space that define the pencil, and the illusion of the pencil formed by the binocular-SgM. The locations of the visual receiving neurons is in the corresponding superposed collectives of the Cyclopean eye, that generate a one to one correspondence between a 3D-image of the pencil in the internal world space and the pencil that is located in the near

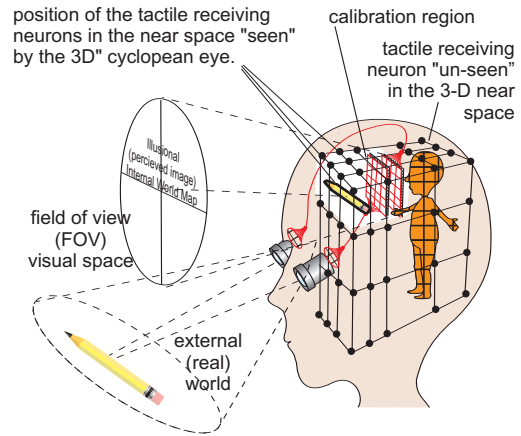


Figure 6 Calibrating the distance-measure in the FOV-visual space. The relative depth distance and size of the pencil-image falls within the FOV of the cyclopean eye. The image-pencil is calibrated with the depth distance and size of the object-pencil, which is determined by the tactile sensors and the tactile receiving neurons within the controller.

space defined by flailing limbs.

Visual depth-distance calibration points are obtained wherever a part of the visual image falls in the near space defined by tactile receiving neurons (see white region in figure 6). In this case, the calibration of visual-FOV distance and size proceeds in the same manner as the procedure for training and obtaining a measure of the near space (the scale distance between two receiving neurons). The tactile size of an object, detected by a robotic finger, may now be applied to the size and distance of a visual image. The visual image shows the size of the finger, a measure of the space in the vicinity of the finger, and an illusion-al object that is perceived in the measured space with a size related to the size of the finger. The procedure for gaining “self” knowledge described by Rosen and Rosen, [2], [3], in the design of the itch-NCM circuit, is modified only by the requirement that the q-visual data of finger position is available at all nodes traversed by the moving finger. The availability of visual q-field data at every node of the Nodal Map Module makes it possible to “see” obstacles that are along the trajectory of the flailing limb, and to re-plan a pre-planned trajectory and thereby practice visual-obstacle avoidance [17].

3.0 DISCUSSION

The binocular visual NCM-circuit generates a FOV-coordinate frame within the controller that is an adjunct to the tactile “self identification and location” coordinate frame, and gives the robot the visual “self identification and location” data used to control the itch type robotic sensory motor control system. The addition of the binocular visual system gives the robot a visual obstacle avoidance capability that is essential for the design of a “volitional” multitasking robot (where “volition is defined as a capability to re-plan a pre-planned trajectory of motion if an obstacle is observed along the pre-planned trajectory [2], [3],

The binocular visual NCM-circuit also sheds light on the functional neurophysiology of the human brain, since the superposed collective modalities, the cyclopean eye of the

system, is also observed in the LGNs and in the striate cortex. In the binocular robotic visual system, the cyclopean eye is a Sensation-generating Mechanism (SgM) that generates a 3D-visual image that corresponds to the 3D-objects present in the space in which the robot is operating. It may be hypothesized that LGNs and striate cortex, in the brain, also function as a 3D- sensation generating mechanism. In this case, a large fraction of the biological visual NCM-circuit (retinal receptors, afferent axons, LGN relays, and striate cortex) is devoted to the function of generating a sensation (a subjective experience) rather than the recognition, identification, and comprehension of the image falling on the retinas [11]. The function of recognition, identification, or comprehension is most likely an extra-striate function that is not performed by the striate cortex, the LGN-relays, or the retinal receptors.

3.1 Reconciliation of the robotic “cyclopean eye” with the visual standard model

In the standard model it is theorized that a visual scene is simultaneously processed by cortical modules in the striate cortex, with each module “looking” at a portion of the scene ([11], [18]). Experimental data supports the hypothesis that the visual image is created by several relatively independent parallel processing channels. Each one appears to be specialized for the analysis of a different facet of the visual scene. The sensation generating functionality of the biological cyclopean eye is rarely taken in consideration in the development of the standard model. When sensation generation is taken into consideration, it is a precept of the SgM of the NCM-model that a) the several relatively independent parallel processing channels form an overlay of retinotopic collectives that correspond to the retinal ganglion collective, b) that each collective is specialized for the generation of a sensation of a different facet of the visual scene, and c) that the superposed set of collectives may generate a “seeing” sensation of the total overlay that is the modality of the superposed collectives. The robotic visual NCM-model is supported by the same experimental data that supports the standard model. A careful study of the experimental data, biological structure and the associated neuronal pathways supporting the standard model, reveals that this data also supports the robotic NCM-model⁴.

⁴ The Physiological structure of the Biological Cyclopean Eye according to the visual-NCM-model:

In the visual-NCM model it is theorized that the right and left LGNs relay collective modality data to the striate cortex. It is assumed that the inter-layer communication within the striate cortex facilitates the formation of the overlaid retinotopic collectives that define the reverse engineered Cyclopean eye, and that the “Cyclopean eye” within the striate cortex is made up of the “cortical modules” observed by the Nobel Laureates Hubel and Wiesel [21]. The right and left LGNs and the striate cortex function as the SgM that obey the laws of physics in generating a 3D-image that is a high fidelity representation of the objects that gave rise to that image.

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