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Limitless Oculus:
Visual Expansion by Animal-Inspired Modification to Visuomotor Mechanism

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Abstract of Master's Thesis of Academic Year 2017

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Category: Science / Engineering

Summary

Humans are trapped in the constraints of visual sense. Through my analysis comparing humans and animals, I figure out the neck is a factor limiting the spatial range of the human vision. In order to help human overcome part of the limitation and hence achieve visual expansion and substitution, I propose the concept of *Limitless Oculus* inspired by the animal superior abilities. The concept is to modify or substitute the visuomotor mechanism, firstly in terms of the spatial orientation. Those modifications, which aims to promote the flexibility of the orientation of vision, have a physiological and cognitive influence. Two prototypes are presented: one employs an extra robotic neck to increase the spatial range of vision; the other one utilizes human own upper limb to control the orientation of vision. Then I conducted experiments to evaluate the performance of the prototypes, and prove the feasibility of the concept. The result indicated that the range of vision was expanded, while the speed of the scan motion could also be augmented in certain range.

Keywords:

Visual Expansion, Human Augmentation, Vision-Motor Coordination, Body Representation, Interaction Design

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Chapter 1
Introduction

1.1 Overcome the Human Limitations

Humans are born with limitations.

The physical and physiologic restrictions exist anywhere and anytime, but we humans mostly are unaware of those somatic limitations; we realize only when their existence becomes weaknesses. The limitation reflects a limited ability, that is, inability or disability, in this sense, all the human have innate defects. The human body has specific channels to communicate and interact with the surrounding environment, for instance, the abilities to hear and speak. Those help us make sense of the world. But do we really? What the human can feel and reach is merely part of the real world. As the society and environment are changing explosively, the human body remains the same as thousands of years ago. The somatic evolution, at the scale of geologic time, falls behind. In the pursuit of greater knowledge and deeper understanding of the world, the human body does limit itself.

My research aims at overcoming a part of the somatic limitations of the human. That is state changing of abilities from *limited* to *unlimited*. In a general sense, my research creates new abilities or reinforces the weak abilities.

Firstly, new somatic experience would be discovered. Beyond limitations, the human is able to see the invisible color, hear the inaudible music, taste the flavorless food and smell the odorless perfume, and the human can be faster than the cheetah, taller than the giraffe and stronger than the elephant. Everything would be renewed. Everyone can be superhuman of himself. The human has already achieved some possibilities by tools (e.g. aircraft for flying and photodiode for invisible light). Change will take place on somatic abilities followed by new minds.

The limited sensation[1] and perception[2] exert an unconscious and inevitable influence on the human's understanding on the world. Both the human behavior and mind could be fenced by the physical inability, because the subjective knowledge is the basis of mind. For example, a person with innate total color blindness does not have any concept of color. Thus, by overcoming the limitation, and going beyond the conventional notion, the human could come to a deeper and further outlook on the real world and the surroundings. More possible forms of existence and being would be recognized and achieved. Metaphysically, the "reality" would be re-defined. The augmented body would unchain the mind.

In the view of thermodynamics, the human body is an open system, which exchanges matter and energy with the surroundings. Those matter and energy involve or carry information; the information flow is what the human input and output, and what the human senses and acts. With the development of computer science, it has a profound impact on the neuroscience. In order to explain my point of human/nonhuman ability, here the thesis presents an analogy between human and computer. Hence I borrow the concept of input and output from computer science, to describe human capabilities that are meaningful, conscious, and controllable. In this metaphor, the mind is software, while the body is hardware. The computer or the integrated circuits is the nervous system, and the peripheral hardware is the device/organ with input or/and output function (I/O). The function is a tangible representation of one specific kind of ability. In computing, the input devices are sensors which import the information into the computer (e.g. microphone, web-cam and MEMS gyroscope). The sensory system is to a human what the input device (sensor) is to a computer. In computing, the output devices are actuators which are used to execute the command of the computer to deliver information or effect the surroundings (e.g. screen, speaker and vibrator). The motor system[3] (actuators) is to a human what the output device is to a computer. This analogy can be extended to all life.

The mind is always the superior ability of humans. Animals do not have brain

1 Sensation is the bottom-up process by which the human senses, like vision, hearing and smell, receive and relay outside stimuli.

2 Perception is the top-down way the human brains organize and interpret that information and put it into context.

3 Motor system of human refers to the musculoskeletal systems, i.e., the muscular and skeletal system.

as complicated as human, but some of them possess better I/O organs, or called the animal superior abilities (animal superpower).

1.2 Human versus Nonhuman

The animals have worlds beyond human experience [20]. Life has diverse forms. Some nonhuman creatures have abilities superior to human. I prefer to acquire inspiration from the natural world firstly, before the fabrication of supernatural or psychic ability, which could come into possible in virtual reality. In this thesis, an animal is defined to be any life form, any creature or any organism other than a human being, but not limited to a mammal, unless otherwise stated.

1.2.1 Unique Animal Abilities

The human has five traditionally recognized senses: sight, hearing, taste, smell and touch. Each has a representative sensory organ: eye, ear, tongue, nose and skin. However, there are some animal senses absent from the human body, and not existing in the human world. Magnetoreception, the sense of magnetic field, which usually employed for navigation through earth's magnetic field, by a number of animals such as migratory birds, homing pigeon and bees [42]. Electroreception, the sense of electric field, which is found in several species of shark, dolphin and platypus, and is used to locate prey and predator [31].

The output action of the human body is mostly related to muscle movements. Walking, blinking, garbing or even speaking: it is the muscles that drive all those actions of the human. The muscle functions to produce motion and force, as a kind of mechanical output, no matter auditory or kinematic information. Meanwhile, the human have parallel abilities to sense and perceive the mechanical stimulus, e.g. hear and touch. Bioluminescence, the luminous ability, enables some animals to emit light, i.e., electromagnetic signal. Some species of firefly use courtship blink with a special pattern for mate selection. Some fishes residing in the deep sea, such as anglerfish and dragonfish, take advantage of the mimicry to attract prey [18]. The electric eel, just as its name implies, has the capability to produce electric currency, called bioelectrogenesis. It is a killer with unique electric weapons, useful for hunting and self-defense. The electric eel possesses certain abdominal organs making up four-fifths of its body to emit a distinguished electric shock [16], which is strong enough to stun small prey.

(a) Eyes of Cat, Owl and Octopus

(b) Various Spider Eyes

Figure 1.1: Different Animal Eyes

1.2.2 Powerful Animal Abilities

What people can see is a small fraction of the full spectrum of electromagnetic radiation, which is in wavelength approximately from 400 nm to 700 nm, between infrared and ultraviolet. Obviously, humans cannot see the cellular waves and broadcasting waves filling all over the modern life. However, some animals can see more. The snake can detect the infrared light for hunting. As is known, everything above absolute zero (-273.15 degrees Celsius or 0 Kelvin) radiates the infrared light which reflects its thermal information. What people can hear is a specific adaption of the sonic waves, in frequencies ranging from 20 Hz to 20 000 Hz. The dolphin can hear ultrasonic sound with frequencies up to at least 100 000 Hz and it uses a wider range of sound for locating and navigation due to the bad sight under the water/marine environment. The bat employs similar echolocation to scan the landscape and identify the prey, which is good for flight and hunt in the dark environment. Sonar is a representative work of biomimetics, which resembles the dolphin's super sense.

The cockroach has amazing locomotion ability, i.e., it is able to pass through cracks and slits, under the door and bracket, and some species can even fly. Even within the mammals, life scales are so various. Though sharing the similar skeleton and organs. From the mouse to elephant, animal body size is completely different, how they manipulate their bodies and the muscle power can therefore be totally different. The giraffe has a distinguishing and disproportionately long neck, which made it the tallest living terrestrial animal.

1.2.3 Diverse Animal Abilities

In terms of the eyes, life form has many possibilities. Eyes are ubiquitous organ of most animals, and different animals have distinct types of eyes[4] (Figure 1.1(a)). The animal eyes range from primitive to sophisticated eyes. For example, various species of spider have various eyes which are different in shape, size, number and arrangement[5] (Figure 1.1(b)).

Some animals get additional "Limbs". The elephant has a trunk, long, strong, flexible and utility, which is a fusion of the nose and the upper lip. The trunk helps the elephant access better to food and water, and wrestle with another elephant. It serves as an extra limb rather than a mere nose. Many primates, for example, the spider monkeys, have highly agile and prehensile tails, playing an assisting role in garb and mobile. The number of legs of animal can be four, six, eight, ten and even more. While some animals are legless, e.g. snake and snail. The snake does not have any leg, but it uses the whole body as a propulsive structure for locomotion instead. The snake thus developed four types of movements, lateral undulatory, rectilinear, concertina and sidewinding.

1.3 Limited Human Vision

1.3.1 Importance of Eyesight

There are five traditional kinds of senses for the human: sight, hearing, taste, smell and touch, and even more senses such as the sense of thirsty or hungry, and the sense of balance and position. Every sense is crucial, but sight is special. Eyesight (or sight, vision), the ability to interpret the surrounding environment through light, is regarded as the dominant sense. Nearly 70% of all the sensory receptors in the whole human body are in the eyes [6, 27] and 40% of the cerebral cortex is involved with processing visual information [3, 44]. Therefore, visual sense is of dominance. The human is a visual animal. In fact, the light sensory organs are rarely absent in various life forms. To see is to believe, but do we really see? Visual information involves attributes such as color, brightness, contrast, depth, acuity, etc., so the visual sensation is limited by visible spectrum, visual field,

4 Source: www.npr.org

5 Source: www.burkemuseum.org/blog/myth-spiders-are-easy-identify

distribution of photo-receptor cells, visual axis, etc. In terms of visual sense, the human eyesight is limited in all aspects. For example, the human eye can only see light within a very narrow range of electromagnetic wave spectrum. The rest, however, is invisible to us and few humans are aware of that.

1.3.2 Narrowness of Eyesight

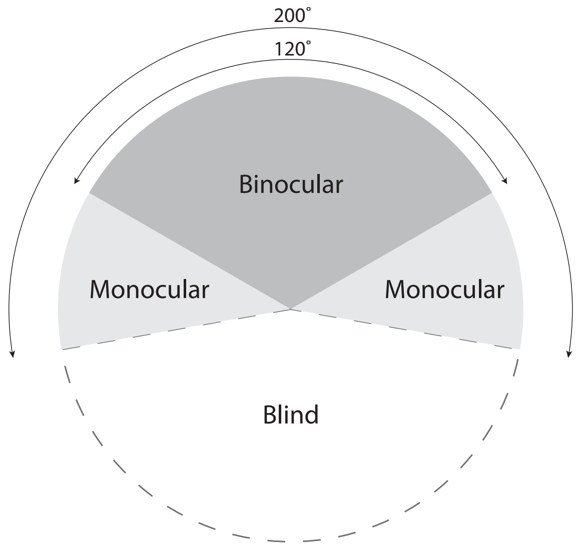
The accessible area in visual space of human sight is limited by certain factors. Firstly, a prime factor is the eye itself. Visual field is one related terminology describing the range of vision, it refers to the full extent of the area visible to an eye that is fixating straight ahead [5]. The equivalent concept in optics is field of view (FOV). Note, in the definition of FOV, eye movements are allowed but do not change the FOV; In the examination of the visual field, eyes are not allowed to move and keep fixating a fixation point.

The visual field relies on retina and lens in eyes. The monocular (one-eyed) visual field of a normal human measures approximately 100° temporally, 60° nasally, 60° superiorly and 75° inferiorly of each eye [35, 41]. Cyclopean[6] vision (total) is approximately 200° wide and 135° tall, with a region of binocular[7] (two-eyed) overlap that is approximately 120° wide [7,8], which is crucial to stereo vision and depth perception. As shown in Figure 1.2(a), the light gray area is the monocular range, while the dark gray overlapped area is the binocular range, and thus the human has a blind range of approximately 120° horizontally.

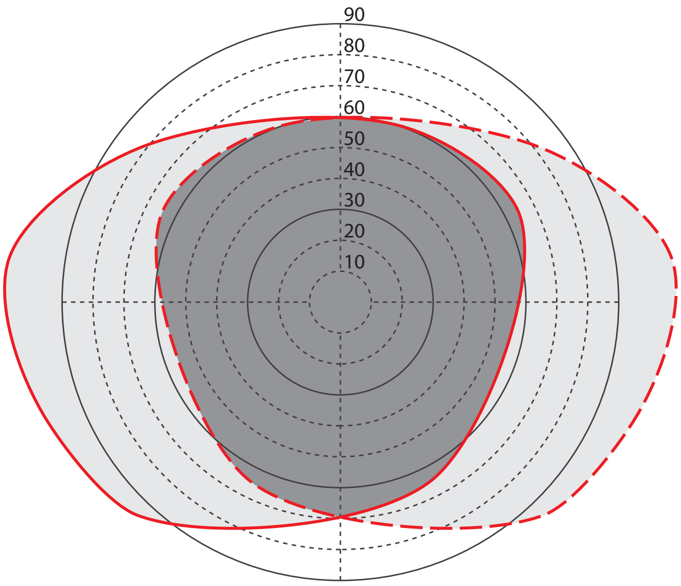
The extent of human eye visual field is not simple rectangles or circle like electronic image sensors, and it varies from person to person. As shown in Figure 1.2(b), the red line indicates the rough outline of the visual field of each eye. Human eyesight has peripheral vision in the edge of gaze center, where the visual quality declines apparently comparing to center vision around the fovea, and even a loss of binocular vision, so the effective visual field shrinks.

6 Cyloepean, literally "circle-eyed", is named after the mythical Cyclops in Greek Mythology who has only a single eye. Thus its extent is the total range can be access by either one or two eyes. The cyclopean image is mentally created in the brain by comprising two images receiving from two eyes.

7 In this thesis, binocular means that "be seen by both eyes simultaneously". In other words, the union of the visual field of each eye, the intersection of each eye. However, the binocular vision is sometimes used to refer to the same concept as cyclopean vision



(a) Distribution of Visual Field in Transverse Plane



(b) Distribution of Visual Field in Frontal Plane

Figure 1.2: Human Visual Field

1.4 Goal

Thanks to the supreme human brain and the rapid development of technology, nowadays a variety of sensors and actuators that mimic and surpass human abilities can be manufactured. I gather inspiration from the biodiversity and the implement the existing modern technologies. I aim to design new or augmented interaction connecting the human and the world, and prove that the human can overcome part of those limitations, physiologically and mentally. New senses and experience will influence the cognition and result in different belief, perhaps a step forward the truth.

1.5 Contribution

- I analyzed the problem of visual limitation in terms of spatial range and figure out the causes;
- I utilized the methodology inspired by animal to solve the problem;
- I proposed a concept to archive visual expansion by changing the vision-head relationship;
- I discussed the mechanism and influence of the concept.
- I fabricated two prototypes providing user a extend vision successfully;
- I tested the prototypes and prove the feasibility of the concept.

1.6 Thesis Outline

The thesis is structured into 6 chapters, and the content of each is as follows:

- Chapter 1 introduces the problem of limited spatial range of human vision, and gives the cues to the methodology inspired by animals;
- Chapter 2 reviews the existing researches and compares with the planed orientation of the thesis;
- Chapter 3 describes the central concept and the biomimetic methodology to solve the problem, and discusses the mechanism and the related influence;

- Chapter 4 presents two prototypes for the concept, and give the detailed configuration of the software and the hardware;
- Chapter 5 records the user tests evaluating the performance of the prototypes, and proves the feasibility of the concept;
- Chapter 6 summaries the whole thesis.

Chapter 2
Literature Review

2.1 Vision Substitution

One direct and obvious solution is to enlarge the visual field of human, by optical or electronic instruments. For example, fish-eye lens can bring a FOV of almost vertical 180° and horizontal 180°, so an array consisting of two or more cameras can generated the 360° panoramic image at any time, whose FOV is vertical 360° and horizontal 360°. As the development of the optical and electronic industry, this type of photography instrument becomes available on the custom market (Figure 2.1). Displaying those contents on a paper or screen will cause severe distortion problem, but virtual environment (e.g. virtual reality headsets) suit those contents.

2.1.1 Wider Visual Field

A conventional solution is to use a wide-angle camera, i.e., camera with a wider FOV. In the project FlyVIZ (Figure 2.2), J. Ardouin et al. [2] used a panoramic

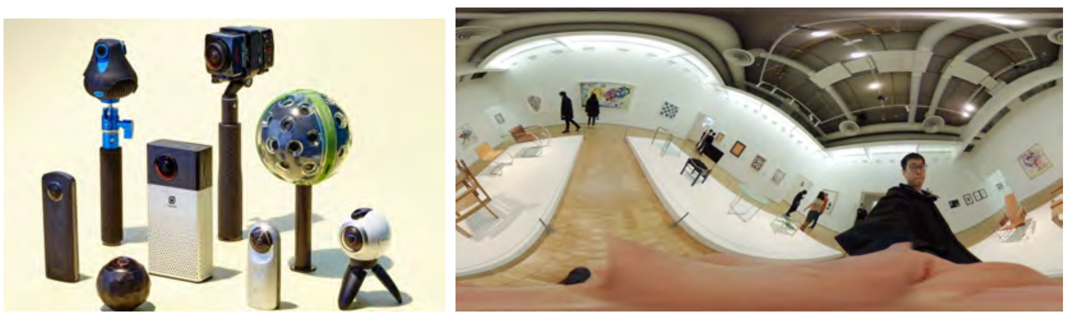


Figure 2.1: 360° Cameras and Photos

Figure 2.2: FlyVIZ [2] and FisheyeVision [29]

image acquisition system to obtain omnidirectional vision and then squeezed the whole image into hand-mount display (HMD) field of view . The system archived a visual field of 360° horizontally and 80° vertically. However, the image content was distorted strongly, and positional information was skewed due to the projection problem when representing the spherical image on a screen plane. The objects were smaller than usual, because the camera videos had to be resized to fit the human visual field. The user had to constantly process videos dissimilar to past visual perception experience. The capture system could cover the top hemisphere. Now 360 degree cameras are already commercially available, that can cover a FOV of 360° horizontally and 360° vertically. Another limit was that camera only produces 2D image without depth awareness. Some other projects provided walk-through experience by changing the view direction of panoramic scene in response when the user was moving. Y. Onoe et al. [28] used a magnetic tracker to track the head motion. M. Fiala and G. Roth [14] employed automatic alignment and building panoramas. In addition, most of them lacked stereoscopic sensation. Those image capturing devices were external to the human body, not in human perspective, and sometimes at fixed location. J. Orlosky et al. [29] fabricated the prototype called "Fisheye Vision" (Figure 2.2) using 180° and 238° FOV lenses. It

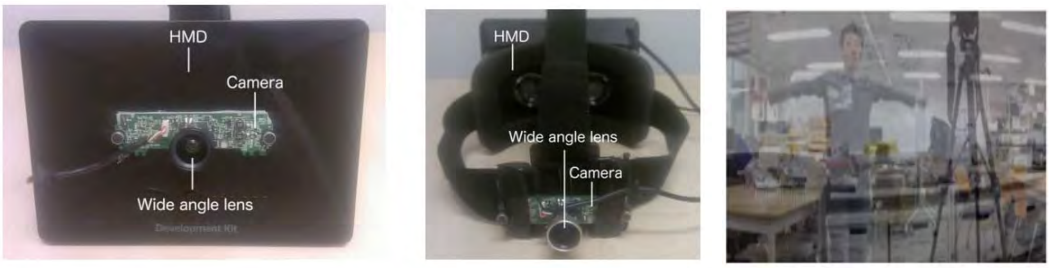


Figure 2.3: SpiderVision [11]

made use of the peripheral vision where the acuity of eyesight is relatively poor, to extend the visual awareness and maintain normal vision at the center. But the user could hardly focus on this area due to the poor equality of eyesight.

2.1.2 Multi Video Sources

The human lacks eyes on the back. K.Fan et al. [11] developed the SpiderVision (Figure 2.3), a headset extended human visual field to mainly augment user's awareness in the back. The system enabled user to focus on front view by the video-see-through HMD, but blended the back view video in only when the system detected dynamic visual change. It kept monitoring the surrounding environment and set an intellectual trigger to activate the augmented content. This system occupied part of the visual field to display the rear view, which inevitably reduces the quality of normal vision: the image became transparency or narrow. This visual augmentation was based on peripheral monitoring, and the trigger for the visual blend was passive for the user so that the reliability of automatic detection limited the whole system performance. In addition, the neck remained stable when the rear view entered, so there was an obvious conflict between the orientation suggested by the neck implicitly and the orientation suggested by rear vision explicitly.

2.1.3 Substitutional Reality

Substitutional reality (Figure 2.4) was a system developed by K. Suziki et al. [39], which was designed to manipulate user's perception of reality. It could shift between live and virtual scene without being noticed by the user. The virtual scene

Figure 2.4: Substitutional Reality [39]

was recorded by a panoramic camera and the vision-head relationship remained unchanged in both scenes, so two scenes were indistinguishable. It provided a novel method to provide a substitution for the reality by visual tricks and proved that the vision was of dominate importance in cognitive progress. The related experiment showed that motion parallax resulting from the head motion was a importance cue for judging whether the experience is immersive and natural, and see-through experience and recorded virtual reality was different for spatial awareness. The result revealed the shortcomings of using a panoramic camera fixed at certain location. K.Fan et al. [12] also used similar concept in specific scenario. They mixed the reality and the past recorded video to create a inter-temporal experience, and the users were able to switch unconsciously between the past and the reality. These researches showed that the human could be easily deceived by visual illusion and the effect was impressive.

2.1.4 Summary

There are existing projects that modify the image, and provide augmented vision different from user common knowledge or instinct. Adaption to the new observation method requires learning cost for users. Besides, the foreign feeling may cause mental rejection and disorder.

Actually, the instinct visual field can not be enlarged medically, compressing the wider image or video into the visual field is the only method. But does it really enhance the sight? The size of the retina and the number of the photorecepter cells remain unchanged, so the amount of visual information that can be received

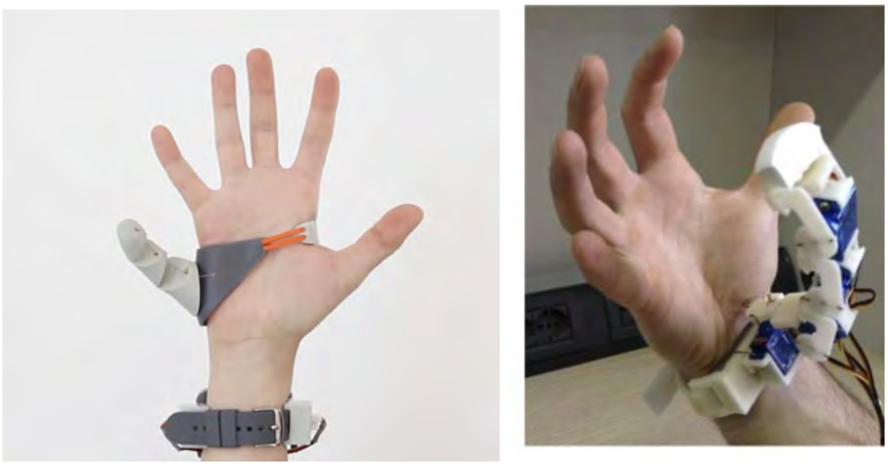


Figure 2.5: The Third Thumb and the Sixth Finger [32]

at any given time dose not increase. Filling more content into the human visual field is very likely to result in less detailed videos.

2.2 Body Augmentation

2.2.1 Alter the Body Schema

The Third Thumb[1] (Figure 2.5) proposed by D. Clode was a concept adding an extra robotic finger to hand, and the extra robotic finger is controlled by a pressure sensor attached to the feet. The interaction and communication was accomplished via wireless connection, and this was a manual control method. Another similar idea, the Sixth Finger (Figure 2.5) presented by D. Prattichizzo et al. [32], also add an extra robotic finger to hand, but the motion of the robotic finger was controlled by a complex object-based mapping algorithm interpreting the whole hand motion in grasping action. On one hand, the procedure was automatic; on the other hand, it was uncontrollable for human will. Those devices could enhance the operation of the hand and finger, but anyway could not archive precise controlling.

MetaLimbs (Figure 2.6) was an implementation of alternating the body schema carried out by T. Sasaki et al. [34], which mapped the motion of toe, feet and

1 Source: http://www.daniclodedesign.com/thethirdthumb

Figure 2.6: MetaLimbs [34]

Figure 2.7: TORSO [43]

leg to an artificial finger, hand and arm. It enabled the human to experience the feeling of four arms, and the extra arms can be controlled relatively. Due to the lack of proprioceptive feedback from the artificial arm, this experience relayed heavily on the visual information.

2.2.2 Telexistence

TORSO (Figure 2.7) was a telexistence [40] (telepresence) system proposed by K. Watanabe et al. [43], which can deliver the head motion and the translation movements of the neck to remote environment, and receive the real-time visual feedback. TELESAR V made by C. Fernando et al. [13] was a more sophisticated implementation. It almost duplicated the senses and movements of the operator to the remote robot. M. Y. Saraiji et al. [33] design a virtual representation using projector to transfer hand motion and position to remote environment. Those projects expened human abilites and were similar to my concept, but they worked as an external part of the user and focused on telepresence operations.

2.2.3 Summary

Those projects proved that the transformation of body schema could be adapted by human. However, without sight, the human was unable to know the postilion of the artificial arm or finger. After all, they were external parts. Moreover, they reinforce the necessity of the participation of the human vision.

Chapter 3
Limitless Oculus

This chapter describes a concept of utilizing the technology and design inspired by nonhuman superior abilities to solve the existing problems that result from human physiological limitations. The particular modality is to examine the problem, and then mimic and adapt the superior abilities of nonhuman beings to suit human, and finally design to enhance, augment and modify the inferior abilities of human beings, with knowledge of computer science, robotics, psychology, neuroscience and zoology.

My research focus on visual expansion, and is called *Limitless Oculus*, where the Latin word of oculus literally means "eye", so the name implies the vision beyond limitations.

3.1 Nonhuman Inspiration

3.1.1 Idea of Bug View

The idea of *Bug View* is to avoid the physiological limitations of the bulky and clumsy human body, by providing the experience of "being a spider". The experience is a delusion but can help take advantage of the superiority of spider.

The problem is that humans or humanoids cannot fulfill all the situations. For example, rescue operation under earthquake debris, or examination and repair inside complex machines or even Mars exploration mission. A bipedal human is too bulky and inappropriate, but a tiny spider can access there through cracks. The idea is inspired by the spider, a tiny bug with 8 legs. Multi-legged locomotion and small scale body result in its superiority. The spider, or bug, has impressive physical agility and mobility. It has the ability to almost access and reach anywhere, all-terrain, especially narrow space and complex topography, for example the spider can easily pass under a door and creep on a wall. Transforming a human into a spider will remain impossible in the foreseeable future, so the research aims to transfer bodily consciousness between a human and a robotic spider. The experience of "being a spider" is a delusion but can help take advantage of the superiority of spider.

Additionally, the idea offers a new form of telepresence. So far telepresence or telexistence technology expands human consciousness to humanoid robots, but the approach of *Bug View* is to embody human awareness in non-humanoid robots of distinct body schema. Compared to duplication of human body schema, non-humanoid robots are more universal to have more possibilities.

Mapping is the key to the research, which indicates the connection between two different body schema, human and non-humanoid robot. Mapping comprises the sensory part, about how to feel, and the kinesiological part, about how to behave. The research work focus on the locomotion mapping and the visual feedback of the spider robot. Possible body mapping patterns include finger-leg mapping, limb-leg mapping, gestural mapping, etc. Spider vision should be at lower position, fixed, and only partly awareness of own body.

3.1.2 Avian Vision and Owls' Neck

Vision is the most important sense for birds, because they are born pilots, and the excellent eyesight is crucially necessary for safe flight. Birds have a superior eyesight in the animal kingdom, and eagle eye is a byword for excellent eyesight. Impressively, some species have two fovea on their retinae, which means they can stare forwards and sideways at the same time. Depending on the different life styles, the their eyes have developed corresponding visual adaptations. For example, the birds of pray have eyesight of extremely high visual acuity and precise depth perception, the nocturnal birds are sensitive to dim light, and the prey animals have an almost all-round view (panoramic vision).

Birds usually have a wide visual field, though the eyes of most birds are fixed in the eye sockets, which means that they must rotate their heads to scan the environment or track an object. Birds usually possess highly flexible necks consisting of 13 to 25 cervical vertebrae, while humans have only 7 ones. A owl's neck is of extraordinary mobility and agility.

The owl, a predator, has its own unique adaptation in eyesight: fixed forwards-facing eyes and a extremely flexible neck. The two front-facing eyes, similar to a human, provide a wide binocular vision. The wide binocular vision with depth information is helpful for preying [21], but thereby narrows the visual field. The species of mallard, one type of duck, has a cyclopean visual field of 360° horizon-

Figure 3.1: A owl is rotating its head

tally, but only 8° binocular vision. While the tawny owl, only has a cyclopean visual field of 210° horizontally, but 48° binocular vision [26]. Their eye placements are different: the owl has front-facing eyes, and the mallard has sideways-facing eyes. However, an owl's vision gets compensation from its neck mobility. Its 14-cervical-vertebrae neck is able to rotate the head up to 270 degrees in either direction [9, 17, 23], or even upside down. This super ability allows the owl to scan the whole surroundings without moving other parts of the body (Figure 3.1).

Therefore, the adaption of the owl implies a cue for visual expansion, that is the neck. The owl bring evidence and motivation to the concept that employing a more flexibility neck.

3.1.3 Human Vision and Neck

Another factor limiting the spatial range of the human vision, is the mobility and flexibility of the neck. To see or scan is not an isolated action of the eye, it is likely to involve the movements of the other body parts, e.g. neck, torso, and even legs. The body position also decides the orientation and location of the eye. Previous work showed the vision orienting is a resulting coordination of the eye and the rest of body [22]. The range of motion of the eyeball is restricted, through the eyeball is the lightest and easiest to move. Torso and leg motions need to bear the weight of the whole body, and involve several groups of muscles. so they are heaviest and hardest to action. The neck is at a balanced position: it only bears and drives the head; its range of motion is relatively wide.

More specifically, gaze direction, the direction of the visual axis in space or the line of sight, is the sum of the eye-in-head position, the head-in-torso position, torso-in-space position. The eyeballs locate inside the eye sockets, having only very limited ocular motor range (oculomotor range, OMR), typically not exceeding $\pm 40°$ to $\pm 45°$ [15]. The eye-only range (EOR), where no head motion tends to happen, is approximately $\pm 15°$ [38]. The customary ocular motor range (COMR), where the eye movements tend to happen with a probability of 90%, is approximately $\pm 20°$ [24]. The eye movements even have an inappreciable probability to occur if the final position is predicted to be more than the COMR. As shown in Table 3.1, the type of movements which is very likely to happen, depends on the different target position (T). Thus the eye movement can only compensate the range of vision in a limited scale, and the body movements is employed to compensate in larger scale. Among all the body parts, the neck is of chief prominence. It is perhaps the most direct and frequent used body part except eyes during dynamic vision, for it is the closet to head and relatively flexible.

Saccades are very rapid, abrupt, ballistic eye movements whose function is to bring new objects of interest to the fovea; they are frequent and important in the exploration of the visual environment [30]. The gaze shifts within the customary ocular motor range can be accomplished by a ocular saccade, but a saccade-like head motion must participate when the gaze exceeding this range [19]. This combination can be called eye-head saccade, so there is a eye-head coordination with a complex trigger mechanism. The head is moved by the neck directly, and in fact electromyographic (EMG) activity can be detected even when the head is mechanically stabilized, indicating a deeper link between the neck and the vision.

In conclusion, the neck motions therefore affect and limit the gaze direction and the visual range.

Table 3.1: Different Types of Movements

Condition	T<EOR	EOR<T<COMR	COMR<T
Type of Movements	Eye only	Eye and head	Head only

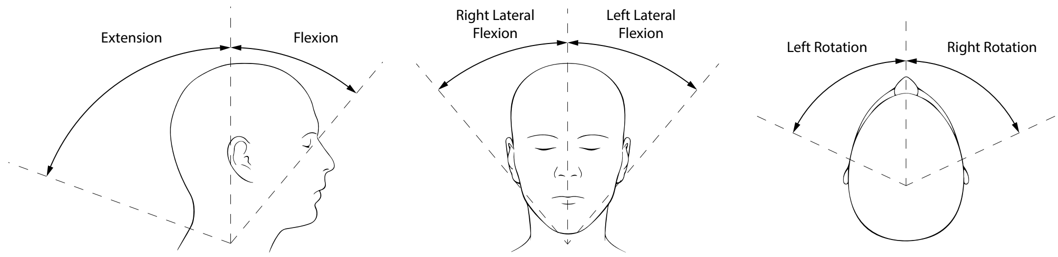


Figure 3.2: Six Types of Neck Motion: (A)Extension, (B)Flexion, (C)Right lateral flexion, (D)Left lateral flexion, (E)Left rotation, (F)Right rotation

3.1.4 Rigidity of Human Neck

Our visual sense is limited in terms of the spatial range due to the limited neck range of motion.

Neck, the top portion of the spine, joining the head and the torso. There are 7 cervical vertebrae in a human neck, while 14 ones, double, in a owl's neck. Neck is important to the flexibility of vision. For instance, when having got wry neck during the sleep, people can feel stiff to look around. Compared with the eyeball, the head is relatively heavy to drive by the neck. Thus everybody can benefit from a more agile and flexible neck, especially who are old or hurt. In clinical medicine, range of motion (ROM) is used to describe the mobility and flexibility of spine or joints; it refers to the distance and direction a joint can move between the maximum flexed position and the maximum extended position. Cervical active range of motion measures six types of neck active motion: extension, flexion, right lateral flexion, and left lateral flexion, left rotation and right rotation (Figure 3.2). Active ROMs of neck indicate the space that can be reached by head, which is at the end of cervical spine.

Age and gender affect the cervical active ROM: they decrease significantly as getting old; females usually have a greater value than males. Thanks to the statistic data in the research of J. Youdas et al. [45], the normal values at all ages can be estimated/predicted with a linear regression mode. The data for the age of 20 and 30 years are listed in Table 3.2, who will be the target subjects for experiments.

Table 3.2: Estimates of Active Range of Motion of Neck

Motion	20 years		30 years	
	Female	Male	Female	Male
Flexion	56.9	56.9	53.9	53.9
Extension	82.9	77.8	77.9	72.8
Left lateral flexion	46.5	44.5	43.5	41.5
Right lateral flexion	49.4	46.7	46.4	43.7
Left rotation	72.5	70.3	69.5	67.3
Right rotation	75.7	71.3	71.7	67.3

Quantify the Range of Vision

The spatial range of human vision is difficult to describe. So far there is no term to quantify the range of vision based on the body movements and positions. In order to quantify this notion.

In this thesis, Visual Range of Motion (VROM) or Scanning Visual Field (SVF)

is used to address the involvement of the motion of body in the spatial range of the vision.

Visual motion is the combination of the relative motion of every single part of human body. With torso and limbs still, e.g., sitting, the visual motion is only generated by the neck, whose range of motion has a limit. If I define the visual area human eyesight can cover with visual scanning range of motion (VROM), it is easy to conclude that its value should be equal to the visual field (VF) of human eye plus the sum of the relative ROM of every part of the body:

$$\Theta_{\text{VROM}} = \theta_{\text{VF}} + \sum \theta_{\text{ROM}}$$

If the human only use the neck, the head motion is restricted by neck only, then the equation can be simplified. Moreover, with a extra neck, its motion also should be counted in:

$$\Theta_{\text{VROM}} = \theta_{\text{FOV}} + \theta_{\text{CROM}_{\text{human}}} + \theta_{\text{CROM}_{\text{extra}}}$$

Note when doing flexion towards the chest, the line of sight will be blocked by the torso.

3.1.5 Define the Orientation of Vision

In this thesis, the orientation of vision (visual orientation or vision orientation) geometrically refers to the normal orientation at the frontal point of the visual field. In other words, it is equivalent to the gaze direction when the eye is in the primary position (or neutral position), i.e. looking straight ahead. This definition is necessary because some animals possess fixed eye, for example, most birds.

The human eyes locate at the head facing forwards. The gaze direction is specified by eye-in-head position (eye relative orientation, caused by eye movements), head-in-torso position (head relative orientation, caused by neck motions), and the torso-in-space position (torso relative position, in the world coordinate system). Thus, the positional change of head orientation and vision orientation is strictly synchronous and identical, i.e. at the same time, same magnitude and same direction. The orientation of head is decided by the neck.

For normal humans, this two orientations coincide, (have the same direction) but they are different. The orientation of vision is an attribute of the eye. Especially for those animals (usually prey, but not always), with sideways-facing arrangement, the two eyes locate oppositely and usually move independently , so the orientation of vision may be nearly orthogonal to the orientation of head. For example, a fish or a horse (Figure 3.3). Nevertheless, the orientation of vision and orientation of head are still associated and synchronous.

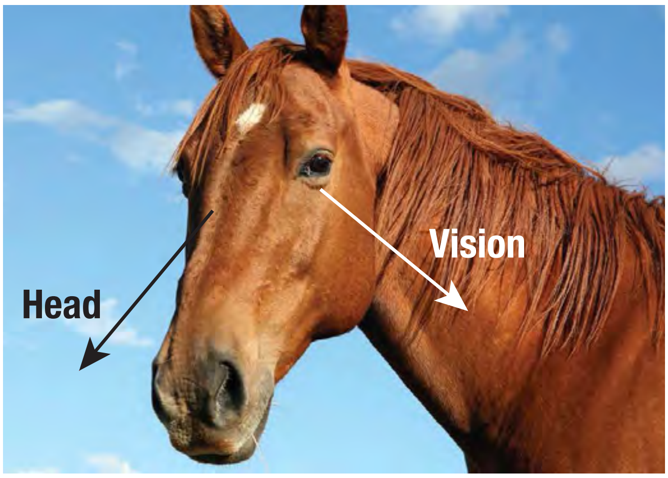


Figure 3.3: The Orientation of Vision and the Orientation of Head in a Horse

However, there is an exception to everything, and in this case, it is the chameleon vision. Its remarkable eyes can move independently and switch between sideways-facing and forwards-facing. This unique feature mean they can switch between stereoscopic and panoramic and thus benefits both the prey capture and the predatory avoidance of the chameleon.

3.2 Concept of Limitless Oculus

Direct modification to human neck or eye medically seem to be impossible so far. In order to help the human overcome constraints in term of the spatial range of vision, with the inspiration from the animal superior abilities previous discussed, in the realm of human-computer interaction, I propose a concept called *Limitless Oculus*.

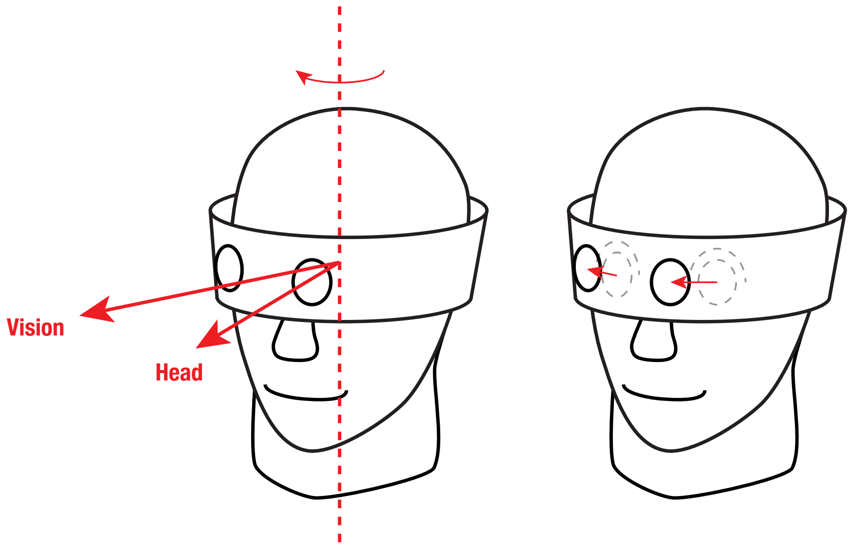


Figure 3.4: The Dissociation of Two Orientations

In this concept, the neck-head-eye system, which controls the orientation of human vision, is functionally replaced by an artificial system which monitors human motion as the systemic input, then provides visual substitution as the systemic output. The systemic vision-motor mechanism powering and controlling the orientation of the visual substitution, overrides the original vision-head relationship. Another equivalent statement is adding an extra layer between the eye and the head. Thus the gaze direction depends on the eye-in-layer position (by eye movements) plus the layer-on-head position (by layer internal mechanism) in addition to the head-on-torso position (by neck motions). This layer can add extra degrees of freedom to the orientation of vision (imagine that the eye-socket can relocate on the head).

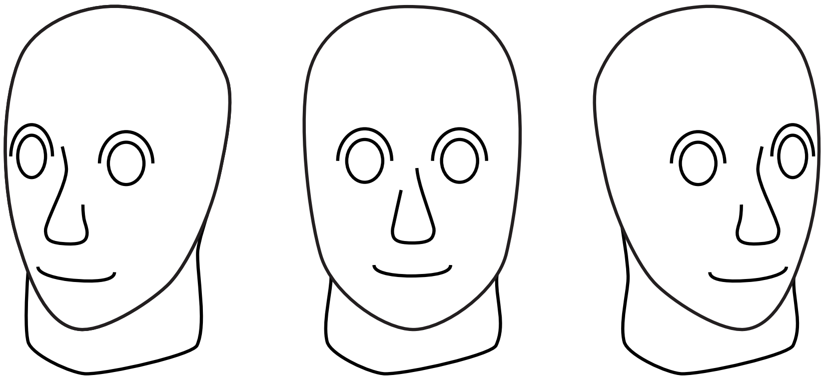
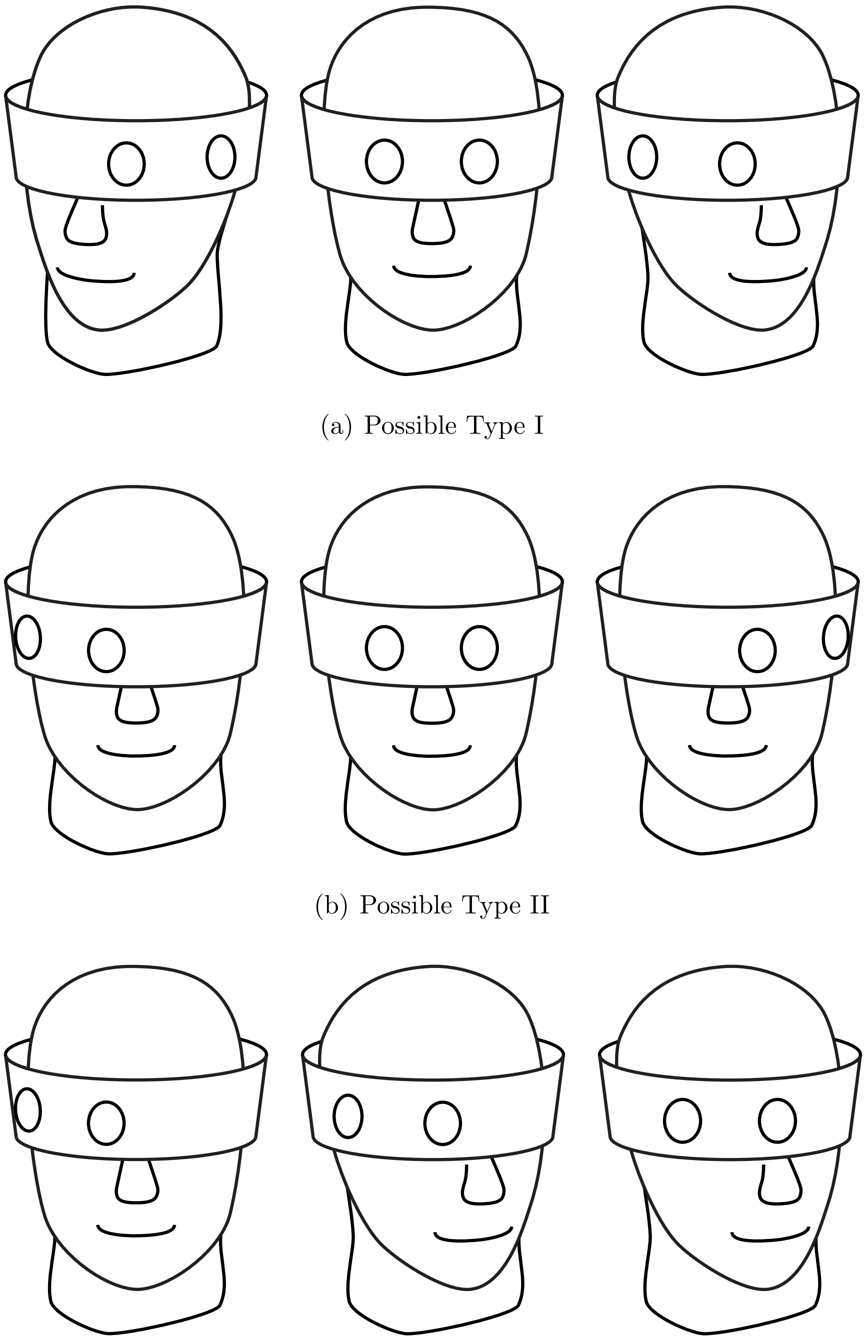


Figure 3.5: Natural Vision-Head Relationship

This modality consequently makes modifications to the normal vision-head relationship of the human. It brings a superhuman experience that the orientation of vision and the orientation of head dissociate. In other words, what the human sees no longer matches what the head faces (Figure 3.4). In a natural state, the orientation of vision is absolutely identical to the head orientation driven by the neck (Figure 3.5). In my concept, however, this relationship can be modified, rebuilt, and even replaced (Figure 3.6). An initial step is to modify the vision-head relationship. For example, a revised vision-head mechanism with different mapping: neck motions can have an influence on vision twice the magnitude of the influence on head orientation, so the visual orientation and head orientation are still related but scaled. A further step is to change the subject of the relationship and create new control mechanism. For example, a vision-hand mechanism: the hand motions are used to control the vision orientation instead of the neck motions, so two orientations are (partly) independent.

The concept starts with control mechanism of visual orientation in the loop of vision-motor relationship. (Vision-head relationship is one type of the vision-motor relationship.) Vision-motor relationship is one part of the sensory-motor coordination relying on the body schema, the body representation at the phys-



(a) Possible Type I

(b) Possible Type II

(c) Possible Type III

Figure 3.6: *Limitless Oculus*: Modification to the Vision-Head Relationship

iological level. The body schema interaction with the cognitional level, so the human can form a new experience and notion. Therefore this concept can expand the human vision physically and help the human adapt to this superhuman experience.

Since the human neck cannot be modified directly, I choose to dissociate the orientation of vision and the orientation of head. Its implementations not only is limited to neck substitution, but also can be a system driving the orientation of vision.

An implicit hypothesis for this concept is that the human can adapt to the new experience and obtain a benefit of wider spatial range of the eyesight.

3.3 Vision-Motor Relationship

The supreme notion of the *Limitless Oculus* concept is to change the somatic mechanism and mapping of vision motion, i.e. change the way human body operate the vision. New mechanism and mapping is the consequence of new body schema, and the cause of new visuomotor coordination. Body schema provides the basis of sensory-motor coordination.

3.3.1 Proprioception

Human visual sense and robotic neck augmentation is associated with proprioceptive sense. Proprioception is a term introduced by Sherrington in 1906 who classifies the receptions into extero-ceptive, intero-ceptive, and proprio-ceptive [37]. Exteroceptive senses are relative to external stimulus and information outside the organism, e.g. sight, hearing, and taste; Interoceptive senses are the feelings produced by internal organs, inside the organism, e.g. hunger, thirst, and vasomotor activity; Propriceptive senses refers to the awareness of one's own body, position and movements(or the change of position), or the kinesiological state, e.g. senses of motion, position, and balance. However, sensory mechanism and receptor of proprioception are still not as clear as those of traditional senses, so its definition or classification is under debate. In the context of this thesis, proprioception is defined as a group of senses including vestibular sense (sense of balance), kinesthetic sense (sense of motion), joint position sense (sense of position).

It monitors and guides the motor actions of body and body parts: the sensation derives from the muscle, tendon, joint, etc; its receptors detect some kinematic factors of every part, such as force and torque, linear/angular distance, speed and acceleration, the position of joints, and the tension of muscle; the brain form an integrated/coherent perception of the kinesiological state of the whole body containing all parts. Therefore, the proprioception is vital to motor coordination.

Proprioception keeps running at background and stays neglected and subconscious, and sometimes tends to become the component of instinct reflex. For example, the vestibulo-ocular reflex is using compensatory eye movements opposite to head movements to stabilize the retinal images. Another example is the muscle memory, with which humans do not need to think how to use legs when walking.

3.3.2 Sensory-Motor Coordination

Sensory-motor (sensori-motor or sensorimotor) coordination is the integration of sensory and motor system. In neuroscience, the human nervous system consists of central nervous system (brain and spinal cord) and peripheral nervous system, which has sensory and motor division. The sensory division is a bottom-up pathway receives outside stimuli from sensory organs, and pass the sensation, while the motor division is a top-down pathway transmits the response signal to musculoskeltal system and execute an reaction.

Vision and proprioception are distinct but in cooperation. The proprioception includes the perception of the body movements, so it takes control of all the motor coordination. The motor coordination is an integration of the proprioceptive information detailing the position and movement of the musculoskeltal system with neural processes in the brain and spinal cord which control, plan, and relay motor command. The body schema provides the basis for sensori-motor coordination.

Visuo-motor coordination is the ability to coordinate vision with the movement of the body or parts of the body. Here the primary coordination exists between the altered eye vision and the substitute neck movements. However, as the vision is altered, all the visuo-motor relationships are affected.

Scanning is a dynamic action, involving the body position and movements e.g. neck, torso, and even limbs. The body motions generate proprioception, so the logical sequence is that proprioceptive sense plays a role in the process of seeing in the correct direction. One evidence is in the spatial awareness. The imagery information from the retina is insufficient to define the coordinate in visual space; gaze direction is also required [4]. Gaze direction is specified by eye-on-head position and head-on-torso position, and the nervous system sources the latter from the proprioceptive information from the neck. Vice versa, the proprioception needs visual information to recalibrate the movements and position of body. For instance, human can still walk with eye closed due to the proprioception, but with eye open, human can walk even more steady and accurately. On the other hand, vision is possible to mislead/deceive the proprioceptive judgment. For example, the rubber hand illusion.

In addition, the eyeball is moved by the coordinated use of six small, strong muscles, called the extraocular muscles, so shifting gaze direction involves conscious muscular sense, one aspect of proprioception. For example, the vestibulo-ocular reflex uses eye movements opposite to head movements to stabilize the retinal images. Another representation is the hand-eye coordination, in which the visual perception guide the hand reaching and grasping, meanwhile the proprioceptive sense guides the eye movement.

3.3.3 Body Schema

Body schema is the basis underneath sensory-motor coordinate. Modification to the vision-neck mechanism and mapping results in updating the body schema. Body schema is the conscious body representation at the physiological level, while body image is unconscious at the cognitive level. The body schema and the body image interact with each other: usually the body image configures the physiological representation through top-down interference; at longer time scale, the body schema is also able to structure the cognitive representation (See Figure 3.7). Therefore, the change of the vision-motor relationship has an influence on cognitive process. Body schema is the topology of body part, for example, the relative position of hand and eye. A spider has body schema totally different from human, but when a human bear the extra neck, its body schema is also changed: its eyes locate at a new place. In the human augmentation, limited change of body schema can be relative easy to form the sense of embodiment, though exaggerated change can bring more possibilities.

The body representation needs proprioceptive sense to acquire the positional data of the body no matter consciously or unconsciously. Furthermore, the proprioception implies that the particular body part is within the own body. Therefore it helps create a embodied perception of the fusion of human and robotic necks. This is important in valid human augmentation.

A phantom limb pain is the sensation that an amputated or missing limb is still attached, and the majority of the sensations are painful. One theory

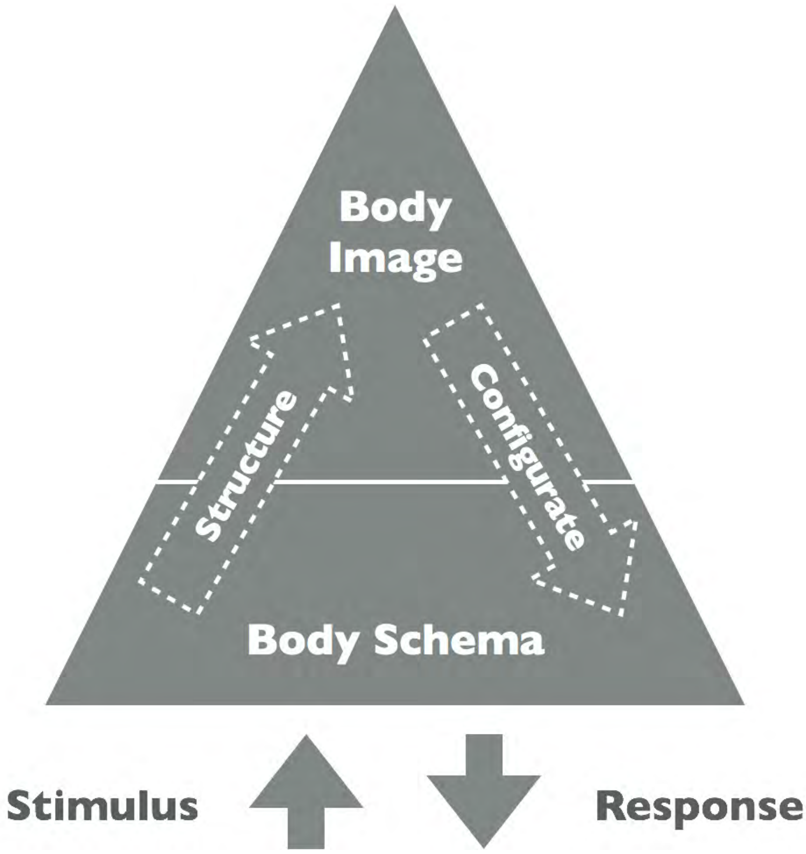


Figure 3.7: Reationship between Body Schema and Body Image

regard the phantom limb pain as a phenomenon of the proprioceptive memory [1]. The rubber hand illusion is a famous embodiment phenomena: Participant form a incorrect perception that rubber hand is one part of own body, when they observe a rubber hand receiving stimulus synchronously with their concealed hand. In this illusion, body schema is distorted and the sense of embodiment occurs in the rubber-hand system. Those are all explicit body schema awareness, so proprioceptive sense is the medium, but also easily to be overridden and have a disorder.

3.4 Design Considerations

In order to archive a wider range of vision but maintain a coherence of visual experience with/without the substitution system, some requirements need to be fulfilled.

3.4.1 Vision

The visual sensation should be as identical to the original human vision as the technology permits. Those methods do not modify or change the visual field, so the original visual field should be maintained.

Stereopsis is one obvious and important aspect of depth perception. The stereopsis does not affect the range of vision, so it should be preserved if possible. The retina is a 2D surface, but the world is a 3D space. When the 3D world projects onto the 2D retina, one spatial dimension of light information is lost during the process: depth. The depth information can partly be recovered inversely from the 2D retinal image, and the brain employs complex processes to generate depth perception. Two depth cues source from the binocular vision: the binocular disparity and the convergence. The convergence is eye movements. The perception produced by brain combating two different retinal images with binocular disparity (or static parallax) is called stereopsis.

The binocular vision is the result of two lateral separated eyes and the overlapped region of visual field. One vital parameter to define binocular placement is interpupillary distance (IPD), the distance between the centers of the two eyes. IPD varies from person to person, the average IPD is approximately 63mm [10]. The change of IPD affects the depth perception: a wider effective IPD leads to hyperstereopsis (or telestereopsis, enlarge relative depth, objects appear larger); a smaller effective IPD leads to hypostereopsis (or microstereopsis, reduce relative depth, objects appear smaller).

3.4.2 Robotics

The substitute human-robot neck system requires enforced agility and flexibility.

Workspace (or effective workspace) of a robotic manipulator refers to the reachable physical volume of the end effector. The workspace of human neck is the the spatial location head can access, thus related to the gaze direction of vision, and the workspace of robotic neck, is the area that the camera can access. Without any obstacle, the workspace is constrained by degree of freedom (DOF), and angular range of travel (ROT) at every joints. Range of travel (ROT) is a mechanical engineering concept equivalent to the rang of motion mentioned above in clinical medicine, describing the linear or angular distance that a kinematic can reach.

Human neck structure can be simplified as a mechanism containing a single spherical kinematic pair (ball joint), with 3 DOFs and limited ROT. Neck can perform more movements than a ball joint, such as translation motion, so this simplification is rough, and only for convenience during the analysis of spatial range.

In order to meet the requirements of the substitute integrated system, a structure with higher DOF and greater ROT is necessary. One concrete solution is to add joints with greater rotation angle range.

3.4.3 Immersive Experience

The altered vision should achieve utmost seamless immersion, reducing the isolated and singular feeling in virtual reality or augmented reality. Although the visual perception of the eye is absolutely dominant in this process, the proprioceptive sense is important, especially in spatial awareness. I suggest, it furthermore indicates that the particular body part is within own body. Therefore visual motion and direction of the human sight are influenced by the neck motion and position. The mapping between neck and vision is the key, so I want to explore new experience bought by different mapping. The neck is the representation of proprioception. The alternative vision by the neck augmentation, together with the eye vision and the neck proprioception, try to trick the brain, letting human be under the sensation illusion that rotating the head beyond the physical limit.

Chapter 4
Implementation

4.1 Overview

Proof-of-concept prototypes are fabricated to demonstrate the feasibility of the idea. A prototype can be a neck substitution enhancing the spatial range of vision. The first idea is to fabricate a robotic neck – a new substitution or extra neck. This does no It only moderately modify the body schema and mechanism of vision motion. Therefore, it is comprehensible, novice-friendly. The second idea is to utilize the arms – another existing part of body. The arms and hands are lithe and agile, and already parts internal to human body. It definitely changes the body schema and create a new mechanism, so probably the superhuman feeling is stronger.

4.1.1 Mechanics in Tracking the Human Body

The kinesiological state of body, movement and position, is complex to analyze and describe, because a whole body cannot be considered as a rigid body, and its twist or bending results in deformation. Certain part of the body can be analyzed as a rigid body and its relative motion is the fusion of translation and rotation. Therefore the body part has the linear position (or position) and the angular position (or orientation), relative to the local coordinate of the body. The head orientation is used to measure the neck motion, because the neck deforms in motion and is more difficult to track. As for the vision in space, the prime attribute is the orientation.

4.1.2 Robotics

The workspace required by the concept is $\mathbb{S}^2 \times \mathbb{S}$, equal to 3-DOF space of orientations of a rigid body. If the neck is considered as a spherical joint, then the torso-neck-head system is a 3-joint robotic arm which have a configuration space (c-space) of T^3, however it has constraints. If the constraints can not be removed, it can be avoided by higher dimensions. So the obvious solution is to add the dimensions of the c-space, i.e. add the DOF. A mechanism with at least $S^2 \times S$, while a 3-DOF robotic arm (Note, robotic arm is not rigid body.) can provide another T^3, then the integrated system (human and robotic) can have a configuration space of T^6, a work space of $S^2 \times S$ and a task space of S^2.

The orientation of human head can be measured by the MEMS gyroscope, so it represented by roll-pitch-yaw angles about axes fixed in the space frame [25]. Thus it is denoted spatial rotation matrix R_h,

$$R_h(\psi, \theta, \phi) = \mathrm{rot}(\hat{\mathbf{z}}, \psi)\ \mathrm{rot}(\hat{\mathbf{y}}, \theta)\ \mathrm{rot}(\hat{\mathbf{x}}, \phi)\, I,$$

where

$$\mathrm{rot}(\hat{\mathbf{z}}, \psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, \mathrm{rot}(\hat{\mathbf{y}}, \theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix},$$

$$\mathrm{rot}(\hat{\mathbf{x}}, \phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

Writing out the entries explicitly, we get

$$R_h(\psi, \theta, \phi) = \begin{bmatrix} c_\psi\, c_\theta & c_\psi\, s_\theta\, s_\phi - s_\psi\, c_\phi & c_\psi\, s_\theta\, c_\phi + s_\psi\, s_\phi \\ s_\psi\, c_\theta & s_\psi\, s_\theta\, s_\phi + c_\psi\, c_\phi & s_\psi\, s_\theta\, c_\phi - c_\psi\, s_\phi \\ -s_\theta & c_\theta\, s_\phi & c_\theta\, c_\phi \end{bmatrix}$$

where s_θ is shorthand for $\sin\theta$, and c_θ is shorthand for $\cos\theta$.

The orientation of the vision of the system (usually a digital camera) can be parametrized by three independent coordinates. (α, β, γ) are the ZYX Euler angels representing the final orientation. The rotation matrix denoted $R_v(\alpha, \beta, \gamma) \in SO(3)$,

$$
\begin{aligned}
R_v(\alpha,\beta,\gamma) &= I\ \mathrm{rot}(\hat{\mathbf{z}},\alpha)\ \mathrm{rot}(\hat{\mathbf{y}},\beta)\ \mathrm{rot}(\hat{\mathbf{x}},\gamma) \\
&= \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} c_\alpha\, c_\beta & c_\alpha\, s_\beta\, s_\gamma - s_\alpha\, c_\gamma & c_\alpha\, s_\beta\, c_\gamma + s_\alpha\, s_\gamma \\ s_\alpha\, c_\beta & s_\alpha\, s_\beta\, s_\gamma + c_\alpha\, c_\gamma & s_\alpha\, s_\beta\, c_\gamma - c_\alpha\, s_\gamma \\ -s_\beta & c_\beta\, s_\gamma & c_\beta\, c_\gamma \end{bmatrix}
\end{aligned}
$$

The prototype should able to operate a mapping function $m : R_h \mapsto R_v$ or $R_v = f(R_h)$, and they have similar construction, thus

$$
\begin{cases} \alpha &= f_1(\theta) \\ \beta &= f_2(\phi) \\ \gamma &= f_3(\psi) \end{cases}
$$

4.2 Unconstrained Neck

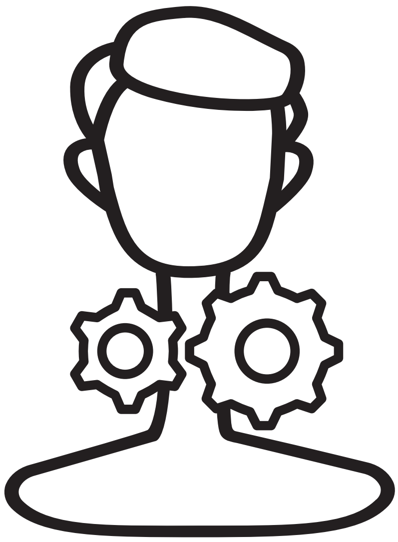


Figure 4.1: Conceptual Drawing of *Unconstrained Neck*

One method is to modify the existing vision-head relationship and apply new mapping between the orientation of the vision and the head motion. For proof-of-concept, a robotic substitution for neck called *Unconstrained Neck* is therefore utilized (Figure 4.2).

Figure 4.2: *Unconstrained Neck*

It has features as following:

- relative natural vision-head mechanism;
- stereo experience and familiar visual field;
- 3-DOF vision and the motion consisting of spatial rotation;

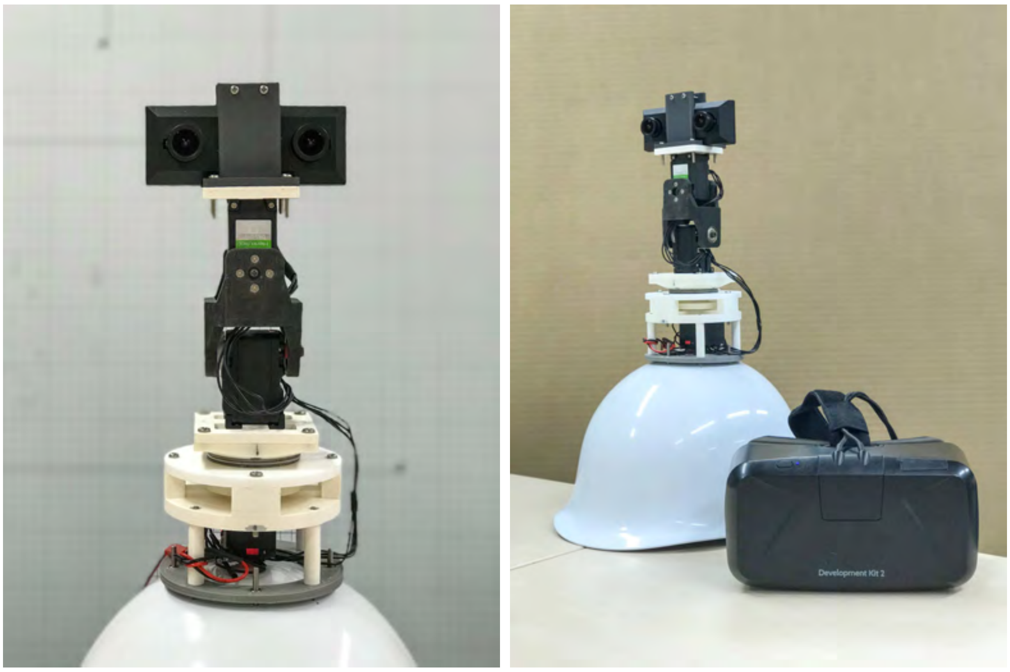


Figure 4.3: Structure of the *Unconstrained Neck*

- proprioceptive cues from the neck;
- mild change of body representation.

4.2.1 Mechanical Structure

This prototype consists of a stereo camera, a helmet-based robotic neck, and head-mounted display (Figure 4.3). The motorized camera is mounted at the endpoint of the robotic neck, allowing the camera and its vision direction to operate in 3-axis rotations: yaw, pitch, and roll.

The robotic neck contains 3 servos (model: Herkulex DRS-0201[1]), and each servo drives the rotation about one axis. A SparkFun[2] micro-controller is embedded to control 3 servos. The extra robotic neck consists of 3 rotational kinematic pairs, so it has 3 degrees of freedom (DOF). The resulting motion of the rotation is thus a combination of human neck and the robotic neck movements. For this

1 Information available: www.dongburobot.com/jsp/cms/view.jsp?code=100788

2 Information available: www.sparkfun.com

prototype, the maximum range of the combined motion is $-180°$ to $180°$ about the three axes, which is almost twice the range of the human neck motion. The range is restricted by the mechanical limits of the servo motors and the structure. The robotic neck is placed on the top of human head to let human feel as an integral part of its own body. The operation of the *Unconstrained Neck* is driven by user's neck orientation, and the positional mapping is defined by the software.

4.2.2 Camera Configuration

The camera set (model: Ovrvision Pro[3]) capturing stereo videos by two individual lenses, streams the videos to the head-mounted display (HMD) (model: Oculus DK2[4]) respectively. The distance between the two lateral placed lens is 65 mm, close to the human interpupillary distance [10], which mean value is approximately 63 mm. The FOV of camera resembles to normal human vision by adjusting the magnification so that it can create a see-through immersive experience.

Due to the height of the robotic neck, the location of the camera set has a vertical offset of approximately 450 mm from the user's eye when wearing this prototype.

4.2.3 Information Flow

The input of the prototype system is the orientation of head and the visual environment, while the output is visual substation including visual information (content) and positional information (orientation).

The orientation of human head is used to control the orientation of substitution vision, which is equivalent to the camera orientation. The front direction of the torso is regarded as the origin. We track the human head orientation by the HMD embedded sensors and use in form of Euler angles as the input of the system. The controlling software produces a corresponding output depending on the mapping. Then the robotic neck commands every servo to act respectively. As shown in Figure 4.5, the orange line stands for the pathway of visual information (video content), and the black line stands for the pathway of positional information (orientations).

3 Information available: www.ovrvision.com

4 Information available: www.oculus.com

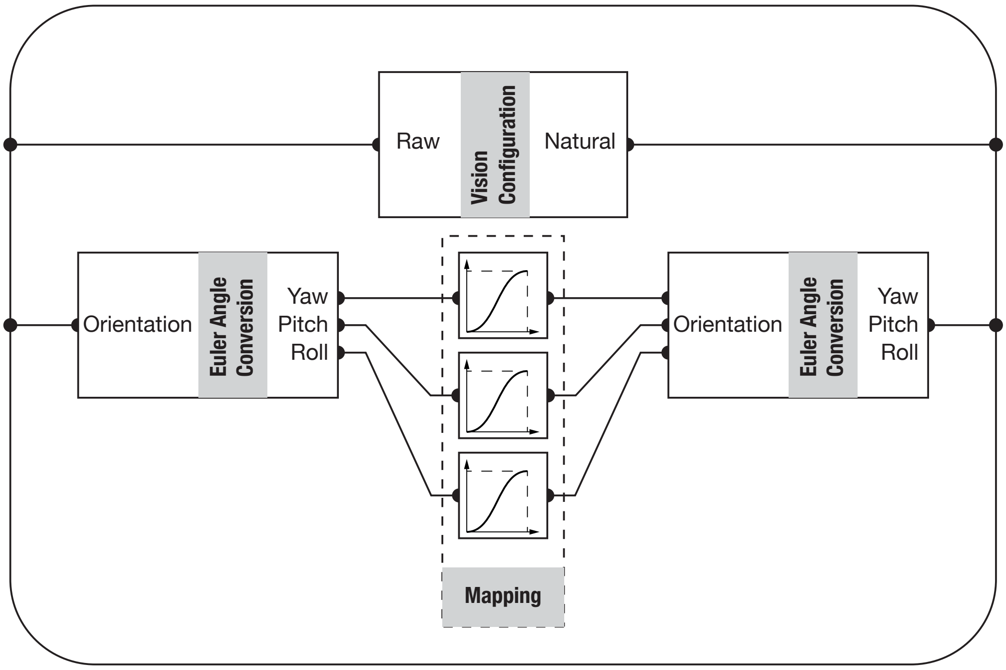


Figure 4.4: Information Flow within the Software

The camera steams stereo video to the HMD for human eyes. The HMD measures the positional data of human head, and send it to host computer. The host computer, according to the mapping pattern setting in software, commands the robotic neck to execute certain rotation. Figure 4.4 show the internal processing logic of the software[5].

4.2.4 Mapping

Mapping Functions

For the *Unconstrained Neck*, the system input and output are all rotational data. When the human head is rotated by a 3D rotation of R_{input}, the system vision will be rotated by a 3D rotation of R_{output}. Then the mapping of orientation in

5 This controlling software is realized based on the Embodied Driven Design developed by MHD Yamen Saraiji.

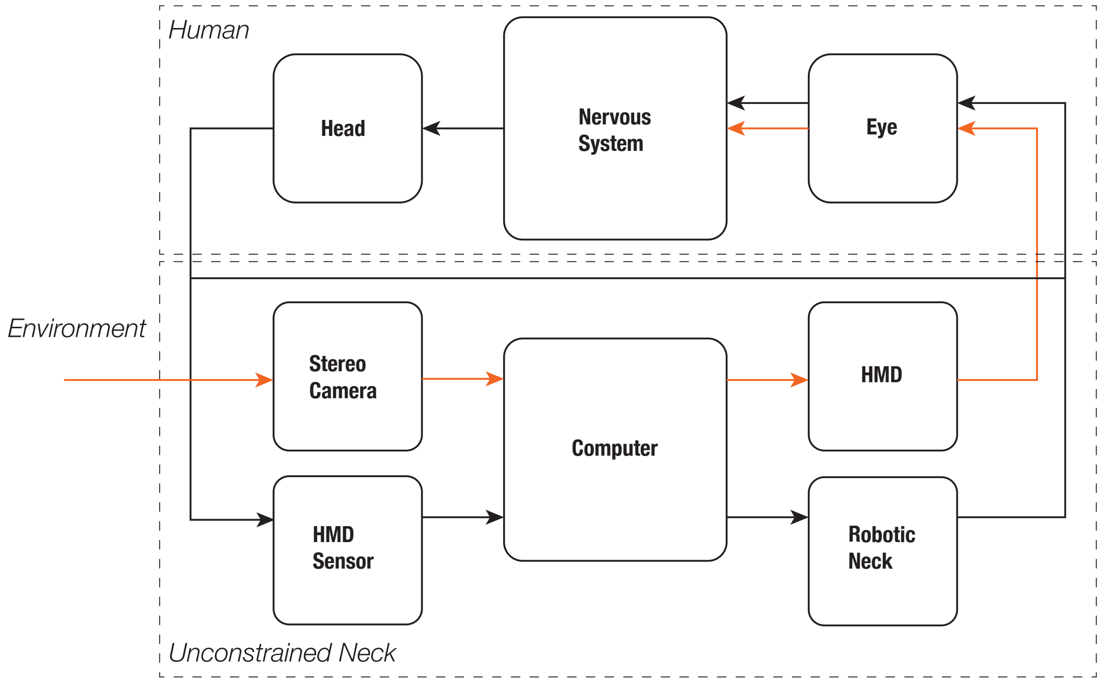


Figure 4.5: Information Flow between *Unconstrained Neck* and Human

3D space can be described as a function:

$$R_{\text{output}} = f(R_{\text{input}})$$

or

$$R_{\text{system vision}} = f(R_{\text{human head}})$$

Any three-dimensional (3D) rotation can be described as a sequence of yaw, pitch, and roll sub-rotations. This prototype regards those Euler angles as the input and the output, so the function can be simplified:

$$\theta_{\text{system vision}} = f(\theta_{\text{human head}})$$

It is possible to have different mapping about each axis, as shown in Figure 4.4. The mapping pattern can be adjusted within the software. The following mapping functions/patterns discussed in this section refer to the mapping functions/patterns about each axis i.e., the mapping of 2D angles of yaw/pitch/roll and the same mapping is applied to each sub-rotation, without extra mention, but different mapping can create asymmetric experience.

Applied Function and Pattern

The system vision motion is the sum of the motion of human neck and robotic neck, so

$$\theta_{\text{system vision}} = \theta_{\text{robot neck}} + \theta_{\text{human neck}}$$

For the robotic neck, the robotic configuration mapping is

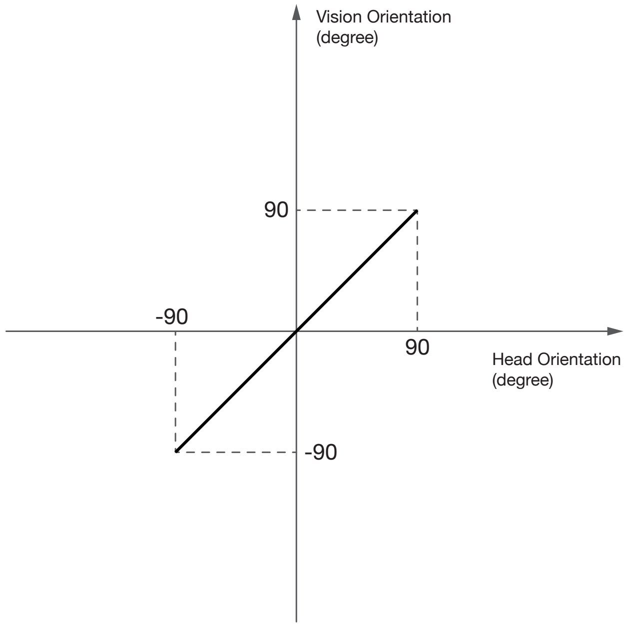
$$\theta_{\text{robot output}} = f'(\theta_{\text{robot input}})$$

or therefore

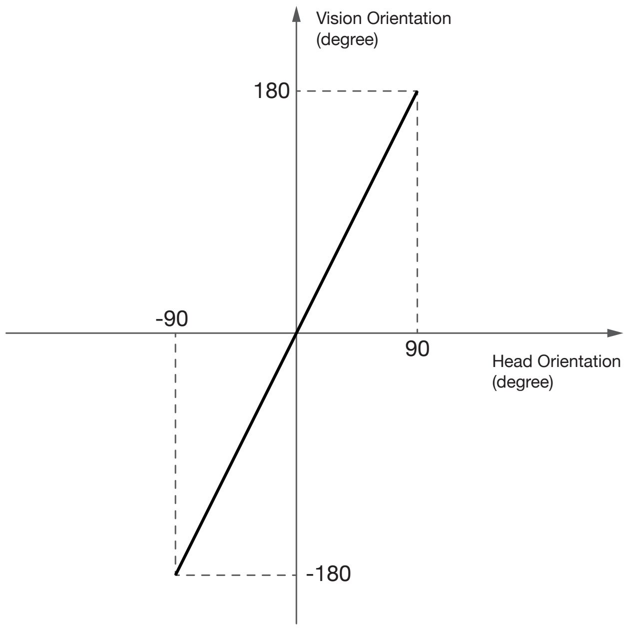
$$\theta_{\text{robot neck}} = f'(\theta_{\text{human neck}})$$

The input of the system is the tracking data of the orientation of head from the HMD, and the output of the system is the executing value of the robotic neck.

If the ROM of left/right lateral rotation is more than 180°, the vision extent will have an overlapped region, which may bring disorientation. Secondly, this action will exceed the maximum mechanical constraint of the servo motors and the structure. In order to make the mechanism understandable and make the



(a) Mapping of Natural Human Neck



(b) Mapping of *Unconstrained Neck*

Figure 4.6: Comparing the Head-Vision Relationship of the Natural Human Neck and the *Unconstrained Neck*

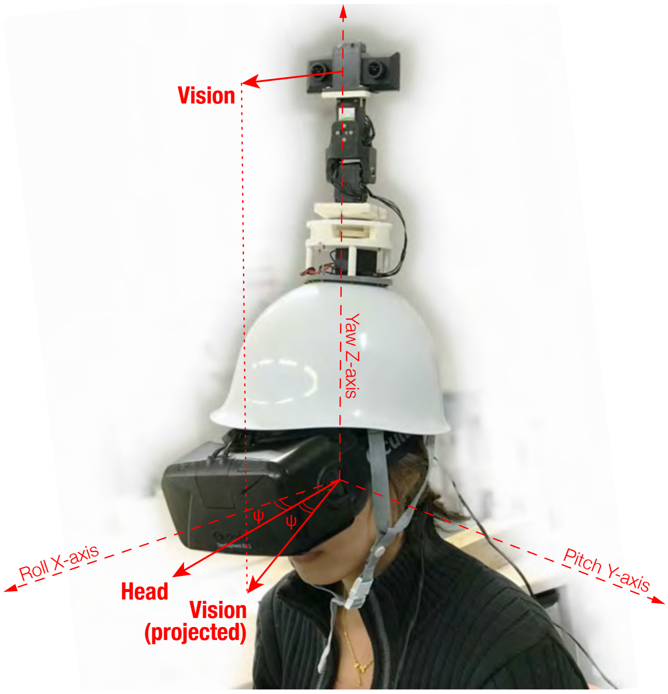


Figure 4.7: An Example of *Unconstrained Neck*

experimental data simple, in the prototype for following experiments, the mapping here is set to a 1:2 linear function with covering $-180°$ to $180°$:

$$\theta_{\text{system vision}} = 2\theta_{\text{human head}}$$

Note this is only the ideal range, in fact the maximum a human can reach varies. The Figure 4.6(a) shows the applied mapping of the *Unconstrained Neck*, indicating a new superhuman relationship between the orientation of the system vision and the orientation of the human head, while the the Figure 4.6(b) show the natural mapping of human. For example, as shown in Figure 4.7, the user's human head (neck) is at a yaw angle of ψ, and the resulting system vision (camera) is at a yaw angle of 2ψ.

Visual/motor gain (g) is used as a parameter to describe the extra compensation from the robotic neck:

$$g = \theta_{\text{robot neck}} \div \theta_{\text{human neck}}$$

so

$$\theta_{\text{system vision}} = \theta_{\text{human neck}} + (g)(\theta_{\text{human neck}})$$

Thus, positive values of gain ($0 < g < 1$) are used to amplify the speed of the motion of the vision, or negative values ($-1 < g < 0$) result in slower operation of the robotic neck. For example, the orientation of system vision in Figure 4.7 can also be calculated by $\psi + g\psi$, where $g = 1$.

Other Mapping Patterns

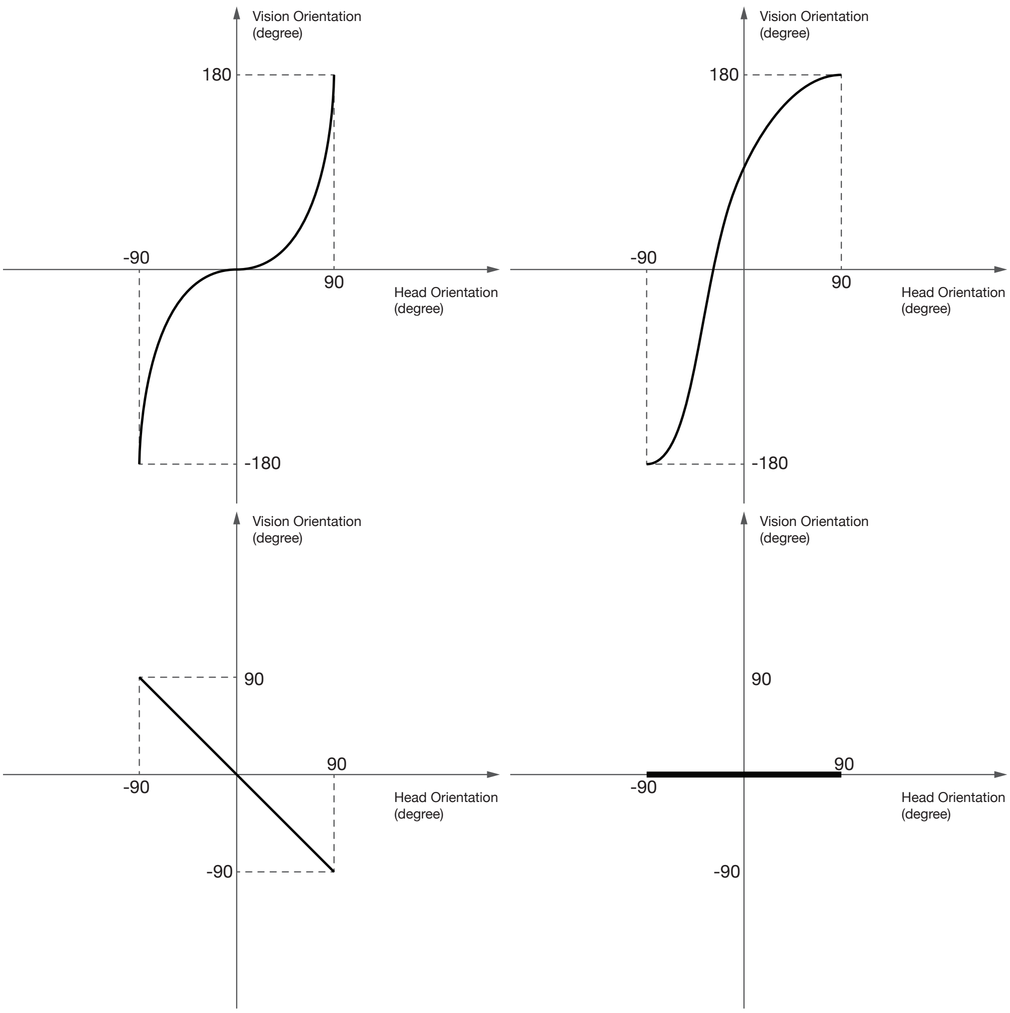


Figure 4.8: Other Possible Mapping Patterns

The mapping patterns can be either linear or nonlinear, convex or concave, and other complicated pattern (See Figure 4.8). A concave function mapping can match past human experience, that neck is relatively easy to mobile near the center position, but become stiff when being close to its constraint. It lets the user feel neck getting more rigid when the angel increase. In contrary, a convex function mapping can compensate past human experience. It lets the user feel neck is getting less rigid when the angel increase. It can also be the inverse of the mapping of natural human neck, which means that the vision orientation is the opposite of the head. If the function product is constant, the prototype behaves as kind of stabilizer.

4.3 Eye-In-Hand

Figure 4.9: Conceptual Drawing of *Eye-in-Hand*

This prototype does not use an artificial neck, but make use of the internal body parts. The upper limb, from shoulder to wrist, is the most flexible and dexterous part of human body. It has 7 DOFs (2 at shoulder, 1 at arm, 1 at elbow, 1 at forearm, and 2 at wrist), and it can easily access and reach the whole workspace. Even duplicating a robotic arm proves quite a challenge. But it has no relationship with vision at all. I therefore present the idea of *Eye-In-Hand* to take advantage of human own upper limbs (Figure 4.10).

4.3.1 Structure

In this prototype, the upper limb serves as a “new neck” controlling the orientation of vision. The original vision-head mechanism is replaced by a vision-head mechanism. Starting with the simplest method, the orientation of visual substitution is set to be identical to the dorsal orientation of hand, i.e. the endpoint of the upper limb. The kinematic mapping is thus about the hand motion/orientation and vision motion/orientation. The issue of visual mapping is about how to map two different videos to the human vision.

It has features as following:

- superhuman/unnatural vision-hand mechanism;
- two different visual sources, two orientations of vision;
- 7-DOF vision and the motion consisting of 3D translation and 3D rotation;
- proprioceptive cues from the upper limb;
- dramatic change of body representation.

Figure 4.10: *Eye-In-Head*

4.3.2 New Mechanism

The hardware of the *Eye-In-Head* is one head-mounted display (model: Oculus DK2 [6]), two separated cameras (model: e-con Systems See3CAM[7]), and supporting gloves (Figure 4.11). Those hand-mounted cameras streams videos to the head-mounted display (HMD) via computer, in the way of the visual mapping embedded in the software.

6 Information available: www.oculus.com

7 Information available: www.e-consystems.com/See3CAM-USB-3-Camera.asp

Figure 4.11: Structure of *Eye-In-Head*

4.3.3 Problem and Solution of the Binocular Rivalry

Binocular rivalry can be regarded as the extreme of stereopsis. The stereopsis is the result of binocular disparity i.e. two eyes register different image. Two images with slight and corresponding differences can form stereopsis, but the binocular rivalry takes place when the differences exceed the threshold of sufficient similarity, the brain can no longer form a fused image but only see one image at a time.

This HMD have a FOV (vertical 90° and horizontal 110°) entirely inside of the binocular area of the human visual field, so the different videos registered to two eyes completely overlaps and the problem of binocular rivalry is surly to happen. My solution is to cropped the videos to avoid the superposition. As shown in Figure 4.12, there are basically two solutions, the two upper patterns stand for the image for left eye and right eye respectively, and the single lower pattern stands for the imagery fusion created by brain. The first solution is using the same image. The second solution is to divide the visual content in the middle of the FOV of HMD, so the left eye only see the left half and the right eye only see the right part. Figure 4.13 shows the final effect: two upper images merge into a lower image. One reason to put the border in the middle of the FOV is that the corresponding position in human visual field is also the boundary of the left hemisphere and right hemisphere of the visual cortex in the brain (Figure 4.14). Yet the effect of this placement, and hopefully it could be explored in following experiments, but it is indeed a natural boundary.

When two cameras are close enough and the stereopsis will come into being again. Putting hands on the HMD can help align the cameras correctly.

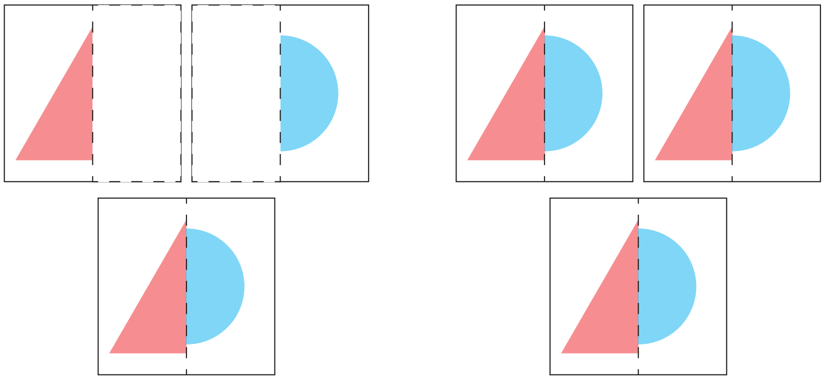


Figure 4.12: Solution to the Binocular Rivalry

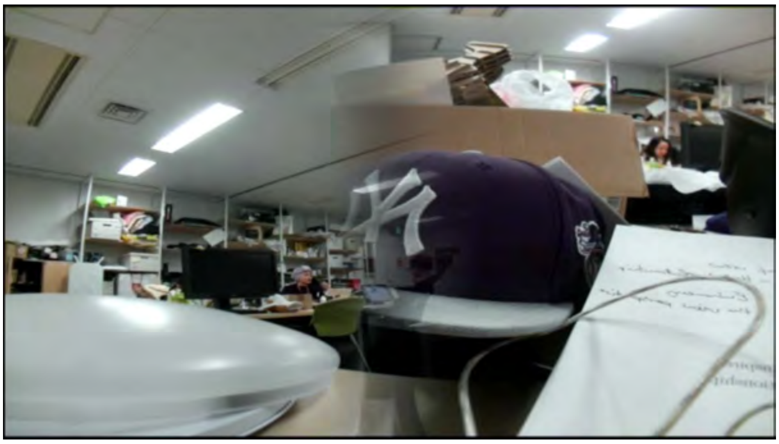
4.3.4 User Experience

The experience sounds like transplanting the eyes to the hands, so it gets the name of "Eye-In-Hand". When two hands (modules) place next to each other on the HMD, and have a distance same as the normal IPD, the stereopsis forms. When the user slowly separate two hands (modules), depth information slowly disappears and the image to each eye become different. The user can adjust the orientation of vision just by moving the hand in the spatial, and the vision motion strictly follows the hand motion. The orientation of vision thus is extremely flexible so it can easily access the rear view and panoramic view (Figure 4.15). The head orientation is used to change the portion of left/right images, when the yaw angel go beyond a threshold angle, the half of the FOV of the HMD, the visual field is completely filled by the videos from one side. For example, set the threshold as 50°, when the user does left rotation more than 50°, the FOV is filled by the video from the camera module at left hand. The process is shown in Figure 4.16, from top to bottom, and the portion of two sources is altered. The human takes advantage of the forwards-facing eyes to perceive depth information, but many other animals employ the sideways-facing eyes for a ultra wide visual field as I mentioned above. This prototype makes it possible to switch between two modes, stereoscopy and wider-visual-field.

This prototype is still under working and requires further refinement.

(a) Right Source Image

(b) Left Source Image



(c) Blended Image

Figure 4.13: Mixture of Two Video Sources

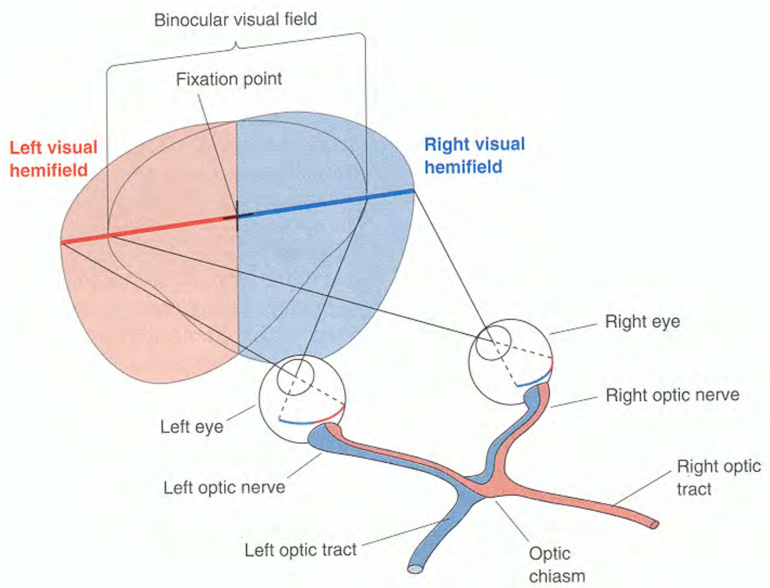


Figure 4.14: Optic Chiasam: The Mapping between Visual Field and Brain Area

Figure 4.15: *Eye-in-Hand* Operation for Wider Spatial Range

Figure 4.16: Alter the Various Portion of Two Sources

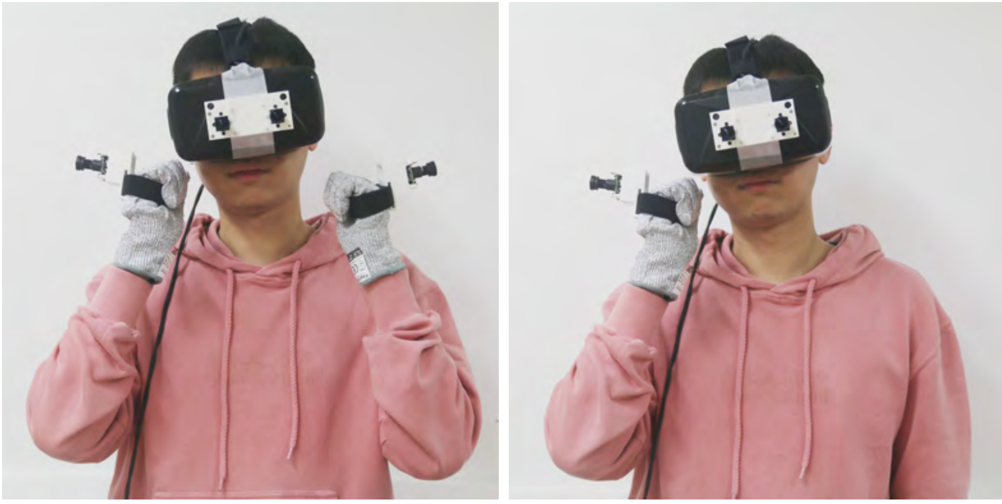


Figure 4.17: Possible Derivative Prototypes

4.3.5 Possible Derivative Prototypes

The system can also be consist of a stereo camera set, and one or two separated cameras (Figure 4.17). Under such situation, the stereo camera set can serve as the main view and keeps providing stereo videos, and the separated cameras as the secondary view providing extra vision.

Chapter 5
Evaluation

Experiments are conducted to quantify the system performance.

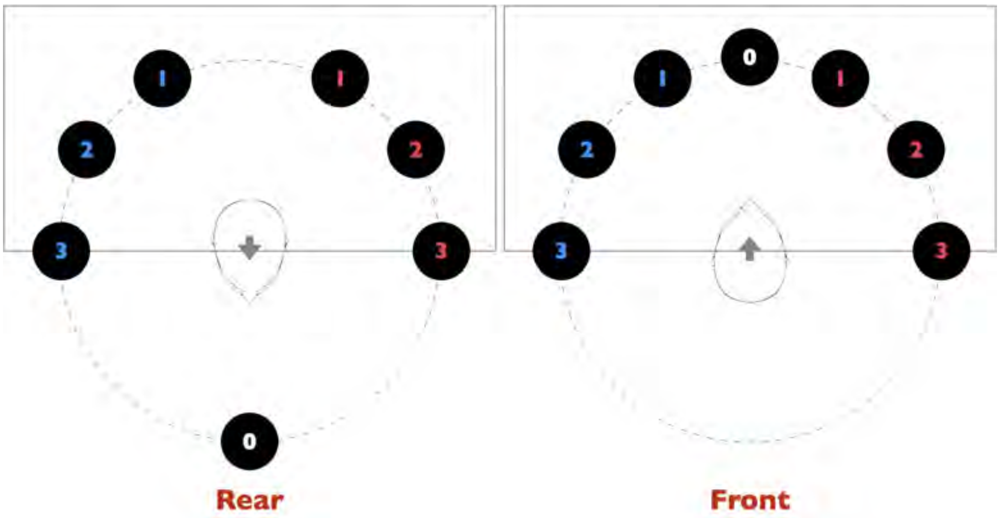
5.1 Experimental Setup

Environment

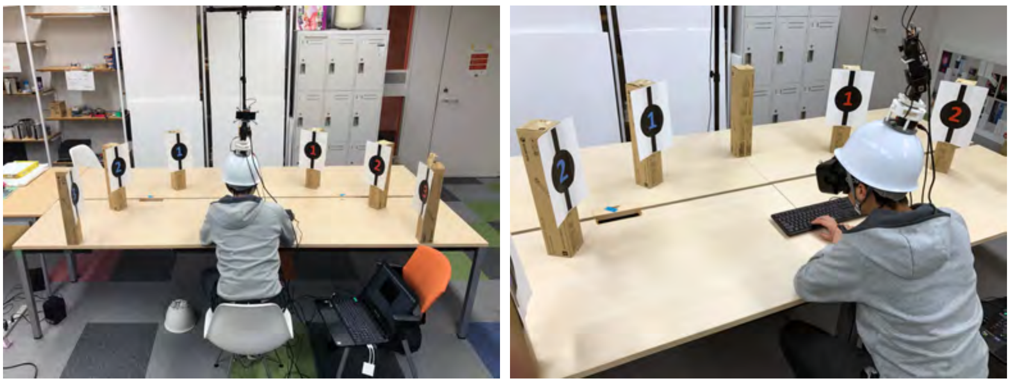
The experiment field was a big room with a table of 140 cm $\times$ 280 cm. Seven signs of target on the table were placed in a semicircle with a radius of 1 meter. The center angle of every two neighbor targets was 30 degrees. The center of the semicircle was at the edge of the table. The subject sited in front of the table and place his neck right over the center. Figure 5.1 showed the floor plan and the relative location, in which the solid line rectangles was the table, and the black dots were targets, and the center arrow stood for facing direction of the subject. There were two arrangements: the targets were at the rear of the subjects, and the targets were at the front of the subjects. The target was a sign printed on a A4 sheet of paper, consisting of a black solid circle, a colored number (blue or red, 1 to 3) in the center, and a vertical black column.

Subjects

The subjects were 9 healthy volunteers (4 females and 4 males) ranging in age from 22 to 26 years. The subjects were recruited from university students. For safety reason, the subjects were all queried to confirm that their condition fulfilled all the criteria. The criteria were (1) no current neck pain, (2) no history of any neck medication, (3) no current eyesight illness, (4) no severe virtual reality sickness, (5) unambiguous communication with the tester. This was written in a questionnaire and reviewed by the subjects before the experiment (Figure 5.2). Virtual reality sickness was introduced to the subjects.



(a) Floor Plan (Relative Location of Subject and Targets)



(b) Experiment Shot

Figure 5.1: Experiment Setup

Questionnaire

Do you volunteer to participate this experiment and cooperate with the experimenter? Yes / No

Basic Information:

Name: Gender: Age:

Health Condition:

Do you currently have any pain, injure or illness on neck?	Yes / No
Did you ever have any pain, injure or illness on neck?	Yes / No
Did you ever have any medication on neck?	Yes / No
Do you currently have any pain, injure or illness on eyes?	Yes / No
Did you ever suffer from severe virtual reality sickness? (symptoms beyond your tolerance)	Yes / No
Are you able to clearly understand the vocal guidance of the experimenter?	Yes / No

Before Experiments:

Describe the degree of the fatigue of your neck before the test.
(from 0 to 9, 0 is no fatigue at all, 9 is extremely severe fatigue)

Describe the degree of the symptoms of VR sickness before the test.
(from 0 to 9, 0 is no dizziness at all, 9 is extremely severe sickness)

After Experiments:

Describe the degree of the fatigue of your neck after the test.
(from 0 to 9, 0 is no fatigue at all, 9 is extremely severe fatigue)

Describe the degree of the symptoms of VR sickness after the test.
(from 0 to 9, 0 is no fatigue at all, 9 is extremely severe sickness)

> ***Virtual reality sickness*** occurs when exposure to a virtual environment causes common symptoms, which includes general discomfort, headache, stomach awareness, nausea, vomiting, pallor, sweating, fatigue, drowsiness, disorientation, apathy, postural instability and retching.

Figure 5.2: Questionnaire

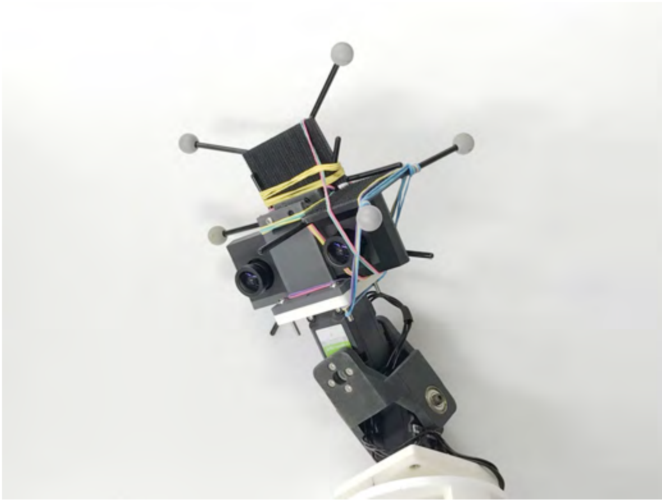


Figure 5.3: The Markers on the Camera

Tester

The author is the tester during the whole test. The tester explained how to use the system and the test procedures. The tester used vocal cues to guide the subjects during the test.

Instruments

A infrared tracking system (model: OptiTrack V120 Trio[1]) was used to track the motion of the subjects at a frequency of 30 Hz. A group (more than 3) of infrared markers were attached to certain location, and the group was regarded as a rigid body. Here, I attached one to HMD and another one to the camera using 3D structure to ensure the performance during rotations with large angles (Figure). The tracking system can monitor the 6 DOF information for every rigid body, i.e., the spatial position in a static three-dimensional Cartesian coordinate system, and the spatial orientation represented by XYZ roll-pitch-yaw angels in this fixed coordinate. It streamed the real-time data to the computer.

1 Information available: optitrack.com/products/v120-trio

5.2 Experiment Procedure

The first experiment measured the response time when the subject was asked to rotate head laterally to a certain angle. The subject performed the test wearing helmet, under two conditions: robot activated and robot deactivated. Before the test, the neck of the subject was at the neutral position, where he align the head with the torso. When the test started, a mark for aiming appeared in the center view of HMD. The mark was a white solid circle with a colored number (blue or red, 1 to 3) in the center (Figure 5.4(a)). The subject read the number implying the position of the target, then performed a lateral rotation by neck until he saw the right target in center of vision (Figure 5.4(b)). To aim was to superpose the centers of the mark circle and the target circle (Figure 5.4(c)). When finishing aiming, the subject pressed the keyboard, and a zero mark appeared to indicate the subject resume to the neural position (Figure 5.4(d)). 3 seconds later, a new mark appeared (Figure 5.4(e)), and then the subject continued to next target. The computer kept recording the time and the rotational data. The response time was the interval between the time when a new digit appeared and the time when the subject pressed the keyboard.

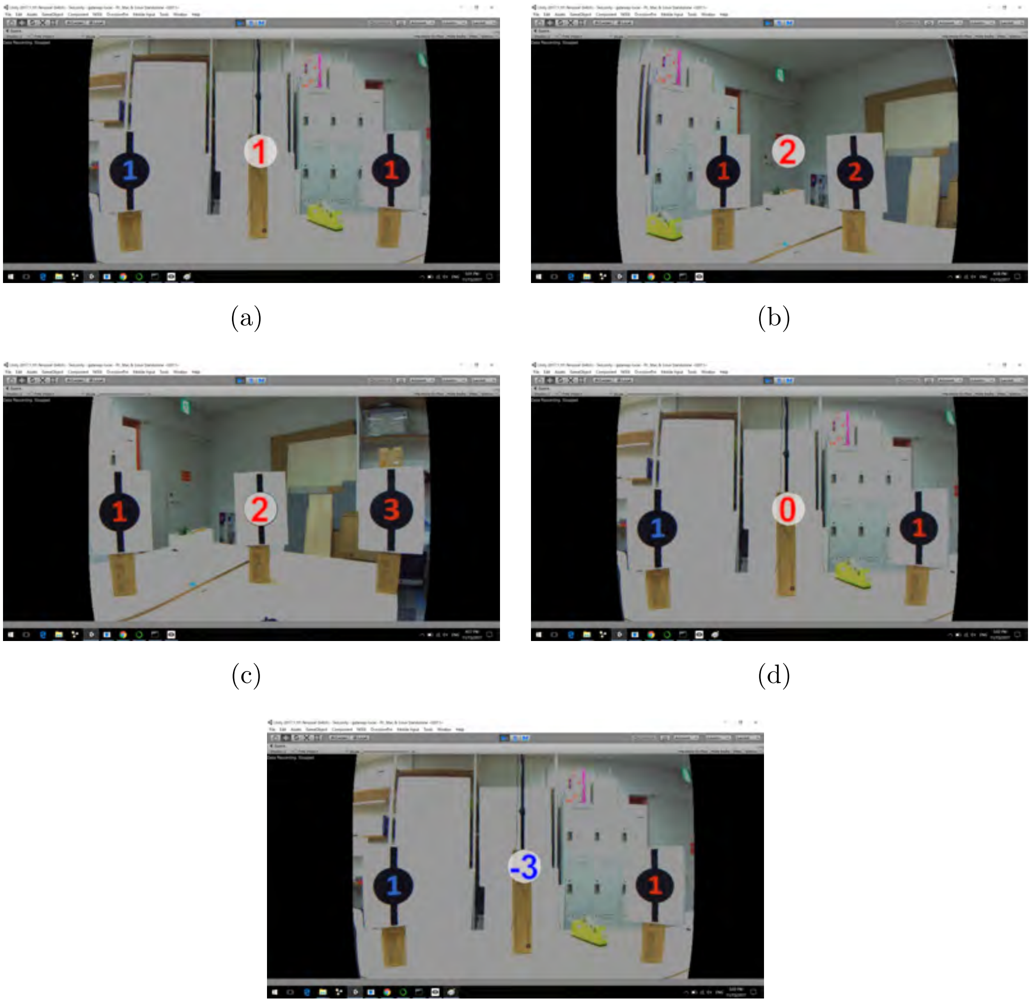
The subject repeated that procedure six times as a subsection. The number mark never repeat within one subsection, but the order was random. The subject repeated the subsection 3 times as a section under each condition. Firstly did the front hemisphere part, sitting face to the targets, and rotating with neck motion only. Then did the rear hemisphere part, sitting back to the targets, and rotating with torso and neck motion.

The second experiment measured the range of motion of the system vision and subject's neck simultaneously. Let the subject do six motions for measuring the cervical ROM with the helmet.

5.3 Result

5.3.1 Data Processing

I filter the motion data slightly for errors (cut out extreme values that are out of range). Then, we calculate the instant speed of motion during every individual test and its average value. Preliminary try-out showed that the left and right rotations have less sickness, and are crucial for panoramic or omnidirectional vision. Therefore, I mainly analyzed the performance of left and right rotations,



(a) (b)

(c) (d)

(e)

Figure 5.4: Procedure and Interface of the Experiment

and the targets were at the horizontal plane. The motion and orientation of the vision is equal to the motion and orientation of the camera.

The response time was the interval between the time when a new digit appeared and the time when the subject pressed the keyboard, i.e., $t_{\text{response}} = \Delta t = t_{\text{target}} - t_{\text{origin}}$. The camera speed (vision speed) is calculated by $v_{\text{camera}} = \Delta\theta_{\text{vision}} \div t_{\text{response}}$. The head speed is calculated by $v_{\text{head}} = \Delta\theta_{\text{head}} \div t_{\text{response}}$.

As shown in Figure 5.5, the values of the response speed of head and camera, are the mean of the data of all the subjects. The blue bar is the condition with robot activated and the orange bar is the condition with robot deactivated.

When the subject was sitting back to the table, he/she did rotations more than 90°. Therefore, the markers on the HMD is easily to be out of the range of tracking.

The camera speed (vision speed) is calculated by $v_{\text{camera}} = \Delta\theta_{\text{vision}} \div t_{\text{response}}$. The gain mean the benefit the subject get from the prototype, and it is calculated by $g = v_{\text{camera(robot activated)}} \div v_{\text{camera(robot deactivated)}} - 1$. As shown in Figure 5.6, the values of the response speed of camera and gain, are the mean of the data of all the subjects. The blue bar is the condition with robot activated and the orange bar is the condition with robot deactivated.

5.3.2 Comments and Feedback

The performance was described as "unexpected smooth" by many users who have experience on practical virtual reality or augmented reality research. Some user also pointed that the scanning by flexion-extension cause more uncomfortable feeling than the scanning by left-right rotation. Some user said that the headset is a little bit too heavy.

The demonstration of this prototype was once showed in public after lab experiments [36], and received high evaluation. I also found out the participants commented that they felt relatively serious sickness with non-linear mapping. The latency also contributed to the sickness, especially during relatively rapid scan motions.

5.4 Discussion

As shown in Figure 5.5, the vision speed grows as the target angle increases. It means that the vision speed is not a constant, but influenced by the final position

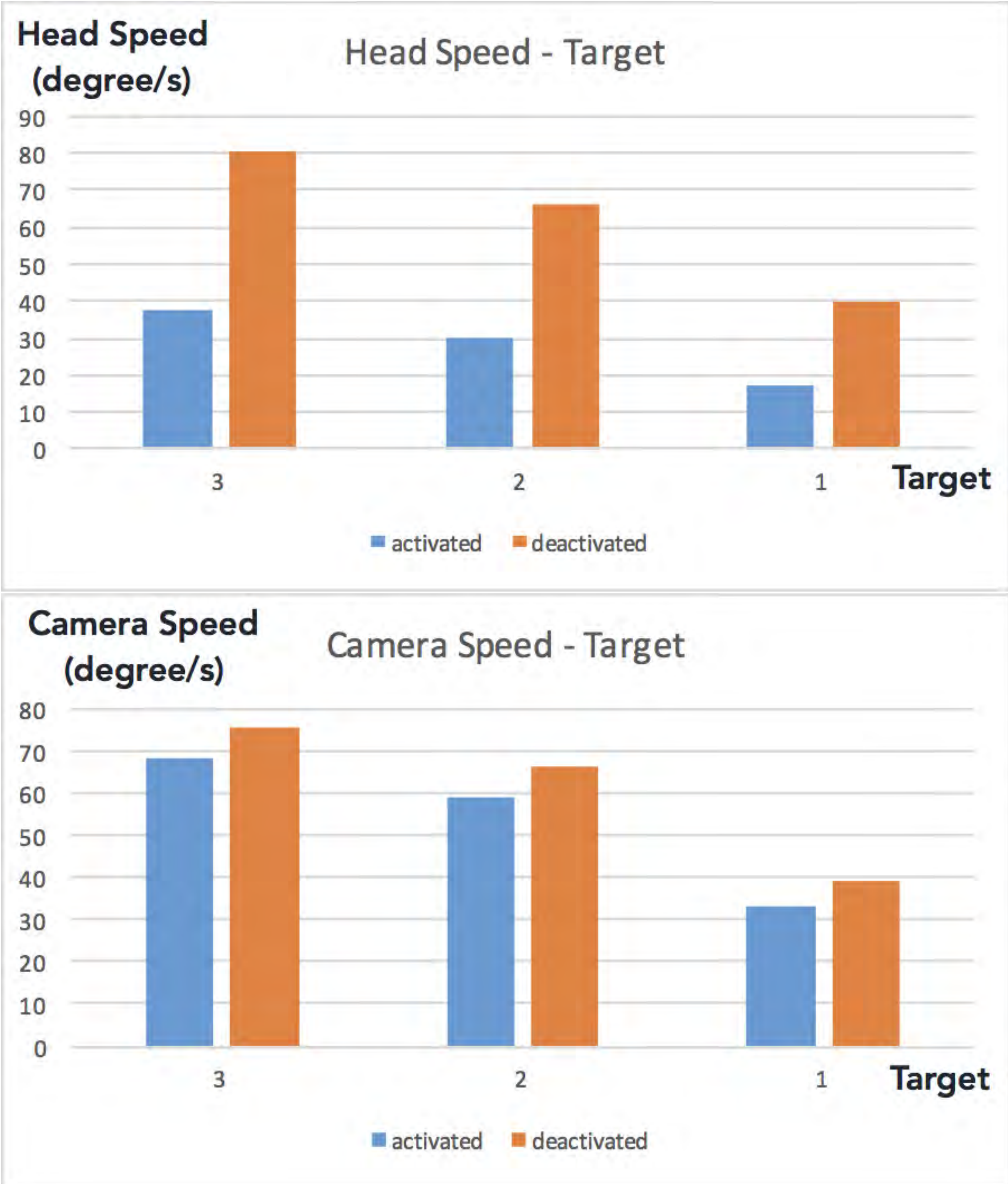


Figure 5.5: Head Speed and Camera Speed to Every Target in Front

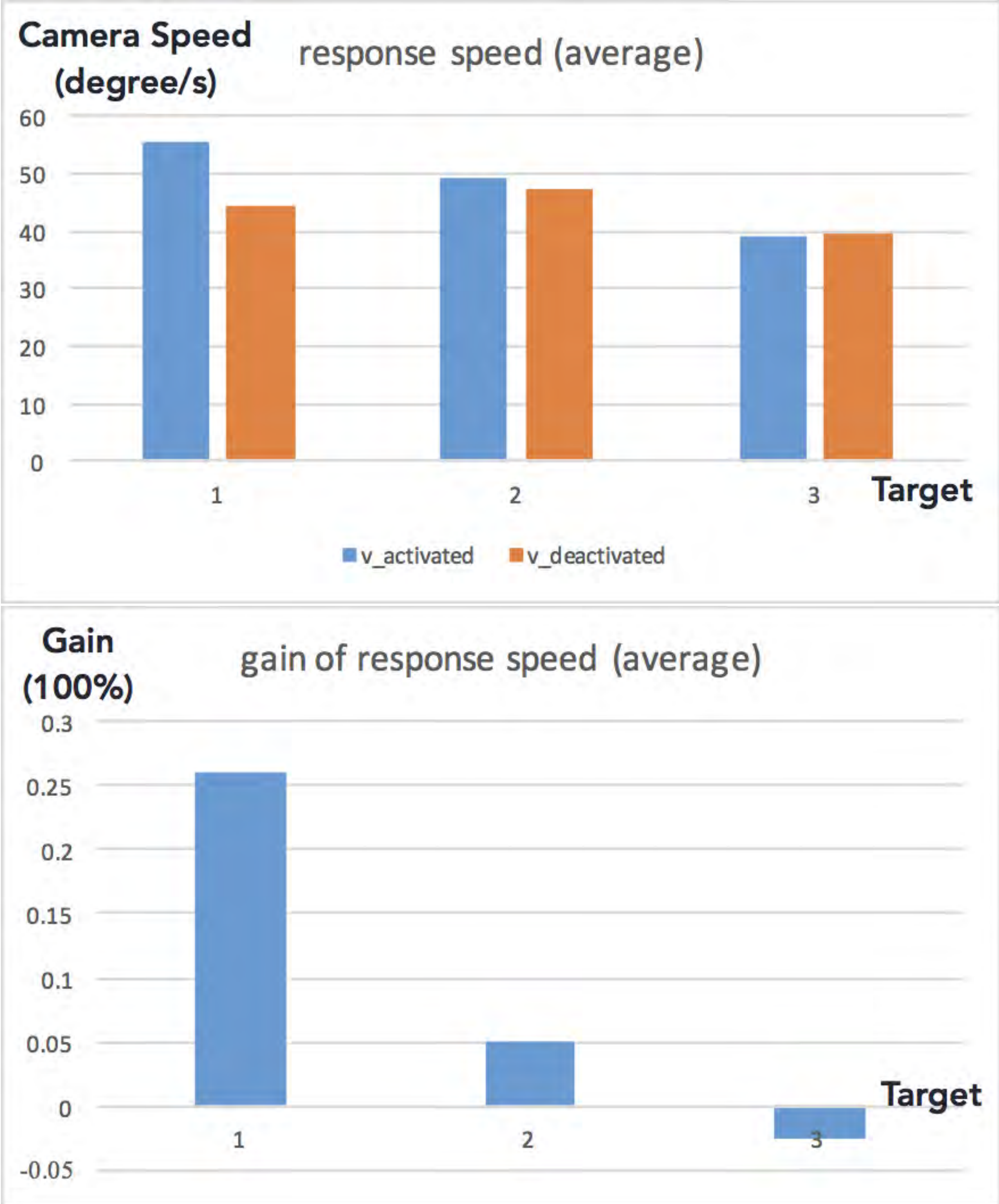


Figure 5.6: Camera Speed to Every Target in Back and the Gain

which the subject knows. The head speed with robot activated is slight than the half of the head speed with robot deactivated. Also, the head speed grows as the target angle increases. I find in the response experiment, for each target, the values of the responsible speed of camera under two conditions are almost same. However, the prototype seems to have a slightly negative influence on the response speed. However, as shown in Figure 5.6, the camera speed increase with the prototype, so the prototype works at the rear hemisphere, especially near the end of it.

It indicates that the robotic neck can reduce the action speed of the human neck. Therefore it can also reduce the output power of the neck significantly (>50%) only with a small increase (<10%) at the response time. As for the range of motion, the range experiments proved that it can be enlarge to twice. A interesting phenomenon is that the prototype does not increase the vision speed, but on the contrary does decrease the head speed (driven by neck). The response speed in back/rear targets increases. When the user need to rotate 150 degrees, it increases up to 30%; when the user need to rotate 130 degrees, it increases about 5%; when the user need to rotate 90 degrees, it decrease 2% at the targets. However, the response speed in front (where the user need to rotate 30, 60 and 90 degrees) decreases 10%, while neck workload decreases 50%.

I suggest the reason is that the visual perception is the dominant sense in the vision motion. The subject achieved very high degree of immersion in the task. The subject built his own spatial coordinate system based on the image (the visual information), to align and aim the target. The proprioception of neck was overridden, and the neck motion (motor) was secondary in this relationship, so human body tends to change the neck motor rather than visual sense. Sensory enhancement is more difficult to achieve than motor adjustment. A further reason may be the limitation of the visual information flux of the retina. Thus the eyes may not adapt to quicker motion perception. All in all, the result indicates that the conflict between head orientation (proprioceptive information) and the visual orientation (visual information) has a limited negative influence on the response time.

In conclusion, the range of vision or scan is enlarged by twice. As for the speed of response, the prototype has various positive effect at the target angels of 120° and 150° and slightly negative effect at the angles of 30°, 60° and 90°.

5.4.1 Health Concerns

In the case of my concept, the dissociation of the orientation of human head and human vision will definitely lead to disorientation. In terms of senses, the proprioceptive sense and the visual sense conflict and therefore cause sickness, that is, the motions are seen and felt (by other sensory organs), but do not corresponds. The common symptoms are general discomfort, headache, stomach awareness, nausea, vomiting, pallor, sweating, fatigue, drowsiness, disorientation, apathy, postural instability and retching. The sickness happens when exposure to a virtual reality environment, so it is called as *virtual reality sickness*, actually subset of motion sickness. By using the questionnaire, I collected the neck pain and virtual reality sickness feedback. I let the subject describe the degree of the fatigue/pain of his/her neck before and after the test respectively (scale from 0 to 9, 0 is no fatigue/pain at all, 9 is extremely severe fatigue/pain). There is a average increase of 0.67 (before: 1.78, after: 2.44), very good, means that nearly no negative effect to neck pain. Let the subject describe the degree of the dizziness/tiredness/unbalance before the and after test respectively (scale from 0 to 9, 0 is no dizziness at all, 9 is extremely severe dizziness) There is a average increase of 3.22 (before: 1.11, after: 4.33), relatively good, mild negative effect. The sickness usually occurred after a long time.

The latency and non-linear mapping also led to unexpected and unsteady difference of the vision and other sense and therefore cause sickness. As for the flexion-extesion motions, the sickness happens because of the flipped ground and sky relationship, i.e. when doing extension toward back more than 90°, the ground is at the top and the sky is at the bottom of the vision, which is strongly conflict with human common knowledge. I suggest that the proprioception provide the vision with an implicit prediction which is partly correct, i.e., same direction but different magnitude. Although proprioceptive information is not completely right, it still contributes to the relief of relative sickness.

Chapter 6
Conclusion

My overall goal was to seek modalities assisting the human to overcome the spatial limitation of human visual sense, for example, the lack of rear view. In other words, I aimed to enhance, extend, and alter the human abilities in terms of the spatial range of the vision.

In Chapter 1, I introduced the problem that humans were living under somatic constraints anywhere and anytime. Compared with the human, the animals possessed various superior abilities which were superhuman but not supernatural. Thus a biomimetic methodology could bring inspiration to the research. As the eyesight was of chief significance to the human, I decided to research on the issue of the eyesight. In Chapter 2, I examined the existing solutions and the related works to summarize the research tendency. Those projects could be sorted into two types: visual substitution and body augmentation. The visual substitution usually focused on the eye itself but isolated the vision from the rest of the body. While the body augmentation had various directions, and the vision always played an important role. In Chapter 3, I did research on the avian vision, which was excellent among animals, and found the owl uses an extremely flexible neck to compensate its relative narrow visual field so that it could get a panoramic vision only with neck motion. Therefore, the relationship between neck and vision was discussed and the idea was extended to the human. I finally proposed the concept of *Limitless Oculus*. It modified or replaced the visuomotor relationship of the human. I explained the mechanism and influence, and then analyzed the adaptation to the superhuman experience. In addition, altering the mechanism and mapping of the vision-motor coordination directly resulted in the revision of the body schema, which furthermore interacted with the cognitive progress. In Chapter 4, two prototypes were fabricated to achieve visual expansion. The successful implementation proved the efficiency of the concept. In the first prototype, a robotic neck substitution was used to modify the mapping between the position of vision and head. In the second prototype, I took advantage of the flexible upper limbs and let them serve as necks controlling the orientation of vision. It had a new vision-hand mechanism. In Chapter 5, the experiments were conducted to test the performance of the prototype and evaluate the feasibility of the concept. The result showed that the prototype could promote the response action, i.e. decrease the response time, especially in the rear hemisphere of the user. The motion speed of neck could be significantly reduced in the front hemisphere. It proved that the prototype was effective though still had some restriction to improve.

In the future, I plan to conduct better experiments to help improve the prototypes. Continuing working on those prototypes, I will design and develop compact and portable products and avoid the known defects. In reverse, the prototype can help explore the human further. New practical applications are expected to be figured out, such as a psychological experimental instrument, outdoor gear, monitor, etc. All in all, the animal-inspired methodology brings many ideas worth follow-up study, and I endeavor to research into more.

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