Hallucination Machine:
A Body Centric Model of Space Perception

by

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Abstract
In this thesis I present a novel approach to space perception. I provide a body-centric computational model, The Hallucination Machine, that integrates bodily knowledge with senses in a common modality which I call “the sphere of embodiment”.
Understanding the human experience of space is an important inquiry not only in the context of design and architecture, but in a broad range of scholarly disciplines where humans are the subject of study, whether as biological, social, or cognitive entities. My vision is that in order to create a knowledge of space shared through different disciplines and to develop tools and methods of scientific inquiry into the “human space,” we have to conceptualize a space perception model that connects sensory experience with the actions and bodily knowledge of the actor. Implications for such a model have been proposed by phenomenologists in the philosophical realm and carried into psychology through concepts of embodiment, situated cognition, and enaction. The Hallucination Machine illustrates the inner-spatial relations between different senses and movements, collected through sensory and inertial recording devices of the machine which experiences space situated by its human carrier. Through this inquiry, I argue that all senses, including proprioception and orientation, are collapsed in one medium, a sphere of embodiment, in which they form a multimodal spatial experience and communicate through it. I demonstrate the practical implications of this medium through a set of experiments.

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to Azize...
A—Would you mind if I sit on that chair?

B—Sure, go ahead... Can I ask you a question? How do you know that you have just sat on that chair?

A—What do you mean?

B—I mean, how can you be sure that particular chair you are sitting on now, is the one you saw?

A—How could it be possible otherwise? I saw this chair, walked towards it and sat on it.

B—But you don’t see the chair right now the same way you saw it a moment ago.

A—Yes. Because, I am sitting on it!

B—So, how can you be sure that what you feel is the same thing with the one you don’t see right now?

A—Well, I know where I am, I know where this chair is... Besides, I see things around me that suggest I am at a particular location in this room, which corresponds to the location that I saw this chair.

B—Ok. Let’s for a second assume that you hallucinated what you saw and what you touched. Would it still be the same chair?

A—Well, if both hallucinations told me the same thing, than that could be the case.

B—Even if you hallucinate that you are moving, walking, and sitting?

A—You mean, if everything I perceive is a hallucination?

B—Yes.

A—How can one hallucinate everything at the same time, see, hear, touch and make sense about something? Or if everything you hallucinate make sense together, how can you tell whether you hallucinate or perceive?

B—Exactly! That’s my question...
Introduction

Imagine that you are in a concert hall, say, Boston Symphony Hall, listening to the orchestra. After the concert, you return home, and with great excitement, you tell the story of your experience to your friend. What would you say? Most of us would probably start with something like “You must see it!” or “It was indescribable!” You would relate certain details, such as how it felt being there, how skillful the performers were, the beauty of the hall, and so on. However, somewhere deep inside, you would know that you could not fully describe your experience, not even close. Because not only did the orchestra play in harmony but all your senses worked in harmony to create that particular experience, from the softness of the seat underneath to the beat of the drums that filled the space. The space transformed in front of you, from the beginning to the end, yet it was all trapped inside your body.

Understanding the human experience of space is an important inquiry not only in the context of design and architecture, but in a broad range of scholarly disciplines where humans are the subject of study, whether as biological, social, or cognitive entities. My vision is that in order to create a knowledge of space shared through different disciplines and to develop tools and methods of scientific inquiry into the “human space,” we have to conceptualize a space perception model that connects sensory experience with actions and bodily knowledge of the actor. Implications for such a model have been proposed by phenomenologists in the philosophical realm and carried into psychology through concepts of embodiment, situated cognition, and enaction. Imagine a model
of space that explains how we interact with the environment through cultural and social means, reveals the spatial syntax unfolded by our linguistic practices, fosters the development of artificial perception applications, and, most importantly, guides us to improve the quality of our built environments. As a step towards this goal, I aim at developing a body-centric computational model of space perception, building upon an evolving theory, enactivism, and phenomenology of perception.

Throughout the course of this thesis, I evaluate different perspectives on space perception and present the criticisms of them. Then I move into the concept of bodycentricity and embodiment. Based on the discussion, I propose the Hallucination Machine, which provides a representational/computational model of space perception, based on a bodily perspective. The model illustrates the inner-spatial relations between different senses and movements, collected through sensory and inertial recording devices of the machine that experiences the space situated by its human carrier. Through this model, I argue that all senses, including proprioception and orientation, collapse in one medium that I call the Sphere of Embodiment, in which they form a multimodal spatial experience and communicate through it. I demonstrate the practical implications of this medium through a set of experiments.

The Hallucination Machine (HM) embraces three important challenges:

1. To what degree does the perceptual presence (something as perceived to be there having partial sensory signal or no signal at all, such as a person behind a fence, or the door behind a person) correspond to the actual perception in a particular modality?

2. How can we represent the spatiality in the totality of our senses and how can each sense contribute to the same spatiality?

3. How can we extrapolate what we sensed from our ex-
periential perspective onto the space around us?

HM demonstrates how the sphere of embodiment allows the extrapolation of a sensorimotor experience into a sensory modality. The model can determine the distances and action potentials through this process, which fosters the learning the spatiality from experience, dynamically extrapolating actions to different sensory modalities. Through this thesis, I provide a new perspective on space perception, stating that space is a modality of 'whereness' and independently exists from sensory modalities. I illustrate how different senses can communicate through a common medium, which I call the sphere of embodiment.
Background

Space Perception:
A Multidisciplinary Area of Inquiry

My thesis is about space; in particular the human experience of space. As it will unfold through these pages, it is about the one and only space: space as it is perceived, or space as is\(^1\). If I am to shed light on it and digest its meaning, then I have to start my inquiry posing the most straightforward question: “What is space?” If I am lucky, I might find a simple answer to this question and place it in an appropriate container amongst my other knowledge. Otherwise, I must continue: I must look at my own understanding of space and at what makes me realize such an existence. Step by step, I must discover the boundaries between me and space to reach to it. If I can not accomplish my goal, then I must live through it, use it and be a part of its existence.

In this section, I provide a guide to this inquiry. I show how our current understanding of space developed through a debate around mind, body and world. The section is divided into three parts philosophy, psychology & cognitive science, and anthropology & social sciences. Each part focuses on one aspect of the space that contributes to a bigger discussion.

In philosophy, the main question is “What is space?”. The philosophical debates on space provide a ground of discussion for many disciplines. The evolution of indirect realism (representationalism) and direct realism (naive
realism) in psychology has a direct precedent in early examples of philosophical literature. The duality of mind and world, space and body has been a longstanding phenomenon starting from philosophical works and reaching contemporary neuroscience and artificial intelligence. Therefore, it is important to look at the roots of this discussion in order to evaluate the current paradigms.

In psychology, the main question is, “How do we perceive the space?” Especially in the 20th century, studies on perception and cognition created a good amount of literature, motivated by the scholars searching for the source of knowledge and intelligence. While being mostly focused on vision, there have been many models developed in cognitive science and neuroscience that explain how humans perceive the surrounding space.

Finally, in anthropology and social sciences, the main question is, “How do we use the space?” One important contribution of ideas in this realm is that they provide a broader perspective on sensing and using space. While scholars of philosophy and psychology have a tendency to elevate vision over other senses, anthropology and social sciences question this priority to a great extent. In fact, moving, touching, and even smelling have a strong dominance in spatial experiences, and the primacy of one to another has been proven to be a result of cultural and social inheritance. How space is used, as discussed in social sciences, thus reveals the important characteristics of space perception.

Philosophy:
What is space?

In Western philosophy, the root of the debate around space, body, and mind goes back to the ancient Greek philosophers. The distinction between the world and the mind starts with Platonic idealism, where the world consists of physical objects, which are perceptible but not intelligible, and abstract objects, which are not percep-
tible but intelligible – as contained in the mind. This dualistic approach still preserves its position in modern cognitive science and artificial intelligence.

From Places to Body-Spaces

Interestingly, a key distinction between space and place, which still preserves its position as a theme in social sciences, was introduced during ancient times by Aristotle. In physics, Aristotle avoided discussing the concept of space in particular, which cannot be rationally described – an infinite existence enveloping everything. Instead, he introduced the concept of place, the specific location of things, and discussed its existence in the material world. For him, a place is a thing and has an existence, but this existence is different from the bodies (material objects). He made two arguments to prove his point:

1. A body can be replaced by another body to occupy the same place. If there were no such thing as a place independent from the body, then we would not be able to refer to it.

2. Places not only have locations relative to us, but also absolute locations in nature. 'Up' and 'down' refer to two distinct places and characteristically have distinct potencies. One carries fire and light, and other carries weight and things made of earth. The elements of nature tend to move towards their natural places.

And after proposing that place has an existence, Aristotle then raises the question: What type of existence does it have? He builds his argument on the following doctrines:

1. Place is what contains that of which it is the place.

2. Place is no part of the thing.

3. The immediate place of a thing is neither less nor greater than the thing.

4. Place can be left behind by the thing and is separable.
Up-down distinction is a repeating theme in many works. James Gibson argues that the up-down is the ultimate axis of reference. See psychology section for further discussion.


All place admits of the distinction of up and down, and each of the bodies is naturally carried to its appropriate place and rests there, and this makes the place either up or down.

Aristotle advocates an absolute space in which bodies and places are located. For him, space is a (giant) container, and places are contained in it about an arbitrary point, which is either the center of the earth or the whole universe. His appreciation of place is a key point in defining spatiality—even though he did not have the intention of doing so. The distinct character of place would exist separate from the things perceived at that place. In following chapters, I discuss how this separation is grounded in neural representations of space.

However, as a counter argument, Descartes introduces body-dependent space as part of his interconnected theme of space, body, and motion. Descartes asserted that space is the essence that defines material qualities in three-dimensions, saying, "the extension in length, breadth, and depth that constitutes the space occupied by a body is exactly the same as that which constitutes the body." In this sense, he rejected a space that exists separate from the body. In fact, space is a concept that refers to the bodily spatial extension:

We attribute a generic unity to the extension of the space, so that when the body which fills the space has been changed, the extension of the space itself is not considered to have been changed or transported but to remain one and the same; as long as it remains of the same size and shape and maintains the same situation among certain external bodies by means of which we specify that space.

Descartes' proposition of space forms the basis of body-mind dualism. As space manifested itself as a bodily extension, only material substance can exist in it. The soul, or mind has no extension in space, therefore, has no existence in the material world. Mind can reach the material space through sensory modalities such as seeing, touching, etc. Forming the grounds of representational realism, body-mind dualism is still defended by
many scholars especially in cognitive science and artificial intelligence. The mind, as a mental representation of the world, can be extracted and isolated from its space; and as primarily defended by symbolic AI, can be reconstructed in computational means.

The body-mind dualism proposed by Descartes resolves the dilemma between the immaterial and material worlds. However, there are many critiques of this view. First, when the mind and body separated as two independent entities, the mind is assumed to be interpreting the incoming data or "percept" and creating a causal bridge to the material world. However, creating a causal bridge implies that the immaterial mind positions itself in space without a spatial extension, thus become material. Moreover, as advocated by representationalism, if the mind is a "representation" of the "real," then it must contain its own representation, which also should have the entire representation of the real, and so on. Especially in the context of visual perception, these phenomena are highly celebrated by direct realists through what they call the "homunculus fallacy." If the mind creates an image of what the eye sees, then this image would also need to be seen by another mind—a little man sitting in the brain—which leads to an infinite regress. Therefore, the mind cannot be a separate entity from the body; they must exist as one.

The World of Ideals

Immanuel Kant provides another view, a rather monistic one, stating that there is no way of being sure about existence of the "real world" because all knowledge relies on perceptions. In the very center of his transcendental philosophy, Kant creates a distinction between the phenomenon that is sensed externally, and a priori knowledge, which cannot be derived through empirical observation. He states that experiences are organized or structured through a priori scheme as a feature of the mind. Thus, the experiences of all humans have common fea-

He further elaborates on this idea, and asserts that space is a scheme originating from the mind's nature. Thus, the mind should have certain categories that form the representations for external sensations. One can not have direct experience of the things, *noumena*, but rather the sense representations, *phenomena*:

Space is not something objective and real, nor a substance, nor an accident, nor a relation; instead, it is subjective and ideal, and originates from the mind's nature in accord with a stable law as a scheme, as it were, for coordinating everything sensed externally.⁸

Kantian idealism dictates that the whole reality be tied to the thinking subject, thus immaterial. Space is the representation of the mind, and the existence of all phenomena depends on this representation; otherwise, it ceases to exist.

...if I remove the thinking subject, the whole material world must at once vanish because it is nothing but a phenomenal appearance in the sensibility of ourselves as a subject, and a manner or species of representation.⁹

A Necessary Unity: Phenomenology

Starting from the early 20th century, a new school of thought emerged, characterized by Husserl and Heidegger.¹⁰ Phenomenologists argue that the world should
be taken as it is perceived (through phenomena) and as it is lived. As a critique against Kantian idealism, Heidegger rejects the idea that space is a priori; rather, he argues that it is unfolded through the “reigning of places of a region.” In phenomenology, the idea of being in the world is a prerequisite for any experience, and, in fact, is a fundamental part of it. Human beings are thrown onto earth and “dwelling” is the form of their being. Australian philosopher Jeff Malpas further elaborates on this idea, stating, "to be is to be in place."¹¹

As a philosophical school, phenomenology studies experiences from the first person point of view. French philosopher Maurice Merleau-Ponty, in particular, focuses on the embodied perception of space. In fact, the body plays a central role in his work, so much so that he basically asserts “I am my body”. From this point of view, there is no subject and object, but there is the intentional body, providing the openness to the world. His work on the phenomenology of perception investigates the role of the human body in experience. He states that every experience is subjective and embodied:

Insofar as, when I reflect on the essence of subjectivity, I find it bound up with that of the body and that of the world, this is because my existence as subjectivity [= consciousness] is merely one with my existence as a body and with the existence of the world, and because the subject that I am, when taken concretely, is inseparable from this body and this world.¹²

While having ideas parallel to those of Kant, he does not follow a Kantian epistemology. His approach emerges from a critical dialogue between epistemology and phenomenology. Regarding space, he takes a similar position with Kant and states that space is primordial, a necessity for perception. However, for him, perception is not a product of a thinking mind but rather it has a primacy over thought. We are not just in space but we are also a part of it. He states “it is not enough to think in order to see.”¹³:

The Real is a closely woven fabric. It does not await our judgment before incorporating the most surprising phenomena, or before re-

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jecting the most plausible fragments of our imagination. [Merleau-Ponty, 1962]

While he expresses the importance of ‘point of view,’ he does not accept that one must perceive one’s own body as a separate being in order to perceive the rest, relative to it. In fact, he argues that body and space are one; one cannot exist without the other.

Psychology and Cognitive Science:
How do we perceive space?

While space, body, and mind problem remains as an ontological debate in the philosophical realm, psychologists are more interested in perceptual processes in the brain. Therefore, debates in this world mostly focus on representation versus embodiment, and they are all grounded in the physiology of the human body. I should note, however, that mainstream psychology and cognitive science still assume a primacy of vision over other senses; their arguments are mainly built on this assumption and usually mention other senses as a point of proof.

An Affording Environment

The psychologist James J. Gibson’s work on visual perception is regarded as the most influential work of the 20th century in the area of perception. While it is worth mentioning other Gibsonian psychologists, his school of thought, namely Ecological Psychology, provides the basis for most of the contemporary ideas related to direct perception and embodiment. His influence also can be seen on social sciences studying human space.

James Gibson provides one of the most important arguments against the mental representations of space that are manifested in Descartes’ and Kant’s philosophies. He argues that we perceive the world through active engagement with our environment, which for him is the ecology.
of perception. Perception is a direct information pickup through the affordances presented by the environment in which the body is an active participant. The world presents structured information in the form of spatial and temporal differences in sensory signals, such as light or heat. This information then is picked up by the body, which is shaped by evolution towards understanding the affordances carried in the information:

To sum up, the characteristics of an environmental medium are that it affords respiration or breathing, it permits locomotion; it can be filled with illumination so as to permit vision; it allows detection of vibrations and detection of diffusing emanations; it is homogeneous; and finally, it has an absolute axis of reference, up and down. All these offerings of nature, these possibilities or opportunities, these affordances as I will call them, are invariant. They have been strikingly constant through the whole evolution of animal life.

The ambient array and theory of affordance provide a good insight into how the human body takes in the environmental information in the visual world. However, we should consider that space, as providing this information to our visual perception, should also provide structures for other senses. If there are such structures in the environment, they should all confirm each other to create a singular spatial perception. Therefore, I argue that, while structures in sensory information certainly guide the perception of space, this perception is not confined by them. Spatial perception can be enhanced or altered without any change in light or sound; senses can fill in missing information for each other, and non-veridical perceptions can occur in subjective experiences in the form of hallucinations and illusions. I conclude that the environment itself is subject to perception, and any structure within it is also inherently subjective.

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16 Yi-Fu Tuan and Michelle de Certeau argue that natural directions are extrapolation of bodily knowledge. See Anthropology section for detailed discussion.

17 Veridical perception refers to a perception that conveys the truth about the physical world. An illusion or hallucination assumed non-veridical.
Cells of Space:
Place Cells, Grid Cells, Head Direction Cells and Boundary Cells

Cognitive science provides scientific evidence on how spatial information is processed in the brain. Existing literature shows that the human brain efficiently learns and uses spatial patterns. In particular, distance understanding, location, and orientation in space have been revealed to be a part of our spatial understanding. Studies on neural representations indicate a sense-independent space perception.

With the latest technological developments in neuroscience and cognitive science, there is increasing interest in understanding spatial representations in the brain. To date, several cell groups in different parts in the brain have been discovered that are related to spatial perception. Each of them has a specialized task to recognize the environment around the body, locate and orient itself relative to it. Current studies on hippocampal activities on rats have revealed characteristics of spatial mapping and navigation, determined by the triggering patterns in place-cells that show an action potential in a unique part of the environment. Recognition of a “place” is an assumed part of this activity. Places cells have unique firing fields, clustered around the corresponding parts of the environment. A place cell activates and tags the ‘place’ when a rat enters a novel part of the environment. Anytime the rat enters the same part; the same cell is triggered allowing it to recognize the place. Moreover, in a recent study by Wilson it has been revealed that, rats are replaying place cell patterns that are triggered through their journey, while they are sleeping. This is a strong evidence that learning the places and paths has a direct correspondence to unique properties of spaces.

Place-cells also counter play with head-direction cells that show an action potential through the change in the head orientation and boundary cells, which are sensitive to environmental boundaries in certain directions and


distances. Place cells and head-direction cells determine a unique location and orientation in the environment, and boundary cells allow the determination of geometrical characteristics of the environment. An interesting behavior of head direction cells is that the firing of these neurons occurs 95ms before the actual action in the head direction; in other words, head direction cells can predict the head direction before it is rotated.

While place cells tag particular “places,” grid cells take a different role in spatial representation in the brain. Grid cells have a grid-like firing pattern in the environment. They are assumed to be a part of path integration and planning of animals. The special grid-like representation forms what is almost a local mental map in the brain. It means that, if we record each trigger in neurons and draw a point to the location of the rat in environment, from a plan view, the result will be a grid-like shape consisting of the points clustered around the intersections of the grid lines. The size of the grids is related to speed and proportionally increases with it.

The Two Streams Hypothesis

Another indication of sense-independent space perception is the two streams hypothesis proposed by neuroscientists David Milner and Melvyn A. Goodale. According to this hypothesis, there are two distinct visual systems in the human body. When visual information leaves the occipital lobe, it follows two paths; one characterized as the “what” path (ventral system) and the other one characterized as the “where” path (dorsal system). Whereas the ventral system’s responsibility is object recognition, the dorsal system’s work is to locate the object. In other words, object recognition is a different perception than locating an object.

Cognitive studies provide strong evidence that there is a representation of space in the brain that integrates spatial cues from the sensory data. When the subject is human, we must also consider characteristics of the

Figure 3: Grid Cells represent space in brain in a grid-like form

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21 Occipital lobe is the main visual processing center in the brain.
‘living space’ as it involves skilled practices and social interactions, which are also integral parts of human experience of space. In the next section, I will look into ideas in anthropology and social sciences.

Anthropology and Social Sciences:
Space in Action

I have introduced key ideas on space and how it is perceived, as discussed by philosophers and psychologists. However, I should now look into another important fact that space is a part of human activities and daily practices, which vary amongst cultures and geographical locations. Incorporating these factors will broaden our perspective on human experience of space. Therefore, in this section, I will look into anthropology and social sciences to uncover the key components of space as it is lived.

Space As an Extrapolation of Body

Experience of space varies between groups of people based on many criteria, such as where they live, their means of survival, cultural inheritance, or environmental conditions. Anthropologists seek evidence of the effects of these criteria on spatial experiences by looking at people’s daily activities, the physical artifacts they create, or spatial expressions in their language. For example, a study by John Berry\(^{22}\) comparing the spatial skills of two groups, the Temne of Sierra Leone and the Eskimo of Arctic Canada, reveals the effect of geographical and environmental conditions on perception. According to this study, Eskimos are far richer in spatial skills and possess a large vocabulary of spatial–geometric expressions. Social geographer Yi-Fu Tuan discusses that the main reason for the richness of Eskimo spatial perception is their bleak environment.\(^{23}\) Visual characteristics of the environment are very homogeneous, a uniform gray-brown in summer and a monotone white in winter.

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\(^{23}\) Yi-Fu Tuan. *Space and Place: The Perspective of Experience*. Univ Of Minnesota Press, 2001
When fog or blizzard appears, the differences between land, water, and sky disappear, removing all visual cues of spatial characteristics. In order to survive in this environment, Eskimos developed multisensory strategies and refined their perceptual skills. They started to recognize types of snow, ice cracks, the quality of fresh air, and the wind direction. We can say that space, as perceived by Eskimos, is not a visual concept that carries structured information about environment, but more of a tactile concept that unfolds through active movements. Yi-Fu Tuan explains that people are able to discriminate between things and places through intentional movements and perceptions, both providing visual and haptic information. At this point, he emphasizes the importance of a person's body in the way he or she perceives space. According to Yi-Fu Tuan, the body does not simply occupy space, but it "commands and orders it through intention." To put it simply, "body is 'lived body' and space is humanly construed space." The structure of the body dictates the means of engagement with space; he asserts:

Upright, man is ready to act. Space opens out before him and is immediately differentiable into front-back and right-left axes in conformity with the structure of his body. Vertical-horizontal, top-bottom, front-back and right-left are positions and coordinates of the body that are extrapolated onto space.²⁴

Michel De Certeau offers a method of inquiry in which he examines space situated by everyday activities. Transitioning from frozen geometrical descriptions, which he describes as places, to lived individual spaces, he asserts "space is a practiced place". His argument revolves around these two types of spaces. For him, the one adopted by scientists which offers dry geometrical representations isolated from the experience, can not possibly describe how humans experience space. Space can only exists when one applies spatial strategies, move through it, and temporalize it:


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A space exists when one takes into consideration vectors of direction, velocities, and time variables. Thus space is composed of intersections of mobile elements...Space occurs as the effect produced by the operations that orient it, situate it, temporalize it,
and make it function in a polyvalent unity of conflictual programs or contractual proximities.25

The idea of practice is a recurring theme in the social sciences. The anthropologist Tim Ingold proposes that the perception of the environment is a “skilled practice”. Integrating ideas from ecological psychology and phenomenology, he argues that an action is not a mechanical behavior, but a result of a continuous “tuning” to the environment. Perception and action are tied together in a loop mediated by the environment.26 He also questions the primacy of vision:

It is almost truism to say that we perceive not with eyes, the ears or the surface of the skin, but with the whole body. Nevertheless, ever since Plato and Aristotle, the western tradition has continently ranked the senses of vision and hearing over the contact sense of touch.27

Instead, he proposes a grounded perception approach. He argues that we have a continuous interaction with our environment through touch, through our feet; we balance ourselves through our ears, which are essential for us to walk; and finally we are mobile. Therefore, the assumption that we perceive things from one vantage point is misleading; instead, we have paths of observations through “a continuous itinerary of movements.”28

A Body Centric Approach

NOW THAT I have expressed the importance of embodiment—as I can put these scholars works under this term—we can look at how this embodiment occurs in our physical bodies. A relatively new approach, enactivism, proposes a phenomenologically inspired theory. According to enactivism, all perception is an active exploration and grounded in sensori-motor capacities of perceivers.

In this section, I will focus on the ideas around the body-centric approach. I will go over the themes of body-centricity and sensing the world around an active body.
Enactivism, comprising most of the content in this section, will provide the framework, while I discuss related approaches as well.

**Embodied Space and Body-Centricity**

As I have discussed in the previous chapter, understanding the relation between the world, body and mind has been a central theme of inquiry for many scholars in philosophy, psychology and anthropology.

The embodied mind thesis states that the nature of cognition is shaped and guided by the form of the human body.\(^{29}\) Being in the world, which is a theme introduced by the phenomenologists, is the main fact behind the dynamic process of perception and action. Perception, is not independent from the active behavior of the perceiver. When it comes to space perception, this theory provides many proofs on how the perception of space determined by the state of the perceivers. For example, studies show that people tend to take a perspective of a person in a photograph, rather than their own. The key aspect behind this theory is the ability to transfer sensori-motor knowledge to other senses. In other words, sensory information is grounded in the active motions of the perceiver. It implies that the nature of perception is solely defined by the physiology of the body and bound to it. As Alva Noe puts it “To see as we do, then you must have a sensory organ and a body like ours”[Noe, 2005]

Enactivism, a sympathetic approach to embodied cognition, can be seen as a heavily action-centric view. As it is derived from the word “enaction” it refers to “the manner in which a subject of perception creatively matches its actions to the requirements of its situation”. It grounds the the existence of the being to a mutual interaction between the sensori-motor capacities and the environment:

our sense of the presence to vision of what is in fact beyond our reach. It is this mastery that is the basis of perceptual content.\footnote{Alva Noe. Action in Perception. The MIT Press, 2005}

In space perception, the active movement theory of Henry Poincare explains how spatial perception is possible without having a presumed structure for space:

To localize an object simply means to represent to oneself the movements that would be necessary to reach it. It is not a question of representing the movements themselves in space, but solely of representing to oneself the muscular sensations which accompany these movements and which do not presuppose the existence of space.\footnote{Henri Poincare. Science and Hypothesis. Dover, 1902}

**Perceived Presence**

The enactive approach emphasizes the importance of amodal perception—or perceived presence of objects. Most of the time, we perceive an object's back sides, or half occluded parts, as wholes. We don't assume, for example, that a cube has three sides just because we can only see three sides at a time. In fact, according to Noe, our bodies create sensori-motor expectations for such things, just because we have experiences of ourselves moving around objects and objects moving around us. He suggests that the perceived presence is a virtual one.

**Sensors of Human Body**

In this section I will provide a brief overview of human sensory apparatus, including body structure, proprioception (sense of one's own body and movement) and exteroception (external senses). While each of these apparatuses comprise a great amount of detail, I will only discuss the parts directly related to space perception.

**Proprioception**

Proprioception refers to the sense of one's own body. This highly complex form of perception is the main actor in determining the common structure of the body, relative positions of body parts, movement of body parts and the force employed in movement. It is generated by the nerves on joints and muscles attached to bones.\footnote{Mosby's Medical, Nursing and Allied Health Dictionary, volume Fourth Edition. Elsevier/Mosby, 1994}
Together with balance information obtained from vestibular system, proprioception allows a precise understanding of body posture and orientation. Patterns of movement are grounded in body's structure, which manifest themselves as muscle memories eventually allow a body to learn and master physical activities. Proprioception is an integral component of sensorimotor integration, allowing a person to distinguish changes in environment due to his or her own movement.33

Although human touch is considered as a part of extrospection, touch also plays an essential role in proprioception. Whereas fine touch allows one to localize an object in space, human skin registers the touch sense anytime a body part moves.

**Extroception**

The *human visual system* is extremely complex and involves many important tasks such as detecting low level features such as edges, brightness or color; determining depth, recognizing known objects, faces and environmental features. Space perception is informed by most of these processes, but stereopsis is assumed to be the main factor in perceiving objects in 3D. Because the eyes are located in different positions and oriented towards relatively the same direction, two slightly shifted images are formed on retinas. Based on the level of difference, objects are perceived at a certain distance. This phenomenon occurs at a small region around the fixation point. Out of this region objects tends to look double. The term ‘horopter’ refers to a hypothetical curved surface which marks an area around the head where single vision occurs for a fixation point.

Humans are capable of recognizing a variety of sounds, understanding speech, filtering noise and echo, localizing and attending to a sound source –precisely to a direction and distance. Similar to vision, a sound source could be localized to an azimuth, an elevation and distance based on intensity, spectral and timing differences. Velocity of the source can also be determined if it is moving. The ability to localize sounds in 3D is called binaural hearing.

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The special form of the human head and ears generates minute differences in the sound waves arriving at both ears. These differences are mainly grouped under ILD's (Interaural Level Differences), ITD's (Interaural Time Differences). ILD refers to the sound level difference caused by the head shadowing. For example, if a sound is coming from the right side, the level of sound is higher because the head shadows some of the sound waves going to the left ear. Similarly, ITD refers to the time difference between the sound waves arriving to ears. Based on the location of the sound source, sound waves arrives at one of the ears earlier, which creates a phase delay in the signals.

Summary

I have presented evolution of a body-centric approach to space perception. Starting from the early philosophical literature to contemporary neuroscience I have seek through theories and models regarding space, body and mind.

In such inquiry it is important to adopt a multidisciplinary framework because each discipline has a different focus and perspective on space and perception. Contemporary approaches such as embodied mind, situated cognition or more recently enactivism provide such multidisciplinary framework bridging philosophy, psychology, cognitive science and artificial intelligence. These approaches emphasize the importance of the active behavior of human body in the way how he or she perceives space. Perception is not a passive information processing nor creation of mental representations of the world. Instead, it is an ongoing engagement with environment, a continuous dialog between actions and senses. It is neither dictated by environment nor the mind. It is the unity of them.

As I have demonstrated through studies in anthropology and social sciences, the active behavior of humans is not limited to mechanical interactions but also involves geographical conditions and cultural inheritance.
Space is not a frozen geometrical description but it is revealed through daily practices and through the totality of senses.

In the next chapter I present my approach on space perception, discussing possibilities of representing the human experience of space.
Hallucination Machine

Overview

In this chapter I present a novel approach to space perception, building upon the existing literature that I discussed in previous chapter. The chapter is divided into three sections.

In the first section, I discuss the components of a body-centric model. Reckoning among the discussions in the literature, I conclude that space should have its own modality independent from the senses. I call this newly introduced modality as the sphere of embodiment, which comprises a spectrum of directions and distances. This idea allows explaining the contingencies between different sensory modalities and sensorimotor knowledge and provides a framework for the development of a computational model of space perception.

In the second section I discuss the development of hardware used in data collection and experiments. In order to collect data from individual experiences of space I have incorporated different types of sensors such as orientation trackers, touch sensors, binaural microphones and cameras into a wearable tool. This tool eventually allowed me to reconstruct a body model in computational realm and correlate it with the sensory input.

Finally, I discuss the software in which I have implemented the HM model and conducted experiments through it. The process involves the reconstruction of the body structure and calculating the spatial positions of the recorded sensory data. I discuss the details of the experiments in the following chapter.
The Model

Components of a Body Centric Model

I HAVE presented various concepts in the context of body-centric space. In this chapter, I introduce my model, Hallucination Machine, which integrates these concepts into a computational model of space perception. As a summary, the following components should be taken into account to develop such a model:

1. **Structure of Body:** As expressed by many scholars, the structure of the human body has a direct effect on perception. In order to extrapolate an embodied knowledge onto space, one should have an understanding of inner relations of his or her body parts. More importantly, certain actions such as walking or sitting require an understanding of the dynamic interaction between different body parts.

2. **Senses:** The model should clearly present a way for each sense to incorporate individual features such as color, as well as global features such as where a particular color is seen.

3. **Actions:** The model should provide a structure for collecting and discriminating different actions based on individual senses and body structure.

4. **Perceptual Presence:** Another key feature is to speculate over space where there is only a partial signal, or no signal exists in a particular sensory modality. As I have discussed before, people incorporate the sense of presence into perception.

5. **Location:** The human brain seems to be able to represent a location for the body through grid cells. Although the underlying structure behind this process is still not clear, the model should represent a location in any environment.

6. **Place:** Finally, space perception relies on understanding and discriminating the surrounding environment.
This phenomenon also has a corresponding representation in the brain, in place cells. The model must provide a structure for recognizing places.

**The Sphere of Embodiment**

Until now, I have presented a survey of ideas that explain space and spatial experience. It appears that solidifying a space perception model depends on how one approaches the existence of space; an ideal schema, a manifestation of sensori-motor knowledge, a representation of the real and so on. Having said that, enactivism and phenomenology emphasize the importance of embodiment, action and totality of the perception.

Here, I introduce the term sphere of embodiment in order to explain the phenomenological existence of space, within and in-between the sensory modalities. As the enactive approach grounds the perception of space to sensori-motor knowledge, I argue that such a grounding requires a common medium of locations. In other words, the enactive approach explains that visual perception is informed by action, but it does not explain how this information goes through different modalities. I understand the depth of a room because I walked inside, but how my body is aware of where it walked by the means of seeing and touching at the same time? How do I bridge where I see and where I touch?

At this point, I go back to Kant’s argument on space. Space is not empirical, he asserts, rather an ideal scheme that originated from the mind’s nature to organize senses. It cannot be represented, it is the source of representation. While we do not need to agree that space is a priori or ideal, without having 'a space' for senses, it is impossible to create a contiguence between them. In Merleau-Ponty’s words 'space is primordial', it is a necessity for perception.

When we accept that space exists apart from the sensory modalities, then the question is where it exists. The sphere of embodiment refers to this phenomenon and explains it in the following way:

If I have a certain sensation of a 'where' through one
sense, say, vision, then that 'where' concurrently exists for all modalities, even without having a sensory input. I can attend to it with my ear, I can listen to it, and the moment it makes a sound, I know that the sound comes from the same 'where'. It has a perceptual presence. 'Where-ness' is a phenomenological matter, similar to a color. Thus it must have its own modality. A modality, that allows me to embody locations—directions and distances. All the 'where's, like different signals of sound or colors, are contained in one single spectrum, as a matter of fact, which is a sphere.

The sphere of embodiment provides a representational medium for space as a modality. Now that I have representation independent from sensory modalities, I can model the relation between the actions and senses. In other words, it provides a solution for two important problems:

1. Modeling a sensori-motor pattern in space

2. Localization of a sensory input
Sensori-Motor Patterns

As I have argued that actions provide the dynamic interaction between different senses, I should now look into the components of an action. An action is simply a sensori-motor pattern, consist of two distinct parts: a sense of motion localized by a certain body part and the sense of touch. Whereas the sense of motion communicates how a particular body part moves, the sense of touch provides a feedback from a particular location in the environment. An action would basically consist of only one pair of motion-touch (grasping an object), it would also comprise a series of them (playing a guitar). While in general this point of view explains many actions, I should also note that the other attentive actions such as looking or listening are not different from the ones involving the sense of touch. Again, “seeing is like touching”34. Visual attention requires a certain sensori-motor activity on eyes to aim at a certain region in space; similarly most times we adjust our head direction to attend a certain sound. However, instead of getting a touch response to our movements, we get either a visual response or an aural response. Therefore, while the sensory modalities would differ from action to action, they always obey the rule of movement-response loop.

Let’s look at a basic action represented in the sphere of embodiment, a walking action. (The representation is in a two dimensional circle for simplicity):

In this example, a walking action is examined in three layers. The first layer shows what changes in feet direction. As one walks, feet direction change between slightly back, center, and slightly front. While these movements go on, the touch layer communicates the content of the feet direction. It shows whether the foot is touching the ground or not. (In the representation, the touch layer is displayed only if the foot is touching the ground). It shows that there is a touch response if the feet are moving backwards. But when it starts moving forwards there is no touch response - as we lift our foot to take another step. Finally, the body movement layer shows how the body moves in response to the first two layers. As we

walk in a direction, there is a sense of movement on the body towards the same direction. The combination of these three layers represents a simple walking action. Of course, in a simple walking action, there are other body parts effected such as hands. However, in order to simplify this example I use the most related parts in the representation.

Figure 5: Walking action examined in spatial layers

Multimodal Representations Explained

REPRESENTING an action through the sphere of embodiment demonstrates the relation between a certain movement and sensory feedback accompanying that movement. I showed that an action is either a simple movement-response couple or a complex set of them. Seeing and hearing are also actions and manifest themselves in the same way. Now, I show how this representation may bridge sensori-motor patterns to various senses through an action.

When a person takes a particular action, returning to the walking example, this action involves not only the movement and immediate sensory feedback, but also particular changes that occur in other senses. When a person walks, the visual field changes in a particular way,
creating the illusion that objects are moving towards the person. Sound in the environment also changes in a similar way, getting closer of passing by. But from the person’s point of view, everything looks steady, because of the expectancy of that particular change generated by the walking action. But multimodal experience is not limited to that. When we walk, we usually don’t look at our feet but more towards the horizon. Nevertheless, we have a certain perception about where our feet are about to step, whether there will be an obstacle, or even the texture of the carpet. As I have discussed in the previous chapter, things have perceptual presence even if we don’t see them.

I argue that such perceptual presence occurs because different pairs of movement-response couples are bound to each other in actions. We do not perceive the world through a sensory input, but through a multimodal engagement. The expected change in visual perception is due to the previous experiences of walking. What we see or what we expect to see is about what we ought to do. Consider a sequence of drinking action is represented in different layers (Figure 6).

At this time there is not one pair of movement-response couple but there are three of them: hand movement-touch, head movement-vision, hand movement-touch (lips). The person takes the bottle from the table while looking at it at the same time and lifts it towards his mouth. When the bottle reaches to his mouth, his head starts to rotate upwards, the bottle touches his mouth, and finally his head rotates upwards to a point so that his eyes loose contact with the bottle. Afterwards he puts the bottle on the table performing the actions in reverse. (Of course, his introception takes part in this action when the liquid fills his mouth and goes down to his stomach. In the scope of this thesis I do not include this type of perceptions.)

The significance of multimodality is revealed in this action. Through the development of the action, we see that the directions of touch and vision, localized by the hands and head, follow each other. They create a similar trajectory. Even though the eyes loose contact with the
bottle, the person does not feel an interruption. One action fills the missing part for the other action. In other words, hands-touching-the-bottle fills the gap in eyes-looking-to-bottle.

Figure 6: Multimodal patterns in actions

This contingency is much clearer when we represent the whole action in one spatio-temporal representation. Here, the each time frame is represented as a shell of a sphere of which radius increases proportionally to time.

We see that the similarity of patterns of motion of touch and vision allowed a coupling between them. Although the image of the bottle goes missing in some part of the action, the feeling of bottle fills this gap. It does not mean that the missing image is regenerated in a literal sense. It causes a perceptual presence to occur. In a way, the spatiality of the touch sense leaks into vision. One can sense the existence of the bottle in visual world without seeing it.
Figure 7: Sensory Contingency: The spatial pattern of touching the bottle and seeing the bottle correlates. When such contingency is strong, one can fill the missing parts of the other.

Figure 8: Left: A sequence of movement, represented in the sphere of embodiment, seen from above. Right: A Grid Representation of the movement.
Location is taken into account

A fundamental implication of the body-centric space perception is that space is not fixed in a global frame of reference but rather offered by the body as a response to the environment. If I may borrow a phrase from Futurama, "the ship does not move, engines move the whole universe around it". From the bodily perspective, we are always at the same location - if location has a meaning in our body-centric space. Nevertheless, we perceive ourselves and things around us moving relative to our environment and more importantly we can keep track of our motion. That's what we may call as location - an embodiment of the patterns of motion.

In this final part of the model, I explain how it would be possible to represent our location as a function of motion. Let's first look at a body movement of a walking person. In figure 8, I represent a sequence of movements in the sphere of embodiment and demonstrate the resulting trajectory in a grid. This representation shows us how we moved so far in space and we can repeat the same action to move the same way. However, it does not immediately tell us how can we go back. We need to reverse each vector of motion and place them in a reverse
temporal order.

I argue that this two-layered process is unnecessary. It assumes a global frame of reference, in which the start and end locations are represented with regards to each other. Representing our location relative to the start position does not provide any advantage to us. However, if our location contains the means of going back, it would provide aid for orienting ourselves in space. Therefore, I suggest that the location is an action potential generated as a reaction to body movement. Going forward generates an action potential of going backwards. In this representation, the body is always in the center. We can say that the location is a body-centric representation of how to go back.

In the sphere of embodiment, representing location is no different than representing an action. However, the patterns of movements should be represented in a reverse temporal order. The last step we take should be the first step in the location representation. This representation always keeps track of previous locations. Assume that the person goes back to the start location. This time the representation of location will communicate how to go back the previous location. This action potential can be integrated with other sensory cues such as vision.

Hardware

In order to test how human experiential perspective and actions correlate in the sphere of embodiment, we need to develop necessary tools and methods to record it. Thus, I have developed a wearable device which comprises a series of orientation trackers, touch sensors, binocular cameras, an eye tracker and binaural microphones. Participants were asked to wear the device and perform tasks while they were being recorded.

Orientation Trackers

Detecting and representing the orientation of rigid bodies have been one of the most dedicated problems for
engines. It is a fundamental problem in the context of unmanned vehicles, navigation systems, rescue robots, computer graphics and entertainment. With advancements in sensor technologies, it has become very cheap to develop such systems through digital accelerometers, gyros and magnetometers. In the context of this thesis, orientation trackers are used to detect the orientation of various body parts including thighs, legs, arms, torso and the head. While the trackers on arms and legs give 2-axis angle information, the one on the torso gives the heading (a compass) and the one in the head gives 360 degrees orientation (pitch, yaw, roll).

In order to create a wearable device carrying the orientation trackers, necessary mounts are designed and 3D printed. There are two distinct parts: the head piece and the body piece. Headpiece is designed to be flexible to fit different head morphologies. A 9-DOF motion tracker is mounted on the headpiece for obtaining head orientation. In addition to the orientation trackers, the headpiece involves mounts for a pair of cameras and eye tracker. The body piece consists of 3D printed mounts and flexible sleeves that are worn to legs and arms.
**Hardware Wiring**

All sensors are connected to an Arduino Uno through I2C protocol. Although I2C bus allows multiple sensors to be connected to the device, sensors with the same ID’s cannot be connected. I2C recognizes each distinct sensor through their ID’s and the same family of sensors shares the same ID. In order to overcome this problem, a pair of analog multiplexers is connected to both SCL and SDA pins on Arduino. By pairing different family of sensors on same line, I created 4 channels through multiplexers. Eventually, when the device starts to communicate to the sensors, it switches between 4 channels and reads corresponding values from the sensors.

![Hardware Wiring Diagram](image)

**Cameras and Eye Tracker**

William Patera and Moritz Kassner, developed an eye tracker called Pupil and discussed how it is used in reconstruction of visual attention.\(^{35}\) (Patera and Kassner). In this thesis, I implement their software to track the gaze position from the camera. The procedure is detecting the pupil from the camera aimed at the eye and calculating the normal vector of the pupil disk. This information itself is enough for modeling where the person looks. But in order to find the corresponding image from the camera heading towards the front, both cameras are calibrated as described in their work.

Binaural Microphones

While stereo microphones can record 3D sound, they are not suitable for recording the sounds as the humans hear. The special technique for recording the sound as human hears is called binaural recording. As I discussed in previous chapter, the sound waves arrive two ears in different forms because of ILD’s (Interaural level differences), ITD’s (Interaural Time Differences) and HRTF (Head Related Transfer Functions). In order to take these effects in account, one should record the sound through replicating the human head physiology or directly through a human ear. In professional settings, this type of recording is achieved through the first type, making a dummy human head and placing high fidelity microphones inside the ears. In scope of this thesis, I have used special microphones that can be worn like usual headphones. Although not as perfect as the professional settings, empirical observations showed a satisfactory result in generating 3D sound in space.

Software

The Hallucination Machine software contains two distinct processes. The first process handles the incoming data streams, creates a fused stream with a time stamp and broadcasts that stream. Because the orientation sensors and eye tracker send data from different
channels I developed a bridge for merging and transforming incoming data. Once all data is merged into one labeled stream, this data is transmitted to calibration and recording module, in which a body structure is visualized. Because placements and orientations of sensors slightly differ among recording sessions, a calibration routine is applied in this module. Finally the data is saved into a Comma Separated Value (CSV) file when requested.

The second process handles the visualization of the sphere of embodiment and related analysis and modeling processes. This process reads a CSV file containing all the data from a recording session, applies necessary transformations and visualize the data. Based on the intention it can visualize only a range of time frame, specified body part, camera image or eye position.

Reading the Data Stream
There are two separate data streams in the system. Arduino sends the sensor data to serial port. If we were to record only this data, then we would simply listen to corresponding serial port and use it. However, I must synchronize this data to the camera image and eye tracker. Therefore, these two data streams should be merged and time stamped. The camera image is accessed through USB and eye positions are broadcasted through Transmission Control Protocol (TCP). Fortunately, this data is already labeled and time stamped.
For merging two streams as well as integrating the camera image, I have developed a bridge module. The bridge module listens to both Serial Port and TCP and creates a labeled stream to be transmitted to calibration module. I used PySerial and ZMQ Socket modules in Python to develop the bridge.

After the streams are merged and labeled, Python bridge broadcasts the data to an Open Sound Control (OSC) server at the calibration module written in Processing. There are two tasks to be handled in this phase:

1. The module reads the incoming data and parses it into appropriate data types. Incoming data consists of a series of raw sensor values. Each orientation sensor registers magnitudes in three axis.

```java
void oscEvent(OscMessage theOscMessage) {
    OscMessage=(String)theOscMessage.arguments()[0];
    String[] OSCtemp=splitTokens(OSCmessage,"(,)");
    if(OSCtemp.length==2)
        OSCvalues=OSCtemp.clone();
        println(OSCvalues);
}

//
void getValues(){
    RUPX=float(columns[0]);
    RUPY=float(columns[1]);
    RUPZ=float(columns[2]);
    ..
    ..
}
```

2. After parsing the incoming data stream, the module calculates the orientation vector from the raw sensor values and converts them to rotation values in radians.

```java
float roll = -r1+(atan2(-fYg1, fZg1)*180.0)/PI-calibration[0];
float pitch = -p1+(atan2(fXg1, sqrt(fYg1*fYg1 + fZg1*fZg1))*180.0)/PI-calibration[1];
float roll2 = -r4+(atan2(-fYg2, fZg2)*180.0)/PI-calibration[2];
float pitch2 = -p4+(atan2(fXg2, sqrt(fYg2*fYg2 + fZg2*fZg2))*180.0)/PI-calibration[3];
```
float roll3 = -r2+(atan2(-fYg3,
fZg3)*180.0)/PI-calibration[4];
float pitch3 = -p2+(atan2(fXg3, sqrt(fYg2*fYg3+
fZg3*fZg3)))*180.0)/PI-calibration[5];

Creating the Body

A digital body structure serves in two ways. First, it provides a real time visual feedback about the state of the sensors, and second, it allows performing a calibration routine and validating the result of the calibration.

The body structure is made of 3D primitives representing the proportions of the human body. It is updated with the each line of stream.

//HEAD
pushMatrix();
translate(width/2,height/2-350);
rotateY(-radians(headY));
rotateX(radians(headP));
rotateZ(-radians(headR));
box(50,50,50);
popMatrix();

//BODY
pushMatrix();
translate(width/2,height/2);
rotateY(radians(-bodyDirection));

box(200,50,50);
translate(0,-150,0);
box(50,300,50);
translate(0,-150,0);
box(200,50,50);
popMatrix();

//ARM
pushMatrix();
translate(width/2,height/2-300);
rotateY(radians(-bodyDirection));
translate(75,0,0);
rotateY(radians(-ARM_UP_Y+bodyDirection));
rotateX(radians(ARM_UP_P));
Calibration Process

Before starting the recording session, we should calibrate the orientation sensors to represent a person’s default standing posture. Because the sensors are placed on the body parts in each session, their orientations slightly differ. The calibration routine compensates this differences. When the system starts sending the sensor values, the person who wears the device is asked to stand in default posture: arms resting vertically in their natural positions, and looking towards horizon. Then, the calibration process starts and collects the sensor values for the default posture. These values are updated to calibration values, which offsets incoming stream data.

```
if (isCalibrating){
    if (abs(calibration[0])>0){
        calibration[0]=(roll+calibration[0])/2;
        calibration[1]=(pitch+calibration[1])/2;
        ....}
    else{
        calibration[0]=roll;
        calibration[1]=pitch;
    }
```

Calibration of eye trackers are achieved through the Pupil Software as described by Kassner and Patera. In this process, the user follows a manual marker displayed in different parts of the environment. Then, a transformation matrix is calculated between world camera and eye camera based on their intrinsic properties.

Recording Process

The recording process starts when the calibration routine is done and the user is ready to perform. During this process, a laptop computer is carried by the user in a backpack, because of necessary USB connections as well as processing power. In future implementations, the laptop would be replaced with a mobile computing device, such as a tablet or an embedded computer that is worn on the body.

The software handles the camera image coming from

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the head mounted camera, and saves it with a time stamp. Frame ID’s are stored inside the CSV file where all other sensor information is also stored. Each stream is saved into the file until the recording process is done.

```java
if (isRecording){
    PImage cp = myCapture.get(0, 0, 960, 540);
    cp.save("new_capture/capture"+counter);
    if (OSCvalues.length==2)
        line=time+","+roll+","+pitch+","+
        roll2+","+pitch2+","+roll3+","+
        pitch3+","+roll4+","+pitch4+....
    lines=append(lines,line);
}
```

Representing the Sphere of Embodiment

The second part of the software handles the representation of the sphere of embodiment and application of different procedures such as computing the location or extrapolating body structure onto images. Based on the intention, software can filter specified sensor data. The module is written in Processing. It provides wrappers and libraries for graphics programming. All 3D representations generated in OPENGL through Processing.

The module reads the specified CSV file comprising a recording data. Each distinct sensor value is stored in a different list. Furthermore, a list of body motion and location is generated from integrating foot direction. I discuss how this process enables representation of locations and places in the following chapter.

```java
String[] pieces = split(line, ",");
    String frame=pieces[20];
    f2=f1;
    f1=float(pieces[2]);
    head.add(float(pieces[12]));
    feet.add(float(pieces[2]));
    body.add(float(pieces[11]));
    hand.add(float(pieces[9]));
    images.add(loadImage("kitchen/capture"+frame+".png"));

    float len=0;
    if(f1-f2>0){
        len=(f1/360)*2*PI*200;
```

Figure 18: An example of recording process.

Figure 19: A spatio-temporal representation of an action. Green represents the foot direction and Red Represents the head direction. Each frame added as an outer shell to the circle.
The representation integrates the time variable as the radius of the sphere. Each of the detected actions, motions or images are located to an appropriate time radius. However, as I discuss in location representation, reverse-temporal representation is more suitable in some purposes.

As you can see in Figure 20, the image data is mapped to a spherical surface towards head directions. Because all sensors share this medium, I can add walking directions, touch registers or sounds as well. In this example, feet and head directions are also shown as purple and green rectangles towards the bottom part of the sphere.

Figure 20: 3D Representation of an Experience. Camera Images are mapped to head directions.
Summary

In this chapter I have presented a body-centric computational model, the Hallucination Machine. Building upon the existing literature, I showed that spatiality is carried through a perceptual modality, which communicates the perception of whereness. This modality provides the main structure for perceiving spatiality, which comprises directions and distances. I argued that such a modality is a necessity for the action-perception loop. I call this modality as the sphere of embodiment because the 'membrane' of this modality is the spectrum of all possible directions and eventually signified by a sphere.

This approach enables exploring the multimodal characteristics of space perception, through which I propose solutions to represent sensori-motor patterns, multimodal contingencies and body-centric location.

In order to explore this idea further in a computational realm, I have developed a wearable device that records body movements and vision. I have also used a binaural recorder to incorporate aural perception to this study.

Finally I have developed computer software to record sensor data, construct a digital body mode, and represent the spatial modality.

In the next chapter I search for empirical evidences of such modality and implement the computational model in various scenarios.
Experiments

In this final chapter I present two examples of how this model is applied in real and digital spaces in different conditions. These experiments serve in two ways. First, they provide empirical evidences of space as a modality, demonstrating how people engage with space without sensory signals and how spatial perceptions leak from one sensory modality to another. Second, they demonstrate the use of computational means for representing multimodal spatial experiences. I have implemented different types of applications in which I test how the sphere of embodiment allows representing the actions and locations as well as extrapolating them onto the sensory inputs.

The first example is called “The Ghost in the Room”. In this experiment, participants were asked to follow a “ghost” that they hear from a recording through the headphones. The recording is taken from particular binaural microphones by myself, from a particular location in the room where the participants were asked to be in during experiments. In the recording setup, there is one person who is using the different areas of space, walking in the room, sitting on a chair etc. The actions are especially designed so that they involve particular sounds of objects that can be discriminated. The aim of this experiment to see if participants were able to distinguish spatial properties of the room and if this spatial experience is tied to that particular place. The hypothesis is that hearing is not carrying final information about space and other senses alters the spatial experience. If this is the case, then participants should perceive a similar and probably more vivid space in the original set-
ting while this perception changes in terms of distances and locations in a different room. In order to prove this hypothesis, I have set another room where participants were listening the same recording in a different room. In both conditions their gaze are recorded through eye tracking camera and they were asked to draw the trajectory that the “ghost” taken. I compare and discuss the results from this study.

The second example is called “Being the Ghost in the Room”. It involves a set of spatial tasks that the participants asked to follow. While they perform the given tasks their actions, motions and orientations are recorded as well as the visual field (the camera image), where they look and what they hear.

The Ghost in the Room

In this thesis I explore the characteristics of space as perceived from the first person point of view. As I have introduced the Hallucination Machine, I argue that space is a perceptual modality and cannot be confined in sensory signals -even in vision. space we see, touch and hear can represent space we perceive if they have a common spatial medium. Space is not mental nor empirical. It is phenomenal. In this section, I search for the evidences of such space. The ghost in the room experiment is designed to test two hypotheses:

1. A person can attend to space through one sensory organ using the signals from another one. In case of this experiment, the claim is that things in space as perceived by ears can be explored with eyes, although there is no visual cue for such things.

2. Space is not a fixed property extracted from senses by a perceived quality. A particular change in one sensory modality would result altering the spatial perception on another one. In this experiment, I explore how the vision effects space perception obtained through ears.

I designed an experiment in two parts in which I test these two hypotheses.
Part 1 - Follow the Real Ghost

Setup

The first part of the experiment is set in Architecture Common Room at MIT Building 7. With the help of a colleague, I have recorded a series of actions - both through binaural microphones and eye tracker- that my colleague performed while I sit down on the sofa keeping a fixed position. The actions involved entering the room, using printer, taking an item from the fridge, washing hands, using microwave, sitting on a chair and exiting the room from another door.

With the help of binaural microphones, I recorded the sounds of actions - even subtle details like footsteps- very close to what I actually hear from space. Any person that listens the recording would perceive the sounds from my point of view as if the sounds are coming from the room with a great precision to direction and distance. I have followed my colleague with my eyes during his performance and recorded my eye positions through the eye tracker.

After I obtained the sound recordings, I have conducted the experiment with a group of students. All students were from architecture department and between ages 20-28. Participants were told that they were going to listen to a sound recording, but in fact, that there were a ghost in the room and they should try to follow the ghost with their eyes. Meanwhile, I recorded their eye positions with the eye tracker.

After the sessions participants are asked a couple of subjective questions about their experience. They were asked whether if they perceived the sound coming from space or inside their heads. All participants confirmed that they perceived the sounds coming from space. Some participants believed to the reality of the recording so much so that they could not differentiate it from the real sounds in the room.I also asked them to briefly describe what the ghost did in the room. They all successfully describe the performance to a high detail.
Figure 21: Architecture Common Room
Results

I compared the recording of my eye positions that is obtained when I was following my colleague to the ones recorded during the experiments. I implemented a synchronization process to match the time stamps of the recordings.

The comparison revealed that there is a strong correlation between eye positions. Most of the times participants had been following the person in space with their eyes - even if they had not see him. All participants confirmed that they had perceived the presence of a person and they had been attending to the position of that person. The results confirmed their subjective evaluations.

This initial result supports my initial hypothesis that spatial characteristics leaks into different sensory modalities and attention to one could be dictated by the other. Furthermore, I suggested that perceptual presence is a spatial one. The results confirmed such a condition that sensing the perceptually present objects is only possible through adopting a spatial modality.

Figure 22: Left: Actual recording of a person. Right: Participants listening to the sound recording and following the 'ghost'. Red Circle indicates where a person looks.
Part 2- Follow the Fake Ghost

Setup

As the first experiment indicated of a spatial modality, I have designed a second experiment to reveal its perceptual characteristics. I hypothesized that the being a perceptual modality, space should not be a fixed property grounded in any sensory modality. It should rather show indications of subjectivity and be open to deformations as response to the change in the other senses. In order to test this hypothesis, I conducted a slightly different version of the first experiment. In this one I changed the room of experiment while using the same sound recording of the Architecture Common Room. In this setup, what they see and what they hear did not necessarily correlate. In fact, the room was approximately one quarter the size of the first one and most of the recorded actions corresponded to the areas outside of the room. The room did not include any of the objects took part in the actions in the recording.

I invited another group of participants, all from architecture and same age group with the previous one. This time, instead of tracking their eye movements, I asked participants to draw the ghost on the plan of the room. They were told that there was a ghost in space but not necessarily in the room - maybe in other rooms. I avoided forcing them to draw the ghost inside the room that would effect their perception.

After the experiment, a subjective evaluation was conducted. I asked participants whether as they heard the sounds from space or inside their heads. They all confirmed that they had perceived the sounds as coming from space around them. They also confirmed that they had felt the presence of the ghost - a similar result to the first experiment.

Results

The experiment gave interesting results as none of the participants were able to locate or follow the ghost correctly during his activities. Or rather, they perceived the
Figure 23: Small Room
ghost in a different spatiality.

I have compared the drawings made by participants to the original positions of the ghosts as well as to each other. As I have suspected, everyone perceived the sounds much closer relative to the original location. As the room was drastically smaller, the visual sense deformed the
spatial perception of the ears. But more interestingly not only the distances but also the directions of sounds altered. And the comparison between participants' drawings showed that the perceived locations and distances were similar between participants.

**Experiment Analysis**

These two experiments demonstrated that the spatial characteristics are not fixed in sensory signals. Furthermore, as I demonstrated in the first part, spatiality leaks from one sense to another one. Space perception as I proposed in my model, requires a distinct modality that allows these two phenomenons to occur. Based on the experiments following results are obtained:

1. One can visually attend to somewhere based on aural sense.
2. This attention is not visual, but spatial.
3. Space perception is not fixed in sensory modalities, and perception from one changes according to the other.
4. There is an indication that this change would be regular, but requires more experiments.

**Being the Ghost in the Room**

In the second example I explore the computational means of Hallucination Machine. I have conducted a series of recording sessions, where various participants conducted spatial tasks in two different rooms. I have demonstrated the model and software in which I represent the sphere of embodiment in the previous chapters. Based on the recordings, I search for:

1. How can a particular spatial experience be represented in a multimodal manner?
2. What are the multimodal contingencies revealed in this representations?
3. How can we extrapolate an action to discover sensory modalities?
4. How is the location represented?

**A sequence of experience**

In first example I represent bodily coordinates and senses in a sequence. I have mapped each image frame to the head direction in the sphere. In the example below, I demonstrate how the sphere changes through the time. In order to represent this change, I used the time as the radius parameter of the sphere at a given moment. By doing so, I have created a spatio-temporal representation of the events. Green squares represents the hand orientation and purple squares represents feet orientation.

Figure 26: A sequence of actions are recorded in the space.

One of the actions that I have illustrated in previous chapter is walking action. Here, I demonstrate how leg rotations and touch response are coupled together in HM and represented in one spatial medium. Again, purple squares represent feet orientation and red squares represents if there is a touch response at that direction.

Modeling the walking action provides the bases for computing the body movement and eventually perform-
ing path integration. I have simplified this task by taking only the forward motion in consideration and integrating the difference in feet orientations. This method quickly determines whether if a person takes a step.

Contingencies in Sensori-Motor Actions

Before I go into the details of detecting the location through actions, I present one more aspect of the model, which is the representation of sensori-motor contingencies. In the Figure 29 a drinking action is shown in different phases. The person is standing so the touch response from feet is directed towards down. As the person lifts the cup —that can be noticed as an array of green boxes towards front/down— head direction starts to change following the hand direction. Person looks downwards. Hand and head directions meet at some point, as we can see the green boxes penetrating through the images. Even it is hard to see in the figure, there is no cup displayed in the images. However, I argue that this particular experience involves the cup. Although learning in multimodal environments is not covered in the scope of this thesis, I speculate through this example that we can generate a visual response of the cup, and examine its visual properties in this context (for example we can answer whether the microwave or the cup is bigger); or in other words we can compute in visual world only through the perceptual presence of the cup. It only requires recognizing the pattern of movement from a previous experience —where we would have observed the relation between our hand and the cup—. Nevertheless, the sphere of embodiment reveals a new method of bridging sensory
modalities through actions and representing them in one medium.

![Diagram showing sensori-motor contingencies in drinking action](image)

**Figure 29:** Representation of sensori-motor contingencies in drinking action. Green - touch response at the hand direction. Red - touch response at the foot direction. Picture array - Visual response at the head direction.

**Representing Location**

I have proposed that the space is about whereness as we perceive it through our bodily perspective. This whereness, to a great extent, explains how we organize our senses so that they can communicate to each other. It is about the locations - directions and distances - that we perceive. However, it is also about the perception of our body's location. As I have introduced before, location has a corresponding representation in neural channels.

In this example, I demonstrate how it is possible to use the sphere of embodiment to represent the location of the body.

For this example, I have used Architecture Common Room, which is the place of the previous experiment (Floor plan can be seen at Figure 21, and pictures at Figure 22). I have recorded a similar set of actions using HM. As I have explained previously, I have integrated the change in feet orientations to determine whether a person takes a step forwards. Using this method, I have calculated the sense of movement towards the walking direction. The Figure 30 demonstrates the spatio-temporal representation of body movements that is used in path integration. It also demonstrates the location - as I have
discussed in previous chapter- as an action potential towards the opposite side of the body movement. Body movement and location are like action-reaction couples. Location is a potential body movement grounded in sensorimotor knowledge and generated by the actual body movement - but in reverse direction.

Figure 30: Upper Line: Path integration from body movement Lower Line: Location as an action potential

However, in a continuous engagement with the environment, generating an action potential towards each point that we walk through is not trivial. Place-cells show that another principle would be possible through recognizing unique parts of the environment. Therefore, a location could be an action potential between known places. The map in Figure 31 is generated when I applied the path integration. Each point on the path represents a step of a person. There are clusters of points that correspond to a particular part of the environment. These clusters are good candidates for representing places.

As a second step, I created a second layer using the touch feedback from the hands. I have put a point to the location if the hands are oriented forwards - reaching to any object in the environment. This time the map becomes the one seen in Figure 32. The map shows how hand actions correlate the initial location map. This correlation would explain how places are represented and shared through different modalities. When we integrate the other sensory feedback obtained around the clusters, such as visual cues, we can represent a particular place. (Figure 33)
The important idea here is that the location can be represented as an action potential grounded in sensorimotor knowledge. Locations can also be represented as a network of places. I defined the locations as the knowledge of going back. Each time I move out from one place I start learning the means of going back to that place. And if there are enough distinct places, then I only need to learn the path between the two. When a new place is introduced, I can start from scratch and always know my location relative to the last place I have been. If there are not enough distinct places, then I might get lost.

Figure 31: Path Integration in HM. Each dot represent a unique location in space
Figure 32: Path Integration in HM: Orange dots represents that there is a particular activity involving hands.

Figure 33: Multimodal Clustering of “Places”
Actions leaked into images

Finally, I implemented an extrapolation method, that would communicate the location and path integration to the sense of vision. Using the images taken from the bodily perspective, one can extrapolate a previous experience of movement to the images. Only through his or her own experience, one would understand the relation between the movement and the perspective of the image. This method would foster the development of machine vision systems that can detect objects and actions using sensori-motor knowledge.

Summary

In the first part of this chapter, I have looked through the evidences of the space as a perceptual modality. In the first experiment, it is revealed that the people have a multimodal attention to the space. All participants were able to follow a person that they hear through a three dimensional recording with their eyes. They were attending to the areas of space that they perceive through their ears. They were not looking at the things in environment but at an invisible object or rather a perceptually present object. I argued that such perceptual presence is spatial, and space is the modality that carries this presence.

The second experiment showed that, the space is not a fixed entity obtained from senses but a perceptual one that can be altered. Participants listening the same recording in a much smaller room perceived the things closer and in altered directions. This time, the space they see altered the space they hear. It provided another evidence that the senses shares a common spatial modality.

In the second part I have explored the computational representations of this modality. I have implemented several algorithms in which I demonstrated to practical implications of this modality such as providing a representational medium for sensori-motor contingencies, comput-
ing and determining location and extrapolating sensori-motor knowledge to visual world.
Contributions and Future Studies

Through this thesis I provide a novel approach to space perception as a step towards understanding human experience of space and developing artificial systems that can appreciate space in its physical, social and cultural aspects. Hallucination Machine is a computational model, which aims at generating knowledge of space perception and fostering the development of advanced tools and models of scientific inquiry into the “human space”.

I have introduced a new understanding of space, which regards it as a perceptual modality. I argued that the space is the modality of whereness and exists independently from the sensory perceptions. The sphere of embodiment, as I call it, eventually provides a common medium as it can be captured by all of the senses and creates contingencies between actions and perceptions. This idea opens up a way of representing the actions and perceptions in the same medium.

Through a set of experiments I have provided empirical evidences for this approach. Using spatial sound recordings and eye trackers I have demonstrated how the space can be attended in a multimodal way as well as how the perception of it altered based on sensory inputs.

I have grounded my thesis to a multidiscipliner discussion of space, body and mind. This thesis contributes to this discussion through extending it to computational realm. The problem of space perception is inherently
complex and involves many disciplines including cognitive science, psychology, anthropology and architecture. This thesis also contributes to the multidisciplinary dialog that is necessary to extend our knowledge on space by integrating a variety of perspectives from different disciplines.

I provided an example tool through developing a wearable device that can capture orientations of various body parts and grab images and gaze positions through a head mounted camera. The tool allows reconstruction of a human body and relate a sensory input this model.

Using the computational model, I have demonstrated the use of the sphere of embodiment in the way of understanding sensori-motor contingencies, communicating spatial information between different senses and extrapolating bodily knowledge as a perceptual presence onto sensory modalities.

I see this project as a first step towards development of artificial intelligence systems that can recognize and compare different categories of spaces, places and boundaries, determine paths and trajectories, understand variety of actions, and generate artificial cognitive maps. Through facilitating the formal representations of space perception generated by the proposed model, different types of sensors, audio, video and even touch sensors will communicate, locate each other and build up more detailed information about the environment without a prior calibration or training. Cameras would work collaboratively regardless of type and resolution and without sharing any image data.

Space stands in the very center of our existence. We live, work, think and create through it. In this sense, this thesis is another step to understand us as human beings and to provide a broader perspective for our humanly inquiries.
Bibliography


Appendix A

Hallucination Machine Orientation Trackers
Cagri Hakan Zaman, May 2014

//Hallucination Machine Orientation Trackers/
//Cagri Hakan Zaman, May 2014
//zaman@mit.edu.
//Built on top of Razor AHRS Library by Peter Bartz
(http://ptrbrtz.net)
//https://github.com/ptrbrtz/razor-9dof-ahrs/

#define HW__VERSION_CODE 10724 // SparkFun 9DOF Sensor
    Stick version "SEN-10724" (HMC5883L magnetometer)
#define OUTPUT__BAUD_RATE 19200
#define OUTPUT__DATA_INTERVAL 20 // in milliseconds
#define OUTPUT__MODE_CALIBRATE_SENSORS 0 // Outputs sensor
    min/max values as text for manual calibration
#define OUTPUT__MODEANGLES 1 // Outputs yaw/pitch/roll in
    degrees
#define OUTPUT__MODE_SENSORS_CALIB 2 // Outputs calibrated
    sensor values for all 9 axes
#define OUTPUT__MODE_SENSORS_RAW 3 // Outputs raw
    (uncalibrated) sensor values for all 9 axes
#define OUTPUT__MODE_SENSORS_BOTH 4 // Outputs calibrated
    AND raw sensor values for all 9 axes
// Output format definitions (do not change)
#define OUTPUT__FORMATTEXT 0 // Outputs data as text
#define OUTPUT__FORMAT_BINARY 1 // Outputs data as binary
float
int output_mode = OUTPUT__MODEANGLES;
int output_format = OUTPUT__FORMAT_TEXT;

#define OUTPUT__STARTUP_STREAM_ON true // true or false
boolean output_errors = false; // true or false
#define OUTPUT__HAS_RN_BLUETOOTH false // true or false

#define ACCEL_X_MIN ((float) -275)
#define ACCEL_X_MAX ((float) 254)
#define ACCEL_Y_MIN ((float) -259)
#define ACCEL_Y_MAX ((float) 262)
#define ACCEL_Z_MIN ((float) -255)
#define ACCEL_Z_MAX (float) 258

// Magnetometer (standard calibration mode)
// "magn x,y,z (min/max) = X_MIN/X_MAX Y_MIN/Y_MAX
// Z_MIN/Z_MAX"
#define MAGN_X_MIN ((float) -600)
#define MAGN_X_MAX ((float) 600)
#define MAGN_Y_MIN ((float) -600)
#define MAGN_Y_MAX ((float) 600)
#define MAGN_Z_MIN ((float) -600)
#define MAGN_Z_MAX ((float) 600)
#define GYROAVERAGE OFFSET-X ((float) 0.0)
#define GYROAVERAGEOFFSETY ((float) 0.0)
#define GYROAVERAGEOFFSETZ ((float) 0.0)
#define DEBUG__NODRIFTCORRECTION false
#define DEBUG__PRINTLOOP_TIME false
#endif

#include <Wire.h>
#include "I2Cdev.h"
#include "MPU6050.h"
#include <HMC5883L.h>
#include <hmc6343.h>
#include <LSM303.h>

#define MMA8452_ADDRESS 0x01 // 0x01 if SA0 is high, 0x1C if low

#define OUT_X_MSB 0x01
#define XYZDATACFG 0x0e
#define WHOAMI 0x0d
#define CTRLREG1 0x2a
#define GSCALE 2 // Sets full-scale range to +/-2, 4, or 8g. Used to calc real g values.

#define FORCE 0
#define FORCE2 1

#define MMA8452_ADDRESS 0x1D // 0x1D if SA0 is high, 0x1C if low

#include <Wire.h>
#include "I2Cdev.h"
#include "MPU6050.h"
#include <HMC5883L.h>
#include <hmc6343.h>
#include <LSM303.h>

// MPU6050 Variables

MPU6050 accelgyro;
MPU6050 accelgyro2;
int16_t ax, ay, az;
int16_t gx, gy, gz;
#define OUTPUT_READABLE_ACCELGYRO

// HMC5883 COMPASS variables
HMC5883L compass;
int error = 0;

// HMC6343 variable
hmc6343 hmc;
float hmc_heading, hmc_roll, hmc_pitch;

LSM303 lsm;
float body_heading;

// Sensor calibration scale and offset values
#define ACCEL_X_OFFSET ((ACCEL_X_MIN + ACCEL_X_MAX) / 2.0f)
#define ACCEL_Y_OFFSET ((ACCEL_Y_MIN + ACCEL_Y_MAX) / 2.0f)
#define ACCEL_Z_OFFSET ((ACCEL_Z_MIN + ACCEL_Z_MAX) / 2.0f)
#define ACCEL_X_SCALE (GRAVITY / (ACCEL_X_MAX - ACCEL_X_OFFSET))
#define ACCEL_Y_SCALE (GRAVITY / (ACCEL_Y_MAX - ACCEL_Y_OFFSET))
#define ACCEL_Z_SCALE (GRAVITY / (ACCEL_Z_MAX - ACCEL_Z_OFFSET))

#define MAGN_X_OFFSET ((MAGN_X_MIN + MAGN_X_MAX) / 2.0f)
#define MAGN_Y_OFFSET ((MAGN_Y_MIN + MAGN_Y_MAX) / 2.0f)
#define MAGN_Z_OFFSET ((MAGN_Z_MIN + MAGN_Z_MAX) / 2.0f)
#define MAGN_X_SCALE (100.0f / (MAGN_X_MAX - MAGN_X_OFFSET))
#define MAGN_Y_SCALE (100.0f / (MAGN_Y_MAX - MAGN_Y_OFFSET))
#define MAGN_Z_SCALE (100.0f / (MAGN_Z_MAX - MAGN_Z_OFFSET))

// Gain for gyroscope (ITG-3200)
#define GYRO_GAIN 0.06957 // Same gain on all axes
#define GYRO_SCALED_RAD(x) (x * TO_RAD(GYRO_GAIN)) // Calculate the scaled gyro readings in radians per second

// DCM parameters
#define Kp_ROLLPITCH 0.02f
#define Ki_ROLLPITCH 0.00002f
#define Kp_YAW 1.2f
#define Ki_YAW 0.00002f

// Stuff
#define STATUS_LED_PIN 13 // Pin number of status LED
#define GRAVITY 256.0f // "1G reference" used for DCM filter and accelerometer calibration
#define TO_RAD(x) (x * 0.01745329252) // *pi/180
#define TO_DEG(x) (x * 57.2957795131) // *180/pi
//Mux control pins
int scl0 = 2;
int scl1 = 3;
int scl2 = 4;
int scl3 = 5;

int sda0 = 8;
int sda1 = 9;
int sda2 = 10;
int sda3 = 11;

//Mux in "SIG" pin
int SCL_pin = 5;
int SDA_pin = 4;

int value = 0;
int value2 = 0;

// Sensor variables
float accel[3];
float accel_min[3];
float accel_max[3];

float magnetom[3];
float magnetom_min[3];
float magnetom_max[3];
float magnetom_tmp[3];

float gyro[3];
float gyro_average[3];
int gyro_numsamples = 0;

// DCM variables
float MAG_Heading;
float Accel_Vector[3] = {0, 0, 0}; // Store the acceleration in a vector
float Gyro_Vector[3] = {0, 0, 0}; // Store the gyros turn rate in a vector
float Omega_Vector[3] = {0, 0, 0}; // Corrected Gyro_Vector data
float Omega_P[3] = {0, 0, 0}; // Omega Proportional correction
float Omega_I[3] = {0, 0, 0}; // Omega Integrator
float Omega[3] = {0, 0, 0};
float errorRollPitch[3] = {0, 0, 0};
float errorYaw[3] = {0, 0, 0};
float DCM_Matrix[3][3] = {{1, 0, 0}, {0, 1, 0}, {0, 0, 1}};
float Update_Matrix[3][3] = {{0, 1, 2}, {3, 4, 5}, {6, 7, 8}};
float Temporary_Matrix[3][3] = {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}};

// Euler angles
float yaw;
float pitch;
float roll;

// DCM timing in the main loop
unsigned long timestamp;
unsigned long timestampold;
float G_Dt; // Integration time for DCM algorithm

// More output-state variables
boolean output_stream_on;
boolean output_single_on;
int curr_calibration_sensor = 0;
boolean reset_calibration_session_flag = true;
int num.accel_errors = 0;
int num.magn_errors = 0;
int num.gyro_errors = 0;

void read_sensors() {
    ReadGyro(); // Read gyroscope
    ReadAccel(); // Read accelerometer
    ReadMagn(); // Read magnetometer
}

// Read every sensor and record a time stamp
void reset_sensor_fusion() {
    float temp1[3];
    float temp2[3];
    float xAxis[3] = {1.0f, 0.0f, 0.0f};

    read_sensors();
    timestamp = millis();

    // GET PITCH
    // Using y-z-plane-component/x-component of gravity vector

    // GET ROLL
    // Compensate pitch of gravity vector
    VectorCrossProduct(temp1, accel, xAxis);
    VectorCrossProduct(temp2, xAxis, temp1);

    roll = atan2(temp2[1], temp2[2]);

    // GET YAW
    Compass_Heading();
    yaw = MAG_Heading;

    // Init rotation matrix
    init_rotation_matrix(DCM_Matrix, yaw, pitch, roll);
}

// Apply calibration to raw sensor readings
void compensate_sensor_errors() {
  // Compensate accelerometer error
  accel[0] = (accel[0] - ACCEL_X_OFFSET) * ACCEL_X_SCALE;

  // Compensate magnetometer error
  #if CALIBRATION_MAGN_USE_EXTENDED == true
    for (int i = 0; i < 3; i++)
      magnetom_tmp[i] = magnetom[i] -
      magn_ellipsoid_center[i];
      Matrix_Vector_Multiply(magn_ellipsoid_transform, magnetom_tmp, magnetom);
  #else
    magnetom[0] = (magnetom[0] - MAGN_X_OFFSET) * MAGN_X_SCALE;
  #endif

  // Compensate gyroscope error
  gyro[0] = GYRO_AVERAGE_OFFSET_X;
  gyro[1] = GYRO_AVERAGE_OFFSET_Y;
  gyro[2] = GYRO_AVERAGE_OFFSET_Z;
}

// Reset calibration session if reset_calibration_session_flag is set
void check_reset_calibration_session() {
  // Raw sensor values have to be read already, but no error
  // compensation applied

  // Reset this calibration session?
  if (!reset_calibration_session_flag) return;

  // Reset acc and mag calibration variables
  for (int i = 0; i < 3; i++) {
    accel_min[i] = accel_max[i] = accel[i];
    magnetom_min[i] = magnetom_max[i] = magnetom[i];
  }

  // Reset gyro calibration variables
  gyro_num_samples = 0; // Reset gyro calibration averaging
  gyro_average[0] = gyro_average[1] = gyro_average[2] = 0.0f;
  reset_calibration_session_flag = false;
}

void turn_output_stream_on() {
  output_stream_on = true;
digitalWrite(STATUS_LED_PIN, HIGH);
}

void turn_output_stream_off()
{
    output_stream_on = false;
    digitalWrite(STATUS_LED_PIN, LOW);
}

// Blocks until another byte is available on serial port
char readChar()
{
    while (Serial.available() < 1) { } // Block
    return Serial.read();
}

void setup()
{
    pinMode(scl0, OUTPUT);
    pinMode(scl1, OUTPUT);
    pinMode(scl2, OUTPUT);
    pinMode(scl3, OUTPUT);
    pinMode(sda0, OUTPUT);
    pinMode(sda1, OUTPUT);
    pinMode(sda2, OUTPUT);
    pinMode(sda3, OUTPUT);

    digitalWrite(scl0, LOW);
    digitalWrite(scl1, LOW);
    digitalWrite(scl2, LOW);
    digitalWrite(scl3, LOW);
    digitalWrite(sda0, LOW);
    digitalWrite(sda1, LOW);
    digitalWrite(sda2, LOW);
    digitalWrite(sda3, LOW);

    setMux(i);

    // Init serial output
    Serial.begin(OUTPUT__BAUD_RATE);
    Serial.println("MMA8452 Basic Example");

    // Init status LED
    pinMode (STATUS_LED_PIN, OUTPUT);
    digitalWrite(STATUS_LED_PIN, LOW);

    // Init sensors
    delay(50); // Give sensors enough time to start
    I2C_Init();
    Accel_Init();
    Magn_Init();
Gyro_Init();

// Read sensors, init DCM algorithm
delay(20); // Give sensors enough time to collect data
reset_sensor_fusion();

// Init output
#if (OUTPUT__HAS_RN_BLUETOOTH == true) || (OUTPUT__STARTUP_STREAM_ON == false)
  turn_output_stream_off();
#else
  turn_output_stream_on();
#endif

//SETUP CHANNEL 2
setMux(2);
initMMA8452(); // Test and initialize the MMA8452
accelgyro.initialize();
Serial.println(accelgyro.testConnection() ? "MPU6050 connection successful" : "MPU6050 connection failed");

//SETUP CHANNEL 3
setMux(3);
initMMA8452(); // Test and initialize the MMA8452
accelgyro2.initialize();
Serial.println(accelgyro2.testConnection() ? "MPU6050 connection successful" : "MPU6050 connection failed");

//SETUP CHANNEL 0
setMux(0);
initMMA8452(); // Test and initialize the MMA8452

//SETUP CHANNEL 4
setMux(4);
lsm.init();
lsm.enableDefault();

// Main loop
void loop()
{
  setMux(1);

  // Read incoming control messages
  if (Serial.available() >= 2)
  {
    if (Serial.read() == '#') // Start of new control message
    {
      int command = Serial.read(); // Commands
      if (command == 'f') // request one output _f_rame
output_single_on = true;
else if (command == 's') // _s_ynch request
{
    // Read ID
    byte id[2];
    id[0] = readCharO;
    id[1] = readCharO;

    // Reply with synch message
    Serial.print("#SYNCH");
    Serial.write(id, 2);
    Serial.println();
}
else if (command == 'o') // Set _o_utput mode
{
    char output_param = readCharO;
    if (output_param == 'n') // Calibrate _n_ext sensor
    {
        curr_calibration_sensor = (curr_calibration_sensor + 1) % 3;
        reset_calibration_session_flag = true;
    }
    else if (output_param == 't') // Output angles as _t_ext
    {
        output_mode = OUTPUT__MODE_ANGLES;
        output_format = OUTPUT__FORMAT_TEXT;
    }
    else if (output_param == 'b') // Output angles in _b_inary format
    {
        output_mode = OUTPUT__MODE_ANGLES;
        output_format = OUTPUT__FORMAT_BINARY;
    }
    else if (output_param == 'c') // Go to _c_alibration mode
    {
        output_mode = OUTPUT__MODE_CALIBRATE_SENSORS;
        reset_calibration_session_flag = true;
    }
    else if (output_param == 's') // Output _s_sensor values
    {
        char values_param = readCharO;
        char format_param = readCharO;
        if (values_param == 'r') // Output _r_aw sensor values
        {
            output_mode = OUTPUT__MODE_SENSORS_RAW;
        }
        else if (values_param == 'c') // Output _c_alibrated sensor values
        {
            output_mode = OUTPUT__MODE_SENSORS_CALIB;
        }
        else if (values_param == 'b') // Output _b_oth sensor values (raw and calibrated)
        {
            output_mode = OUTPUT__MODE_SENSORS_BOTH;
        }
if (format_param == 't') // Output values as t_text
    output_format = OUTPUT_FORMAT_TEXT;
else if (format_param == 'b') // Output values in binary format
    output_format = OUTPUT_FORMAT_BINARY;
else if (output_param == '0') // Disable continuous streaming output
    {
        turn_output_stream_off();
        reset_calibration_session_flag = true;
    }
else if (output_param == '1') // Enable continuous streaming output
    {
        reset_calibration_session_flag = true;
        turn_output_stream_on();
    }
else if (output_param == 'e') // error output
    {
        char error_param = readChar();
        if (error_param == '0') output_errors = false;
        else if (error_param == '1') output_errors = true;
        else if (error_param == 'c') // get error count
        {
            Serial.print("#AMG-ERR:");
            Serial.print(num_accel_errors); Serial.print(",");
            Serial.print(num_mag_errors); Serial.print(",");
            Serial.println(num_gyro_errors);
        }
    }
}

#if OUTPUT_HAS_RN_BLUETOOTH == true
    // Read messages from bluetooth module
    // For this to work, the connect/disconnect message prefix of the module has to be set to ":#".
    else if (command == 'C') // Bluetooth ":CONNECT" message (does the same as ":01"
        turn_output_stream_on();
    else if (command == 'D') // Bluetooth ":DISCONNECT" message (does the same as ":00"
        turn_output_stream_off();
#endif // OUTPUT_HAS_RN_BLUETOOTH == true
else
    { } // Skip character

// Time to read the sensors again?
if((millis() - timestamp) >= OUTPUT_DATA_INTERVAL)
    {
timestamp_old = timestamp;
timestamp = millis();
if (timestamp > timestamp_old)
  G Dt = (float) (timestamp - timestamp_old) / 1000.0f;
  // Real time of loop run. We use this on the DCM
  algorithm (gyro integration time)
else G Dt = 0;

// Update sensor readings
read_sensors();

if (output_mode == OUTPUT__MODE_CALIBRATE_SENSORS) // We're in calibration mode
{
  check_reset_calibration_session(); // Check if this
  session needs a reset
  if (output_stream_on || output_single_on)
    output_calibration(curr_calibration_sensor);
}
else if (output_mode == OUTPUT__MODEANGLES) // Output angles
{
  // Apply sensor calibration
  compensate_sensor_errors();

  // Run DCM algorithm
  Compass_Heading(); // Calculate magnetic heading
  Matrix update();
  Normalize();
  Drift_correction();
  Euler_angles();

  if (output_stream_on || output_single_on)
    output_angles();
}
else // Output sensor values
{
  if (output_stream_on || output_single_on)
    output_sensors();
}

output_single_on = false;

#if DEBUG__PRINT_LOOP_TIME == true
  Serial.print("loop time (ms) = ");
  Serial.println(millis() - timestamp);
#endif

#else DEBUG__PRINT_LOOP_TIME == true
  Serial.println("waiting...");
#endif
//ADDITIONAL CODE
unsigned long time=millis();
value = (int)analogRead(FORCE);
value2=(int)analogRead(FORCE2);

// CONNECT CHANNEL 2
setMux(2);

//++++++++++++++++++++++TEST MPU6050 ++++++++ WORKING !!
accelgyro.getMotion6(&ax, &ay, &az, &gx, &gy, &gz); //RUP
  Acc-Gyro
  Serial.print(ax); Serial.print("t");
  Serial.print(ay); Serial.print("t");
  Serial.print(az); Serial.print("t");
  Serial.print(gx); Serial.print("t");
  Serial.print(gy); Serial.print("t");
  Serial.print(gz);Serial.print("t");

//+++++++++++++++++++END TEST MPU6050

int accelCount[3]; // Stores the 12-bit signed value
readAccelData(accelCount); // Read the x/y/z adc values

// Now we'll calculate the acceleration value into actual g's
float accelGRight[3]; // Stores the real accel value in g's
for (int i = 0 ; i < 3 ; i++)
{
  accelGRight[i] = (float) accelCount[i] / ((1<<12)/(2*GSCALE)); // get actual g value, this
  depends on scale being set
}

//CONNECT CHANEL 3
setMux(3);

//++++++++++++++++++++++TEST MPU6050 ++++++++ WORKING !!
accelgyro2.getMotion6(&ax, &ay, &az, &gx, &gy, &gz); //LUP
  Acc - Gyro
  Serial.print(ax); Serial.print("t");
  Serial.print(ay); Serial.print("t");
  Serial.print(az); Serial.print("t");
  Serial.print(gx); Serial.print("t");
  Serial.print(gy); Serial.print("t");
  Serial.print(gz);Serial.print("t");

//+++++++++++++++++++END TEST MPU6050

readAccelData(accelCount); // Read the x/y/z adc values
// Now we'll calculate the acceleration value into actual g's
float accelGLeft[3]; // Stores the real accel value in g's
for (int i = 0 ; i < 3 ; i++)
{
    accelGLeft[i] = (float) accelCount[i] / ((1<<12)/(2*GSCALE)); // get actual g value, this depends on scale being set
}

//CONNECT CHANNEL 0
setMux(0);

hmc.readHeading(hmc_heading, hmc_roll, hmc_pitch);
    //Library returns Heading, Roll and Pitch to variable heading, roll and pitch.
Serial.print(hmc_heading);
Serial.print("	");
Serial.print(hmc_pitch);
Serial.print("	");
Serial.print(hmc_roll);
Serial.print("	");
/++++++++++++++++++++++++READ COMPASS/./++++++++++++++++++++++++++++++++++++++++++++++++
MagnetometerRaw raw = compass.ReadRawAxisO;
MagnetometerScaled scaled = compass.ReadScaledAxisO;
int MilliGaussOnTheXAxis = scaled.XAxis;// (or YAxis, or ZAxis)
float heading = atan2(scaled.YAxis, scaled.XAxis);
float declinationAngle = 0.260;
heading += declinationAngle;
if(heading < 0)
    heading += 2*PI;
if(heading > 2*PI)
    heading -= 2*PI;
float headingDegrees = heading * 180/M_PI;
Serial.print(headingDegrees); // Direction
Serial.print("\t");
/+/++++++++++++++++++++++++END READ COMPASS+++++++++++++++++++++++++++++++++++}

// +++++++++ READ ARM ACCELEROMETER++++++++++++++++++++
readAccelData(accelCount); // Read the x/y/z adc values
float accelARM[3]; // Stores the real accel value in g's
for (int i = 0 ; i < 3 ; i++)
{
    accelARM[i] = (float) accelCount[i] / ((1<<12)/(2*GSCALE)); // get actual g value, this depends on scale being set
}
// +++++++++++++++++++END READ ARM
ACCELEROMETER+++++++++++++++++++++++

// +++++++++++++++++++READ COMPASS+++++++++++++++++++
setMux(4);
  lsm.reado;
  body_heading = lsm.heading(); // Library returns Heading, Roll and Pitch to variable heading, roll and pitch.
Serial.print(body_heading);
Serial.print("t");

// +++++++++++++++++++END READ COMPASS++++++++++++
  // tabs in between axes
Serial.print(time);
Serial.print("t");
// Print out values
for (int i = 0; i < 3; i++)
{
  Serial.print(accelGRight[i], 4); // Print g values
  Serial.print("t"); // tabs in between axes
}

for (int i = 0; i < 3; i++)
{
  Serial.print(accelGLeft[i], 4); // Print g values
  Serial.print("t"); // tabs in between axes
}
Serial.print(value); // Right Touch
Serial.print("t"); // tabs in between axes
Serial.print(value2); // Left Touch
Serial.print("t"); // tabs in between axes

// Serial.print("ARM: ");

for (int i = 0; i < 3; i++)
{
  Serial.print(accelARM[i], 4); // Print g values
  Serial.print("t"); // tabs in between axes
}

void setMux(int channel){
  int controlPinSCL[] = {scl0, scl1, scl2, scl3};
```c
int controlPinSDA[] = {sda0, sda1, sda2, sda3};

int muxChannel[16][4] = {
    {0, 0, 0, 0}, // channel 0
    {1, 0, 0, 0}, // channel 1
    {0, 1, 0, 0}, // channel 2
    {1, 1, 0, 0}, // channel 3
    {0, 0, 1, 0}, // channel 4
    {1, 0, 1, 0}, // channel 5
    {0, 1, 1, 0}, // channel 6
    {1, 1, 0, 0}, // channel 7
    {0, 0, 0, 1}, // channel 8
    {1, 0, 0, 1}, // channel 9
    {0, 1, 0, 1}, // channel 10
    {1, 1, 0, 1}, // channel 11
    {0, 0, 1, 1}, // channel 12
    {1, 0, 1, 1}, // channel 13
    {0, 1, 1, 1}, // channel 14
    {1, 1, 1, 1}  // channel 15
};

// loop through the 4 sig
for(int i = 0; i < 4; i++){
    digitalWrite(controlPinSCL[i], muxChannel[channel][i]);
    digitalWrite(controlPinSDA[i], muxChannel[channel][i]);
}

void readAccelData(int *destination)
{
    byte rawData[6];

    readRegisters(OUT_X_MSB, 6, rawData); // Read the six raw data registers into data array

    for(int i = 0; i < 3; i++)
    {
        int gCount = (rawData[i*2] << 8) | rawData[(i*2)+1];
        gCount >>= 4;
        if (rawData[i*2] > 0x7F) {
            gCount = -gCount + 1;
            gCount *= -1;
        }
        destination[i] = gCount;
    }
}

void initMMA8452()
{
    byte c = readRegister(WHO_AM_I);
    if (c == 0x2A) {
```
Serial.println("MMA8452 is online...");
}
else
{
    Serial.print("Could not connect to MMA8452Q: 0x");
    Serial.println(c, HEX);
    while(1); // Loop forever if communication doesn't happen
}

MMA8452Standby();
// Set up the full scale range to 2, 4, or 8g.
byte fsr = GSCALE;
if(fsr > 8) fsr = 8;
fsr >>= 2;
writeRegister(XYZ_DATA_CFG, fsr);

MMA8452Active(); // Set to active to start reading
}

void MMA8452Standby()
{
    byte c = readRegister(CTRL_REG1);
    writeRegister(CTRL_REG1, c & ~(0x01));
}

// Sets the MMA8452 to active mode.
void MMA8452Active()
{
    byte c = readRegister(CTRL_REG1);
    writeRegister(CTRL_REG1, c | 0x01);
}

void readRegisters(byte addressToRead, int bytesToRead, byte * dest)
{
    Wire.beginTransmission(MMA8452_ADDRESS);
    Wire.write(addressToRead);
    Wire.endTransmission(false);
    Wire.requestFrom(MMA8452_ADDRESS, bytesToRead);
    while(Wire.available() < bytesToRead);
    for(int x = 0 ; x < bytesToRead ; x++)
    {
        dest[x] = Wire.read();
    }
}

byte readRegister(byte addressToRead)
{
    Wire.beginTransmission(MMA8452_ADDRESS);
    Wire.write(addressToRead);
    Wire.endTransmission(false);
    Wire.requestFrom(MMA8452_ADDRESS, 1);
    return Wire.read();
}
```java
Wire.endTransmission(false);

Wire.requestFrom(MMA8452_ADDRESS, 1);
while(!Wire.available()) { //Wait for the data to come back
    return Wire.read(); //Return this one byte
}

void writeRegister(byte addressToWrite, byte dataToWrite) {
    Wire.beginTransmission(MMA8452_ADDRESS);
    Wire.write(addressToWrite);
    Wire.write(dataToWrite);
    Wire.endTransmission(); //Stop transmitting
}
```