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Experiential Learning for Interdisciplinary Education on Vestibular System Models

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Upon graduation he became an Assistant Professor of Engineering Science and Mechanics at the Virginia Polytechnic Institute and State University. In 1987 he joined the Department Electrical and Computer Engineering at UMASS Lowell as its Analog Devices Career Development Professor. Dr. Thompson has served on the executive boards of the Cooperative Research Fellowship program of Bell Laboratories (1991-1999) and the AT&T Labs Fellowship Program (1996-2006).

At Bell Laboratories Dr. Thompson created with the Vice President of Research and Nobel laureate, Arno Penizas, the W. Lincoln Hawkins Mentoring Excellence Award (1994). This award is given to a member of the research staff for fostering the career growth of Bell Labs students and associates. This award is ResearchÄôs highest honor for mentoring contributions. In 1998, AT&T Labs instituted a similar award named for Dr. Thompson.

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His awards include the US Presidential Award for Excellence in Mentoring; Tau Beta Pi Eminent Engineer; James E. Blackwell Scholar; AT&T Bell Laboratories Cooperative Research Fellowship. He is cited in WhoÄôs Who among African Americans, Education, and Technology Today; American Men and Women of Science, West Babylon Alumni Hall of Fame; He is a Fellow of the Acoustical Society of America and cited for his fundamental contributions to theoretical and computational acoustics. He is senior member of IEEE, and a member of the American Physical Society and Sigma Xi. He has published reesearch in acoustics, control theory, fluid mechanics, heat transfer, linear and nonlinear systems, and telecommunications.

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Abstract

The vestibular system (VS) allows humans to have a sense of balance and orientation. Within the VS, fluid displacement occurs within the ear canal, triggering nerve signals to be translated by the nervous system, allowing for the interpretation of the head's orientation. When there is a disturbance to this system, vestibular dysfunction occurs potentially causing vertigo and a loss of balance. It is estimated that 35 percent of adults 40 years or older in the United States have experienced vestibular dysfunction. The vestibular balance system poses a robust, unique topic for developing interdisciplinary education curricula as its function encapsulates many fundamental mechanical, chemical, biological, and physical phenomena that can be studied with engineering concepts and principles. In this work, we present a survey of models of the vestibular sensory system. Following which, selected models are presented in an experiential learning format for students to better understand the relationship and sensitivity of model parameters and external stimuli to physiological system behavior. By conducting simulations of these models, students can visualize outcomes, pose questions, and potentially identify areas of research interest. This paper is the outcome of an Innovations in Graduate Education project supported by the National Science Foundation. The authors are graduate students from three engineering majors from the University of Massachusetts Lowell and the University of the District of Columbia co-creating an educational module with faculty and experts on human balance. The developed module related to analyzing the vestibular balance system mechanics will be integrated into undergraduate courses across engineering departments in partnering institutions.

Index Terms

Vestibular System, Experiential Learning, Co-creation, Simulation

I. Introduction

The vestibular system (VS) is vital to many functions of everyday life. For example, the VS and balance in humans have a highly interconnected relationship. The VS is among the organs responsible for providing the brain with sensory information about the position and movement of the head and the body [1,2,3]. The visual system and sensations felt by legs and feet referred to as proprioception are other sources of sensory information that support the brain's response to maintain balance [2,3]. The information from the VS signals the brain to generate reflexive movements to compensate for the effect of changes in orientation of the head. The sensory information from the VS is also vital to autonomous muscle control required to keep the body balanced [3,4].

Figure 1 shows a schematic of the VS located in the inner ear. It includes the vestibular labyrinth, which houses three semicircular canals (SCCs), referred to as the anterior, lateral, and posterior, and the two otolith organs, the utricle, and the saccule. The three SCCs located perpendicular to each other detect angular acceleration with respect to the three axes. For example, the lateral SCC, located horizontally, detects angular rotations of the head turning left or right. The posterior and anterior SCC's detect left and right head tilts and head movements up and down respectively. The utricle and the saccule detect linear or translational motion, in the horizontal and vertical directions, respectively [3,4].

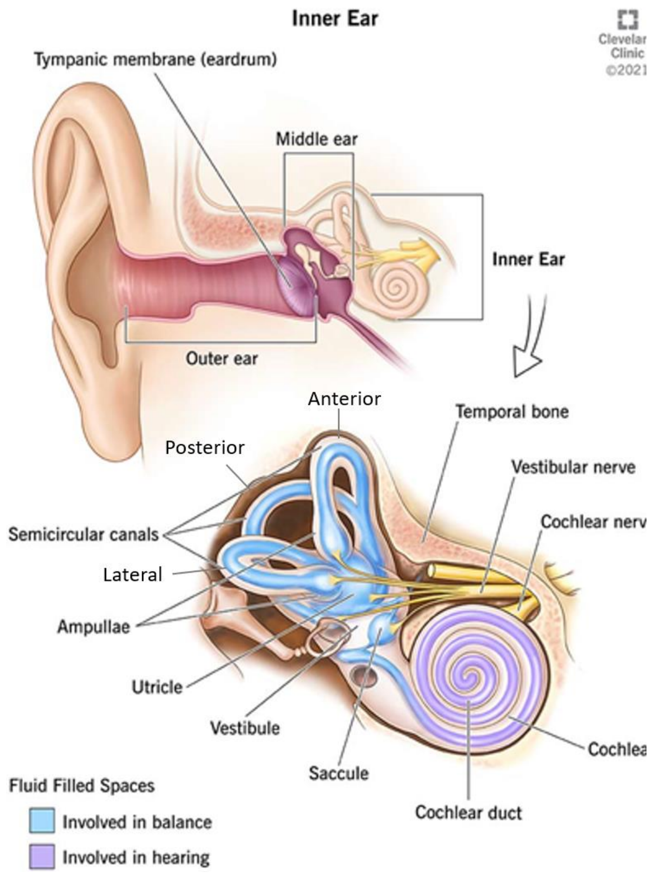

Figure 1: Inner ear and details of its structure including the semicircular canals, the utricle, the saccule and the vestibular nerve responsible for balance from Ref. [5].

Each of the SCCs terminates into an enlarged region known as the ampulla that is capped by a gelatinous structure, the cupula, as shown in Figure. (2) and they merge into the larger region known as the utricle. The enlarged section in the ampulla of the SCC shows the crista which is a sensory structure consisting of hair cells that is located at the base of the cupula. The SCCs are filled with a fluid known as the endolymph [2,3].

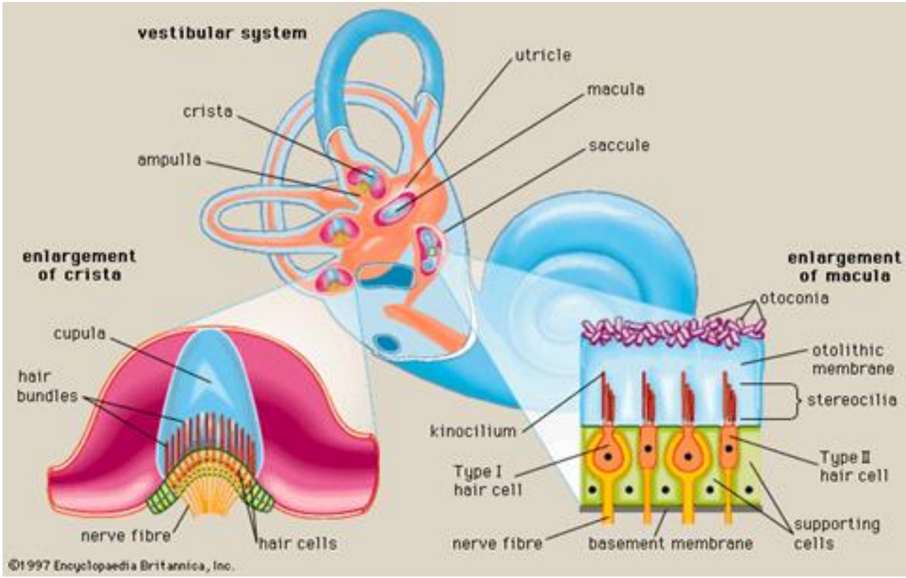

Figure 2: Expanded view of the Vestibular System from Ref. [6].

The primary mechanism behind detecting angular acceleration is attributed to the endolymph movement within the SCCs. When the head moves in one direction, the inertia of the endolymph causes it to move in the opposite direction, deflecting the cupula and subsequent bending of the cilia that are on the hair cells. The hair cells are responsible for transduction of the mechanical movement of the cilia into electrical signals. The bending of the cilia causes a change in the pattern of conduction of the electrical signals from the hair cells to the vestibular nerve which is connected to the brain stem and four vestibular nuclei within it. These nuclei are the main integration centers of vestibular sensory information and send the signals to the brain to create the appropriate compensatory response action [2,3,7].

The functions of the utricle and saccule are similar to that of the SCCs in responding to linear acceleration of the head in the horizontal and vertical directions, respectively. These organs are approximately perpendicular to each other, with the utricle being larger than the saccule. Both include a region known as the macula, a cross-section of which is shown in Figure 2. It includes the otolith, a gelatinous region composed of calcium carbonate to which are attached hair cells and the cilia (a longer kinocilium and a cluster of shorter stereocilia). This membrane is weighed down by a layer of calcium carbonate granules, the otoconia. When the head tilts forward or backward from its upright position, the otoconia move in response, exerting a shear force on the otolith membrane, moving the stereocilia and changing the sensory electrical signals generated by their hair cells which are then transmitted to the brain through the vestibular nerve [2,3].

Any disruption or disorder to the VS and its function can severely hinder one's ability to maintain balance. Some of the most common vestibular disorders are referred to as benign paroxysmal positional vertigo, Menière's disease, vestibular neuritis, and bilateral vestibulopathy. Meniere's disease, for example, is a condition characterized by an excess of endolymph in the semicircular canals, leading to imbalances in the body and sudden movements, such as when transitioning from a lying down position [8]. Symptoms of these disorders range from double vision, migraines, lack of muscle control (ataxia), or the illusion that the environment around you is moving (oscillopsia). Many neural pathways related to the VS's translation of sensory information and the control of cognitive functioning remain undetermined. Most VS dysfunctions are attributed to medicines causing vestibular toxicity, infections, poor circulation in the inner ear, calcium deposits in the semicircular canals, and traumatic brain injury [9]. Understanding the mechanism behind these dysfunctions will improve treatment methods and the fundamental understanding of the VS. To further improve our treatments of vestibular dysfunction, we must first improve our understanding of the VS and the pathways involved in the integration of sensory information. Therefore, the VS remains a significant research interest.

This paper has been developed to introduce the vestibular system and its functions to an interdisciplinary audience. There are two primary goals with respect to engineering education. The first is to develop a novel model of graduate education for students in different disciplines to learn how to collaborate on a new research problem using foundational knowledge they have gained in their respective areas of study. The second addresses building skills in technical communication to a diverse audience. This will be demonstrated in future work by mapping this research to an online educational module to introduce this topic to undergraduate students in different courses such as Feedback Control Systems, Survey for Biomedical Engineering, Design of Control Systems, and Biomechanics. Section II discusses the training that graduate students underwent as participants in the Innovations in Graduate Education – Cyber-Physical Systems Engineering project. The rest of this paper focuses on developing the material that will be mapped to an online lesson module in the next phase of this project. Section III presents a survey of some of the modeling methods that have been considered to simulate the functional behavior of the VS organs. Section IV develops an experiential learning activity through the design of a feedback control system that captures some of the macro-level dynamics of the VS. Section V presents the students' perspectives on their learning outcomes of the graduate education model.

II. Graduate Education Model: Co-Creation Process

This project is the product of a collaborative initiative for developing an innovative model of graduate education. The thesis of the educational model was that graduate students co-creating educational modules on an interdisciplinary topic with faculty mentors would lead them to acquire important professional and technical skills that would benefit in their future research and career roles. It was structured in a project-based learning framework, utilizing the gold standard model proposed by John Larmer [10] and its seven essential steps. These steps include: (i) A challenging question or problem; (ii) Sustained inquiry; (iii) Authenticity; (iv) Student voice and choice; (v) Reflection; (vi) Critique and revision; and (vii) Public product. The public product in this instance was this publication.

The four graduate student members of this project came from two different institutions, three from the University of Massachusetts Lowell, majoring in Biomedical Engineering, Electrical Engineering and Mechanical Engineering and one from the University of the District of Columbia, majoring in Mechanical Engineering. The group co-created the material for this research with feedback from three faculty mentors in the two participating institutions. Faculty and student interaction is crucial in the co-creation process, and it has been found to provide many benefits on students' educational development and class engagement [11]. Co-creating or co-designing education modules can lead to deeper interaction, benefiting both students and faculty [11].

Before starting the co-creation process of developing the model, the group first had to understand that this was an interdisciplinary co-creation work. Therefore, the first challenge was to find a way to see how people from different academic backgrounds (Biomedical, Mechanical, Electrical, and Computer Engineering) at different academic levels (graduate and faculty members) can collaborate with each other successfully. To address this, at the beginning of the project, the group participated in several workshops to develop a deeper understanding of co-creation work, its advantages, and challenges. For instance, one of the common challenges involved in collaboration is microaggressions. To solve this, the group thought to create an environment in which each member could feel comfortable sharing their thoughts without having a bad feeling of being judged that their opinion is not correct or appropriate, regardless of their academic level.

Several ideas were investigated during the co-creation process. The faculty and students came together to discuss the best approach to educate students about the human vestibular system. The first step in the process was to understand the target audience. Target audience refers to the students for whom the educational model is intended. To understand who our target audience is, the faculty and students discussed what level of background knowledge the audience would need, what experiences, and what courses they have taken, among other topics. By understanding the target audience, the group developed a module to meet their students' needs and further their knowledge about the human VS.

The next step was to determine a suitable method to instruct the students. The researchers co-created the educational module using an experiential learning approach. Experiential learning, much like co-creation, is a student-focused approach that has gained popularity in recent years [12]. "Experiential education is a teaching philosophy that informs many methodologies in which educators purposefully engage with learners in direct experience and focused reflection in order to increase knowledge, develop skills, clarify values, and develop people's capacity to contribute to their communities" [13]. This method is about the students learning through direct experiences. An objective was to ensure students' experience on how the VS can be affected by a disease such as Meniere's disease. In the guide by the Center of Innovative Teaching and Learning at Northern Illinois University, the experiential learning process is discussed and outlined [14]. Students will go through the process of experiencing, reflecting, analyzing, generalizing, and applying. Faculty will play a part in facilitating the module but will not have a significant role in the students' learning.

This co-creation process gained much of its inspiration from the students within the group identifying weaknesses in the current approach to teaching about the vestibular system. Two of the members within this group are biomedical engineering majors and much of their curriculum was focused on anatomy and physiology as well as the quantitative physiology of the human body. The general approach that was taken to instructing students about the vestibular system was through an introduction to the definition of all anatomical parts and their function. Then, an investigation into diseases related to the vestibular system can be addressed through engineering interventions. This approach lacked an interactive component and does not satisfy all types of learners' needs. Thus, there is a need for a more engaging curriculum format to incorporate hands-on learning.

The graduate students were provided training on a variety of topics, typically in workshop format, at bi-weekly intervals, during the Fall and Spring semesters. Each workshop addressed a topic relevant to the broader goals of students learning how to co-create with faculty and also to help develop the teamwork skills necessary for the project-based learning e model that anchored the research. Table 1 outlines the workshop topics and highlights some of the key learning outcomes that students applied in their collaborative work.

Table 1: Objective of each co-creation workshop participated and their learning outcomes.

Workshop Topics	Student Learning Outcomes
Introduction to the workshop by emphasizing the project goals	• The main goal of the project was explained, which is to co-create a public product in the form of a conference paper and an online educational module.
Writing exercise about the project topic, Vestibular Systems	• Wrote short paragraphs of our interpretations of the vestibular system and feedback was received from faculty members about how to improve our explanations, such as using references properly and defining key terms.
Defining co-creation and the interdisciplinary collaboration	• Discussed how to handle micro-aggressions and how to support co-creation through collaboration and defined interdisciplinary collaboration by providing different categories of collaboration and their definitions.
Facilitating the question formulation technique and finding and reviewing literature	• Learned how to produce and improve our questions, strategize on how to use our questions, and reflect on what we have learned. • Learned about closed-ended and open-ended questions, their advantages, and how to change a closed-ended question into an open-ended question and vice versa. • Learned how to use databases to find sources for literature review and how to use keywords.
Creating a message box for an issue	• Developed the message box concept that aids in solving an issue by asking and solving questions such as, who is impacted by this issue; what can be done to address the issue; how the solution impacts them.
Defining Bloom's Digital Taxonomy verbs and structuring online educational modules	• Defined Bloom's Taxonomy verbs which are action words that helped to clarify and communicate the intended learning outcomes of the research topic. • Discussed how to structure online educational modules by answering several questions such as: What are the learning outcomes? How will students demonstrate what they have learned?
Determine our core values	• Discussed with faculty as to what would be the most important thing to learn from the online educational module and how it would influence academic and career choices.
Literature review preparation and writing topic sentences	• Conducted a comprehensive search for relevant literature using databases. • Evaluated the literature by assessing their relevance to the VS research topic. • Organized and wrote concise topic sentences for each paragraph in relevant papers that summarized the main idea or argument in that section.
Revisiting our message box	• Identified and defined the problem to be addressed in the paper. • Defined our audience. • Organized our thoughts to address the problem and create a solution. • Implemented the planned solution to fulfill our goal to solve the defined problem. • Discussed benefits of the defined solution to the problem.

Improving our message and those of other teams	• Continued to improve upon the message box from previous workshops by comparing our message box to those of other groups attending the workshop. • Critiqued the other groups' message box and understanding of their audience by addressing the relevancy of their answers to the topic sentence.
Effective collaboration and sequencing and presenting information in online educational modules	• Listened to every team member's opinion and learned to respect their opinions. • Exchanged feedback on individual work and provided constructive criticism to grow and improve as a team so everyone can be benefited by the paper's outcome. • Exchanged ideas and opinions while also being inclusive of each member in the team.
Ways to promote intercultural collaboration and cultural competency	• Understood and acknowledged that diverse cultures and even different people in the same culture exist. • Assessed diverse cultures from multiple points of view. • Exchanged experiences on an individual level as well as a team so we could understand each other better which resulted for our project to yield the best possible outcome.
Assessing student learning in online educational modules	• Discussed methods to assess student learning by exploring the types of assessments: o Diagnostic - Assess students' prior knowledge about VS. o Formative – Assess students' understanding of the topic periodically in the form of quizzes. o Summative – Assess students' obtained knowledge learning after each section or module is finished.

During the workshop training, the process of generating questions aided the team in the development of this paper, as well as in investigating what questions can be developed for the classroom setting. For example, one of the questions that arose was how the vestibular system can be modeled to be interactive and how the interactive model can be used in a classroom setting. The students conducted research to answer such questions and refined their responses with the assistance of the faculty. After refining these questions, they would be added to the online educational module as a method to assess the students. The questions would be implemented in the form of quizzes for students to understand the outcomes of the experiential learning method. After each section of the module, the students would be asked to write a summary of what they have learned from the section, thus, aiding in their understanding.

III. Survey of Vestibular Models

This section presents some of the approaches taken by the research community in modeling the vestibular system. One of the earliest efforts in modeling the VS was focused on understanding its functions in the absence of gravity, such as during space exploration. In 1969, Young [15] described semicircular canal mechanics using a model of the torsional pendulum, which is a rigid body suspended by a string or a wire. The model parameters were the moment of inertia of the endolymph, the friction of the endolymph with respect to the skull, and the stiffness of the cupula. The transfer function capturing the ratio of the cupula deflection to the head angular acceleration consists of a second-order characteristic equation with real roots under overdamped conditions. The poles represent two radians per second frequencies corresponding to the long and short time constant of the cupula return phase. This model allows one to predict the position of the cupula for several types of forcing functions that represent the angular acceleration applied to the head. Subjective tests conducted on the sensation of rotation and with measurements of eye movements expected to be proportional to the cupula displacement showed some agreement with the pendulum model. As noted by Young, the torsional pendulum was studied as a model of the semicircular canal dynamics in earlier works by Steinhausen [16] and Van Egmond [17].

A review of mathematical models for simulating the function of semicircular canals is provided by Kondrachuk et al. [18]. They distinguish modeling efforts that have been influenced by advancement in experiments of the SCC morphology and in the development of application software to support finite-element modeling of three-dimensional structures of the sensors with relatively accurate physical and geometrical parameters. They categorize models as reconstructive, microsimulation, integrated, simulation, and alternative models of SCC functioning.

Reconstructive Models

These models result from transforming two-dimensional image sections of the sensory system to three-dimensional structures. This includes imaging nanometer thick samples of the epithelium and X-ray microtomography of the spatial position and orientation of SCC systems. Bradshaw et al. [19], created a mathematical model of the semicircular canals by reconstructing CT scans of subjects from their diagnostic tests for balance problems into 3D datasets. They implemented this model by using the Fourier series equation. Their aim was to present a geometrical description of the semicircular canals to make understanding the morphology of the semicircular canals simpler. A 3-dimensional model of the cochlea and VS of a chinchilla's inner ear was presented by Liang et al. [20]. They built a geometrical model of a chinchilla's inner ear based on a set of X-ray micro-computed tomography scanning of an adult chinchilla. The model included all the surfaces of the components of the VS such as the semicircular canals and the bony structures which had physical geometrical structures. These surfaces were reconstructed based on the CT scans of the adult chinchilla to create a finite element model that included these components of the inner ear.

A powerful low-cost, and flexible imaging system with high spectral variability and unique spatiotemporal precision for simultaneous optical recording and manipulation of neural activity of large cell groups was developed by Direnberger et al. [21], to overcome various constraints such as visualization of neural network activity in the available imaging systems. The system is comprised of eight high-power light-emitting diodes, a camera with a large metal-oxide-semiconductor sensor, and a high numerical aperture water-dipping objective, which allows fast and precise control of excitation and simultaneous low noise imaging at high resolution. Adjustable apertures generated two independent areas of variable size and position for simultaneous optical activation and image capture. They conducted experiments using semi-isolated in vitro preparations of axolotl (Ambystoma mexicanum) larvae, which revealed specific cellular properties and synaptic interactions between excitatory and inhibitory inputs responsible for spatiotemporal-specific sensory signal processing. The discovery of these previously unknown properties of vestibular computations demonstrates the merits system for practical applications in neurobiology.

Microsimulation Models

These models are improvements on the classical lumped parameter model of the torsional pendulum to examine the frequency dependence effects on the ratio of angular displacement of the cupula to the angular rate of the head movement. The work by Vega et al. [22] is an example of a fluid-dynamical model of the mechanical coupling in the semicircular canals that also includes distributed morphological parameters in its set of differential equations. This model combines the pendulum model with hydrodynamics by considering the cupula as an elastic piston in a viscous fluid (endolymph). Boselli et al. [23], developed a computational fluid dynamical model of the endolymph and its interaction with the semicircular canals and the utricle. They found vortical flow in the utricle and the ampulla that had higher flow velocities than that in the SCC. They also presented a parametric study on how the morphology of the labyrinth affects the formation of the vortex and how that influences the endolymph flow in the VS. The model also showed that the wall stresses in the utricle and ampulla were maximized at the sensory epithelia. Gastaldi and Sorli [24], designed a model of semicircular canals which can detect only the rotational movements of the body. They presented a mathematical model of the semicircular model. Additionally, they also conducted a fluid-dynamic analysis of the semicircular canals based on the geometry of the semicircular canals. These models were of two types, a mono-canal model, and a three-canal model.

Integrated Models

These models develop a transfer function of a mechano-electro-chemical system to incorporate transduction by the hair cell. Such models are designed to allow comparison of the results of biomechanical models with data from electrophysiological experiments [25].

Simulation or Imitation Models

These models attempt to simulate the results of physical experiments, particularly some of the pathological states of the SCCs such as mechanical failure of the VS functioning causing symptoms of vertigo.

Andreou et al. [26], presented an alternative approach for angular-rate sensing based on the method by which the VS, specifically the semicircular canals, naturally function. Gyroscopes are commonly used as a method of vestibular therapy [27]. Their main goal was to design a gyroscope that would consume less power than vibration-based gyroscopes. The gyroscope they designed was created with the help of MEMS-Microfluidic solutions that enabled the implementation of microfluidic channels in etched glass layers, which sandwiched a bulk-micromachined silicon substrate consisting of the sensing structures. Micro-Electro-Mechanical System (MEMS) gyroscopes are motion sensors that detect and measure the angular motion of an object [28]. They compared the angular rate sensitivity results of the designed gyroscope with a reference device, indicating an angular rate sensitivity of fewer than 1°/s, equivalent to that of the natural VS. An ultra-low power consumption of 300 μW was achieved without continually excited vibrating mass, which makes this device appropriate for implantation as opposed to the traditionally used gyroscopes.

Alternative Models

This class of models deviate from the classical assumptions such as attributing a piston or membrane like structures of the cupula and that the interaction between the endolymph and the cupula deflects it from its equilibrium position. Rather, to support experimental observations these alternative models such as in Damiano [29] have assumed a two-component poro-elastic structure for the cupula with solid and fluid inclusions. Models have been proposed that assume the VS integrates sensory information with prior knowledge about the environment in a Bayesian framework. This model suggests that the brain combines vestibular cues with other sensory cues and contextual information to estimate self-motion and the orientation of the body in space. For instance, [30] proposes a Bayesian model of visual-vestibular interactions in the rod-and-frame task, where participants adjust a tilted rod to the vertical in the presence of a surrounding tilted frame. The model considers the uncertainty of sensory signals and prior knowledge and predicts that the visual and vestibular signals are weighted according to their reliability and integrated to estimate the rod's orientation. The model's predictions are compared to human behavioral data in a series of experiments, showing that it can account for the effects of frame tilt, frame roll, and sensory conflict on the perception of rod orientation. The results support the idea that the brain combines visual and vestibular cues in a statistically optimal manner and provide insights into the neural mechanisms underlying perception of spatial orientation.

Vestibular System Models for Experiential Learning

In the paper by Canelo et al. [31], they presented a human-inspired orientation and balance control system that simulated a person sitting on a platform with the help of virtual reality. This system was based on the VS by acting on the behavior of the semicircular canals and otoliths in the presence of stimuli- that is, by modifying the parameters on the cartesian axes. They used a robot head that was based on the human VS. They simulated this with the MATLAB/Simulink environment to show that the head's orientation in space can successfully be controlled by a proportional-integral-derivative (PID) with a noise filter for each DOF (degree of freedom).

In the paper "Modeling the Human VS as a Controlled System" by Lu et al. [32], the authors aimed to develop a simulation using MATLAB/Simulink. Only one semicircular canal was considered, as each channel would have the same input and output but in different planes. Second, only the body mass was accounted for in the simulated model, forgoing damping or stiffening of the body.

A mechanical model of the semicircular canal was proposed as angular accelerators in a specific kinematic environment by Selva et al. [33]. This model was developed and implemented with MATLAB/Simulink. Their model was aimed to simulate rotary chair testing. A rotary test is used to determine if the VS is functioning appropriately and is considered one of the most common diagnostic tests to detect balance problems related to the VS [34]. Their model enables the simultaneous display of each angular sensor’s excited or inhibited status while simulating multiple head rotations. Their model can be used to interpret sensor behavior during any type of motion and understand the functioning of the VS.

IV. An Experiential Learning Model of the Vestibular System

In this section, the first stage of an interactive simulation of the VS's response to an input force is presented. In this context, the VS functions as a sensor, with the corresponding semicircular canal capturing the angular accelerations that may occur with respect to its perpendicular axis. The intent is that students understand the role of the VS and its function in sensing and transmitting information to the brain. The system presented also includes a simple model of the response of the brain in producing the compensatory reflex signal, which is modeled in the feedback control system as reducing the error between the nominal and changed position of the head. The students will also benefit by exploring the relevant parameters of the system and their effect on the VS system response.

To explain this further, the equations to be used in this simulation should be understood. The classical model of the VS in Young [15] and in other publications [31, 32, 33] is based on a torsional pendulum, which is used to determine the response of the semicircular canal. The behavior of the endolymph in the semicircular canal can be represented by a second-order differential equation. The equation is given as:

$$m\frac{d^2q}{dt^2} + c\frac{dq}{dt} + kq = f \tag{1}$$

where q(t) is the displaced volume of endolymph, c is the damping coefficient and k is the stiffness of the cupula. The mass of the fluid in the canal is represented as m. The applied inertial force is represented as f(t).

The transfer function allows one to characterize the system dynamics. The input force is represented in terms of the angular velocity ω(t), such that $f(t) = d\dot{\omega}$, being the coefficient of the force and $\omega = \dot{\theta},\ \theta(t)$ the angular rotation applied. The transfer function,

$$\frac{Q(s)}{\theta(s)} = \frac{\frac{ds^2}{m}}{\left(s^2 + \frac{c}{m}s + \frac{k}{m}\right)} \tag{2}$$

Factoring the denominator, the roots of the second-order polynomial in s can be represented as $p_1 = \frac{-\frac{c}{m}\left(1-\sqrt{(1-\zeta)}\right)}{2}$ and $p_2 = \frac{-\frac{c}{m}\left(1+\sqrt{(1-\zeta)}\right)}{2}$, where $\zeta = \frac{4km}{c^2}$ is assumed to be less than one. The given equations represent the roots p1 and p2 in terms of the constants c, k, and m, which are properties of the cupula and the fluid in the semicircular canal. The parameter ζ is a dimensionless constant that represents the damping ratio of the system. This was derived under the assumption of overdamped condition, leading to two real roots, both negatively valued. The roots p1 and p2 can be used to calculate the time constants of the system, which represent the rate of change of the system's response to a stimulus. In this case, the time constants are represented as s $\tau_1 = -1/p_1$ and $\tau_2 = -1/p_2$. The smaller of these time constants corresponds to the rapid deflection of the cupula, while the larger time constant characterizes the cupula's return to its nominal position.

The deflection of the cupula in the semicircular canals of the ear generates sensory signals from the hair cells that are transmitted to the brain and the central nervous system. In response, the brain produces reflexes that are needed to compensate for the externally applied force. This compensation response is modeled as a control signal in this system, with the objective of reducing the error between the nominal or vertical position of the head and the position it moves to under the application of the force.

The output of the system is the force that makes the person move to the new position. In this context, the response is modeled by a proportional and derivative controller (PD), which is a type of feedback controller used in engineering systems. The PD controller produces a control signal that is proportional to the error between the desired setpoint, and the current state of the system being controlled, with an additional term that is proportional to the rate of change of the error. The control signal in the frequency domain is given by:

$$F_c(s) = K_p + K_d s \tag{3}$$

Where K_p is the proportional gain and K_d is the derivative gain. The proportional gain determines the magnitude of the control signal based on the error, while the derivative gain determines the rate of change of the control signal based on the rate of change of the error. The derivative gain provides a damping effect, reducing overshot and oscillation in the system response.

This force from the control signal must be converted to a new body position. This is accomplished by $F_c(s) = Ms^2\theta(s)$ where M here represents the body mass of the person, and $\theta(s)$ is the position of the body in response to the applied force. The term Ms^2 represents the inertia of the body, which is the resistance of the body to changes in its state of motion.

Figure 3 illustrates the input force generated by the tilting platform block that drives the vestibular system (VS) and produces an angular motion measured in radians. The angular motion is then compared with the reference input at the nominal vertical position, resulting in an error signal that is processed by the proportional and derivative (PD) control module of the brain subsystem. The PD control module produces a corrective force, which is then converted into a corrective angular position and displayed on the scope.

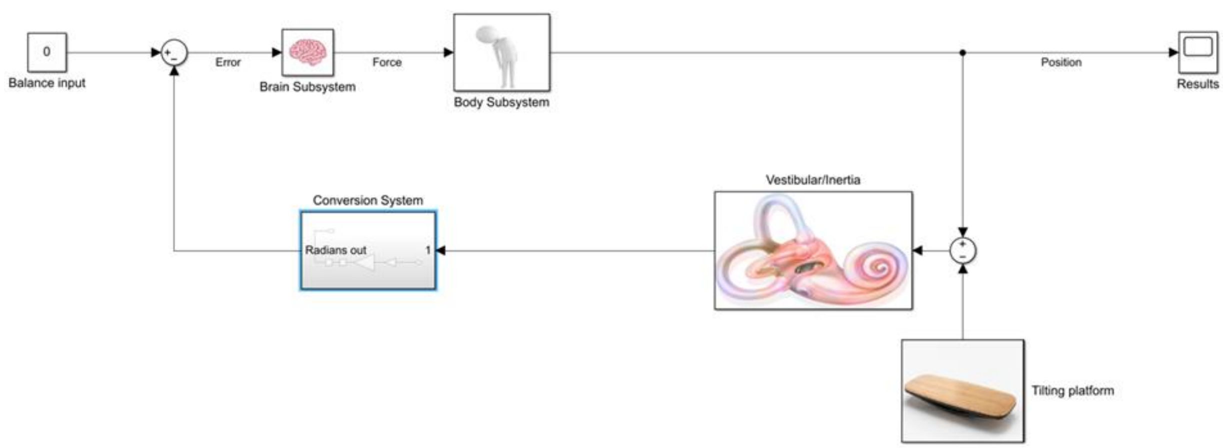

Figure 3: Simulink Block Model of the vestibular system and the feedback control from the brain subsystem.

The block diagram of the Body Subsystem is shown in Figure. 4, where $\frac{1}{s^2}$ represents the frequency domain transfer function that describes the relationship between the force applied to a system and the resulting position of that system and the body mass is denoted as M. Specifically, $\frac{1}{s^2}$ means that the system has a second-order response, which is characterized by a double pole at the origin of the frequency domain (i.e., at s=0). This indicates that the system has a natural frequency of zero and a high degree of damping, which means that it responds slowly to changes in the applied force and does not oscillate.

In practical terms, a system with a transfer function of $\frac{1}{s^2}$ would be expected to have a very slow and gradual response to changes in the applied force, with the resulting position changing slowly over time. This type of response might be appropriate for systems that need to be very stable and resistant to sudden movements, such as a building, a bridge, or the human body.

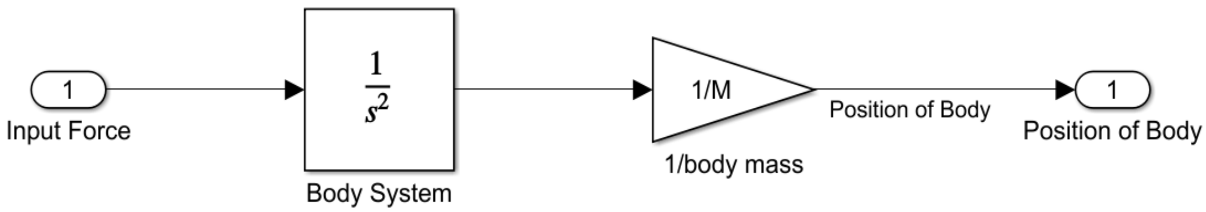

Figure 4: Body Subsystem Simulink Model.

The vestibular subsystem is a transfer function module as shown in Figure. 5.

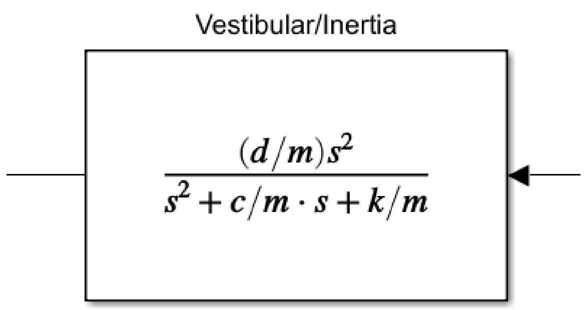

Figure 5: Transfer function Simulink Model of Vestibular/Inertia.

Finally, the conversion module converts the volume displacement to angular rotation in units of radians.

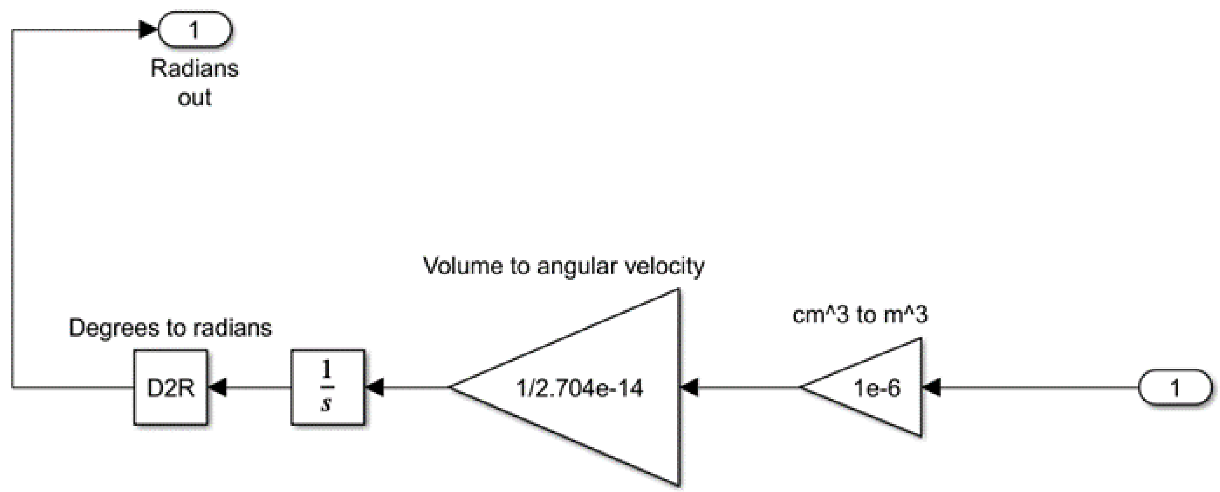

Figure 6: Section of Simulink sensor subsystem that shows the conversion from the transfer function output units to position units.

The system parameters m, k and c can be estimated from geometrical and physical properties of the semicircular canal as shown in Rabbitt [35]. The stiffness parameter $k = \frac{\gamma h \lambda}{A_c^2}$ where γ is the elastic shear modulus of the cupula, A_c is the frontal area of the cupula, h is the thickness of the cupula. The parameter $\lambda \approx 8\pi$ for low frequency movements of less than 6 Hz. The hydraulic resistance $c = \frac{\mu l \lambda}{A^2}$, where μ is the viscosity of the endolymph, l is the length along the centerline of the SCC, and A is the cross-sectional area of the SCC. The mass is equal to $m \approx \frac{\rho l}{A^2}$, and the coefficient of the inertial force is $d = 2\pi\rho R^2 \cos(\beta m)$, where ρ is the endolymph density, R is the characteristic radius of the SCC loop and β_m represents the angle between the maximum response direction and the angular rotation direction. Methods for estimating these parameters are given in Selva [36]. It is shown that values of k range from 2.2 – 13 GPa/m^3 under the assumption that range of the long-time constant varies from 4 to 21 seconds.

Table 1 specifies a characteristic set of parameter values for the model. These parameters when applied in the computation of the poles of the characteristic equation, yield the two-time constants $\tau_1 = 23.56$ and $\tau_2 = 0.0045$ seconds. The value of $\tau_1 = 23.56$ corresponds to the long-time constant taken for the cupula to relax back to its nominal position.

Table 2: Parameters of model of the semicircular canal.

Parameter	Value	Description
k	14,000 dyn/cm^5	Stiffness of the cupula coefficient
m	1500 g/cm^4	Mass of fluid in semicircular canal
d	0.76 g/cm	Inertial force coefficient
c	330000 dyn s/cm^5	Damping coefficient

The stiffness coefficient in the semicircular canal is a measure of the canal's resistance to deformation under an applied force. The result of varying the stiffness coefficient, k, was observed by using a range of k values as shown in Table 2. The magnitude of k significantly changes the long time constant. Table 2 shows these results.

Table 3: Effect of change in k

k (dyn/cm^5)	τ_1 (seconds)	τ_2 (seconds)
1.33 x 10^4	24.8	0.0045
2.6 x 10^4	12.68	0.0045
5.2 x 10^4	6.34	0.0045
10 x 10^4	3.29	0.0046
20 x 10^4	1.64	0.0046

An example of the result from the Simulink model is shown in Figure. 7 under both healthy conditions and unhealthy conditions considering a change in the mass of the endolymph for the case such as in Meniere's disease. For this case, the mass m was increased to 2005 g/cm^4.

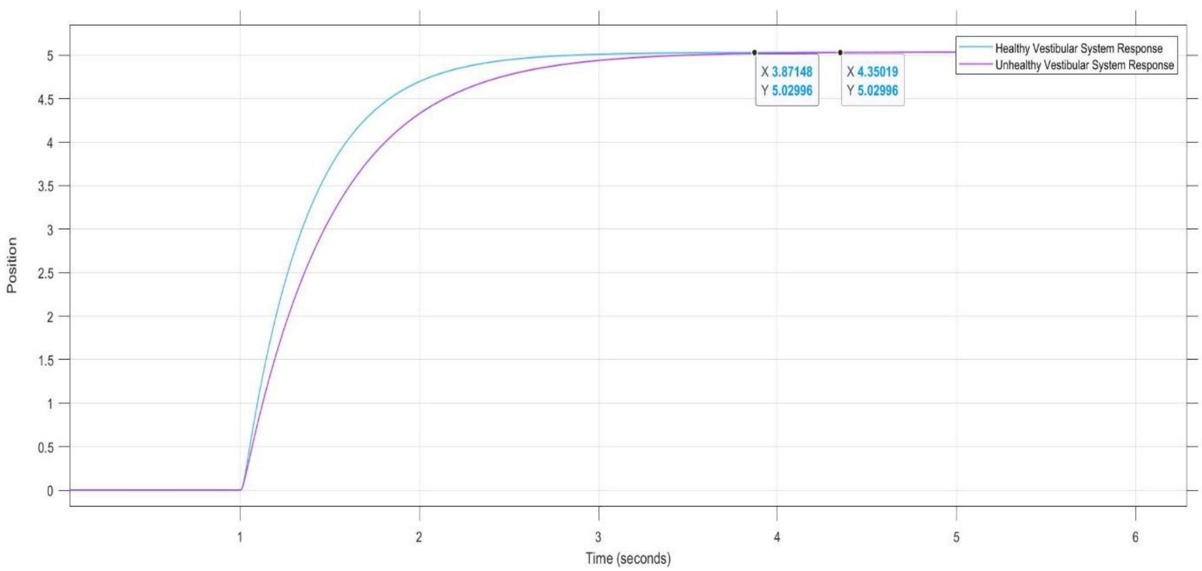

Figure 7: Healthy and unhealthy system response.

From the response, it can be interpreted that it takes approximately 2.87 seconds for the endolymph to settle, thus, stabilizing the body. The body position changes drastically within the first 1.25 seconds and settles around 1.3 seconds. This response shows that the brain acts quickly to deliver a good estimate of correction for the body to be stable, with small adjustments for proper stabilization.

A human VS inflicted with Meniere's disease can be simulated into Simulink by altering the transfer function of equation (2). Meniere's disease causes the body to take more time for the endolymph to settle in the canals, thus, causing the body to take more time to adjust itself to a balanced position [6].

When replaced into our Simulink model, it is expected to see a longer settling time in comparison to a healthy VS, which is evident in the results above.

This MATLAB activity allows for the computation of difference in stabilizing times when a person is healthy versus being diagnosed with Meniere's diseases, which provides an indirect measure of the vestibular system's contribution to balance. By visualizing the stabilizing position data over time, students can see how the balance score is affected by different types of movements and can gain a better appreciation for the importance of the vestibular system in maintaining balance.

This MATLAB Simulink activity can help students learn more about balance and the vestibular system by providing a practical example of how to indirectly measure balance using SCC parameters. The students will be given step-by-step instructions on how to build the model themselves in order to visualize the outcome and understand the inner working of the model. The model would be able to be built during one classroom session, and the students would have enough time to visualize the difference after changing parameters. By studying this model and modifying it to analyze their own SCC data, students can gain a better understanding of how the vestibular system contributes to balance and how stiffness coefficient can be used to indirectly measure it. Students can also pose questions about their results, or other aspects of the vestibular system through the online module, which would be answered promptly by the team of graduate students.

Additionally, by visualizing the stabilization posture over time, students can see how the balance score is affected by different types of movements and can gain a better appreciation for the complexity of the vestibular system and its role in maintaining balance. Therefore, this MATLAB provides a useful tool for students to learn about the vestibular system and balance and can help them develop the skills needed to analyze postural sway data in future research projects or practical applications.

V. Conclusions

In conclusion, this work presented the design of an educational module about the vestibular system that was developed through a co-creation process by a team of four students from three different engineering disciplines and three faculty mentors. This work will be converted to an online research and education module and disseminated to related courses such as Quantitative Physiology, Human Anatomy and Physiology, Control Systems, Biomechanics, and Research Experience and Technical Communication being taught at partnering institutions.

The students used a project-based learning approach, where they learned by identifying and solving problems related to the VS. These problems were identified with the aid of faculty members, the provided workshop trainings, and the students' experience. One problem was a lack of interactive components that do not allow for catering to different types of learners. Thus, the students were able identify an engaging method of teaching about vestibular systems through the using of engineering inventions and software such as MATLAB, which would allow for a more engaging and hands-on type of learning that will cater to different learners. Through using this engineering software, the graduate students involved in the creation of this paper were able to learn about how the vestibular system can be interpreted as an electromechanical model, and how the parameters of it can be changed to simulate the response time of the body and vestibular system. Similarly, students being taught will be able to visualize the outcome of the electromechanical model.

The objective of this paper was to first present an accessible introduction to the structure and functions of the vestibular section. Next, a survey of models of VS dynamics was discussed. Finally, a simulation was created with MATLAB/Simulink utilizing a classical electromechanical model of the VS. This model captured macro-level dynamics of the semicircular canal, such as the deflection of the cupula, and its connection to the brain and body. The VS was modeled as a circuit, with the brain sending balance-correcting signals as inputs and the body's position as the output. The current model was created using MATLAB/Simulink, and future work aims to expand and improve on the experiential learning components of the model.

The team's exploration of various aspects of the simulation helped develop potential questions that can be asked of students while they are doing the simulation in a classroom setting. Furthermore, the questions raised during the development of the experiential learning model assisted the students in writing this paper, which will be utilized to create an online educational module in the second phase of this research. This online lesson module will be utilized to teach undergraduate and first-year graduate students about the vestibular system in the context of core concepts presented in control, feedback, and systems courses. The students will collaborate with instructors and industry mentors to create project-based learning lesson plans related to the vestibular system, and expand the co-creation project so that it is accessible to a wider student audience.

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