Mersivity: XRSC (eXtended Reality Spatial Computing) for Health, Well-Being, and Accessibility

Aydin Hosseingholizadeh, Mete Isiksalan, Steve Mann, Aoran Jiao, Nishant Kumar, Gavin Mok, Emily Chen, Alex Cho, Daniel Ho, Ted Yoo, Mateusz Kazimierczak, Somin Mindy Lee

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Abstract

This paper provides an overview of Mersivity, also known as Vironmentalism or XRSC (eXtended Reality Spatial Computing) with applications in health, well-being, and accessibility. There is a growing interest in technologies that are ’mersive (immersive, submersive, or supermersive), i.e. technologies that encapsulate or enclose or surround us. Examples include “wearables”, immersive VR (Virtual Reality), and electric vehicles such as self-driving cars, vessels, and personal aircraft (ABC = Aircraft, Boats, Cars). It is widely agreed that there is a risk or danger of asymmetry of immersive technologies that can separate us, harmfully, from our surroundings. In order to support human health, well-being, and accessibility, it is essential that we can ’merse any of these technologies that ’merse us. If one can’t go for a hike in the forest or along the beach (and maybe go for a swim as well) with the technologies that claim to help us, then those technologies are actually harming us. Thus an important element of Mersivity is a connection to the physical world = the world of “atoms” = nature = the environment = sustainability = our surroundings. Mersivity therefore is at the nexus of the physical (nature/sustainability/environment), virtual, and social worlds. In this paper we provide a historical perspective on XR+SC, from the early spatial computers of the 1970s, the introduction of XR=eXtended Reality in 1991, and leading up to the latest trends such as the “Freehicle” = vehicle of freedom for those with disabilities. See Fig 1.

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1 Abstract

This paper provides an overview of Mersivity, also known as Vironmentalism or XRSC (eXtended Reality Spatial Computing) with applications in health, well-being, and accessibility. There is a growing interest in technologies that are 'mersive (immersive, submersive, or supermersive), i.e. technologies that encapsulate or enclose or surround us. Examples include "wearables", immersive VR (Virtual Reality), and electric vehicles such as self-driving cars, vessels, and personal aircraft (ABC = Aircraft, Boats, Cars). It is widely agreed that there is a risk or danger of asymmetry of immersive technologies that can separate us, harmfully, from our surroundings. In order to support human health, well-being, and accessibility, it is essential that we can 'merse any of these technologies that 'merse us. If one can't go for a hike in the forest or along the beach (and maybe go for a swim as well) with the technologies that claim to help us, then those technologies are actually harming us. Thus an important element of Mersivity is a connection to the physical world = the world of "atoms" = nature = the environment = sustainability = our surroundings. Mersivity therefore is at the nexus of the physical (nature/sustainability/environment), virtual, and social worlds. In this paper we provide a historical perspective on XR+SC, from the early spatial computers of the 1970s, the introduction of XR=eXtended Reality in 1991, and leading up to the latest trends such as the "Freehicle" = vehicle of freedom for those with disabilities. See Fig 1.

2 Background and context

The term "eXtended Reality" (XR) was coined in 1991 [7] as:

> XR is any combination of a virtual environment with reality where the virtual environment is responsive to a real or complex-valued output from reality, by way of real-time computation. It is generally assumed that the virtual environment remains aligned with or strongly coupled to some aspect of reality, e.g. it may simply be an extended response display of reality itself, or it may be a fun or playful interpretation of reality.

XR is a general framework that interpolates between, and extrapolates beyond, all of the "realities", such as VR (Virtual Reality), AR (Augmented Reality), MR (Mediated or Mixed Reality), etc. [8–10]

Spatial computing architectures [11,11–14] and more recently spatial computing itself [15], as well as XR spatial computing [16,17] has emerged as a new and rapidly growing discipline.

Many embodiments of XR were originally built upon an early spatial computer called the SWIM (Sequential Wave Imprinting Machine) invented in the 1970s [18–21]. See Fig 2. SWIM allowed for accurate alignment between the real and virtual worlds with delays much less than 1 microsecond (i.e. equivalent to millions of updates per second) in a way that could be shared among many observers simultaneously on land, in water [4], or in air.

SWIM is a spatial computer in the sense that it provides exact and instantaneous speed-of-light or speed-of-sound spatial alignment between the physical world and the virtual (audio and visual) world [18–21].

2.1 SWIMotor™

The spatial computing of SWIM operates at the speed of wave propagation, e.g. the speed-of-light for radio wave visualization or the speed-of-sound for audio visualization, etc. By mounting the SWIM on an electric motor, the

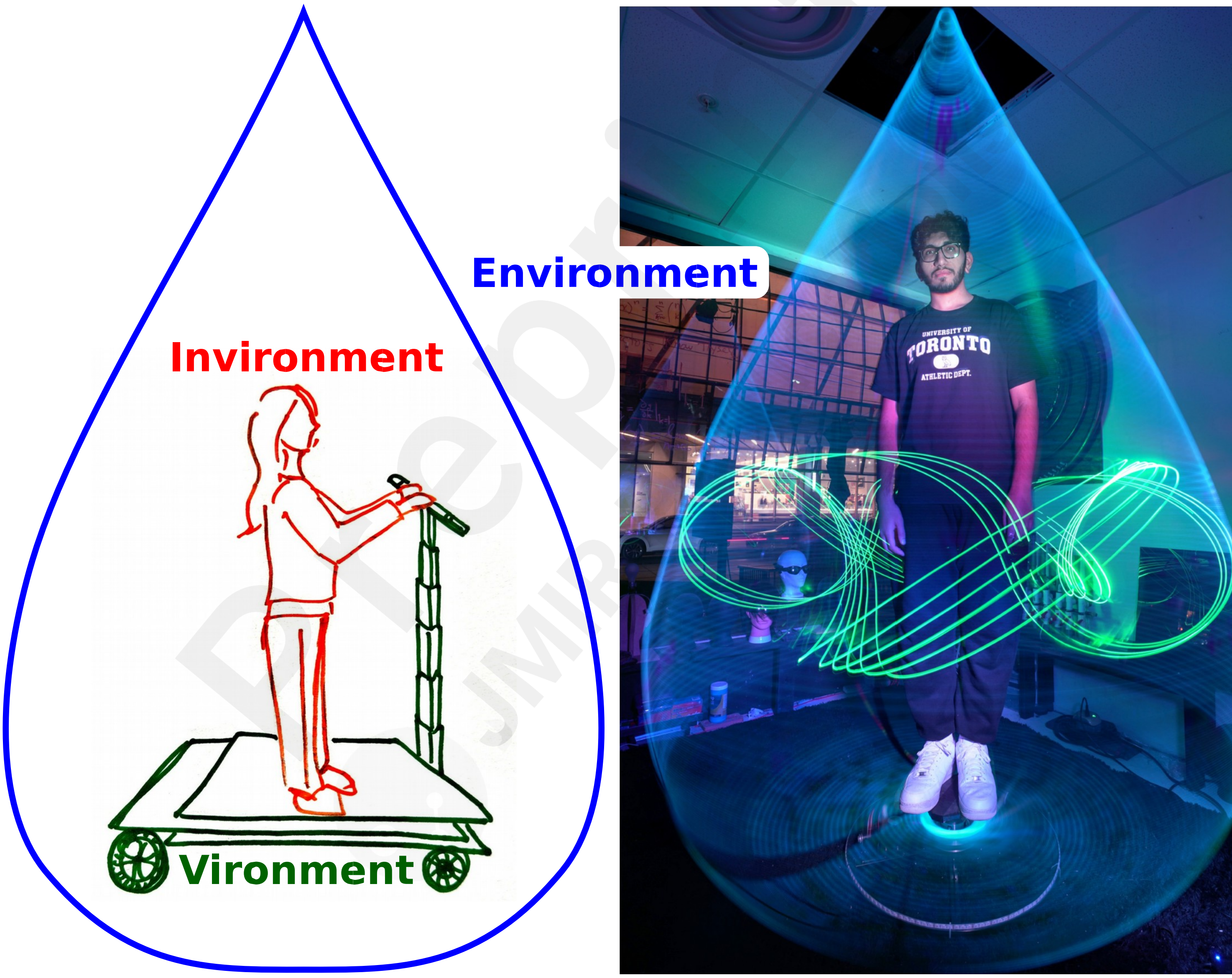

Figure 1. Mersivity (Vironmentalism) considers technology as a loose or well-defined boundary between the Environment (our surroundings) and the Invironment (us) [1–5]. Blue denotes Environment, red denotes Invironment, and green denotes Vironment (the boundary therebetween, e.g. technology), as exemplified by the photograph of the spinning 3-dimensional spatial computer (SWIM) on the right. Examples of vironments include wearable technologies, vessels, and vehicles such as the Freehicle mobility aid for those with disabilities [2,6]. We want to build technologies that

make our surroundings more accessible, rather than building technologies that disconnect us from our surroundings.

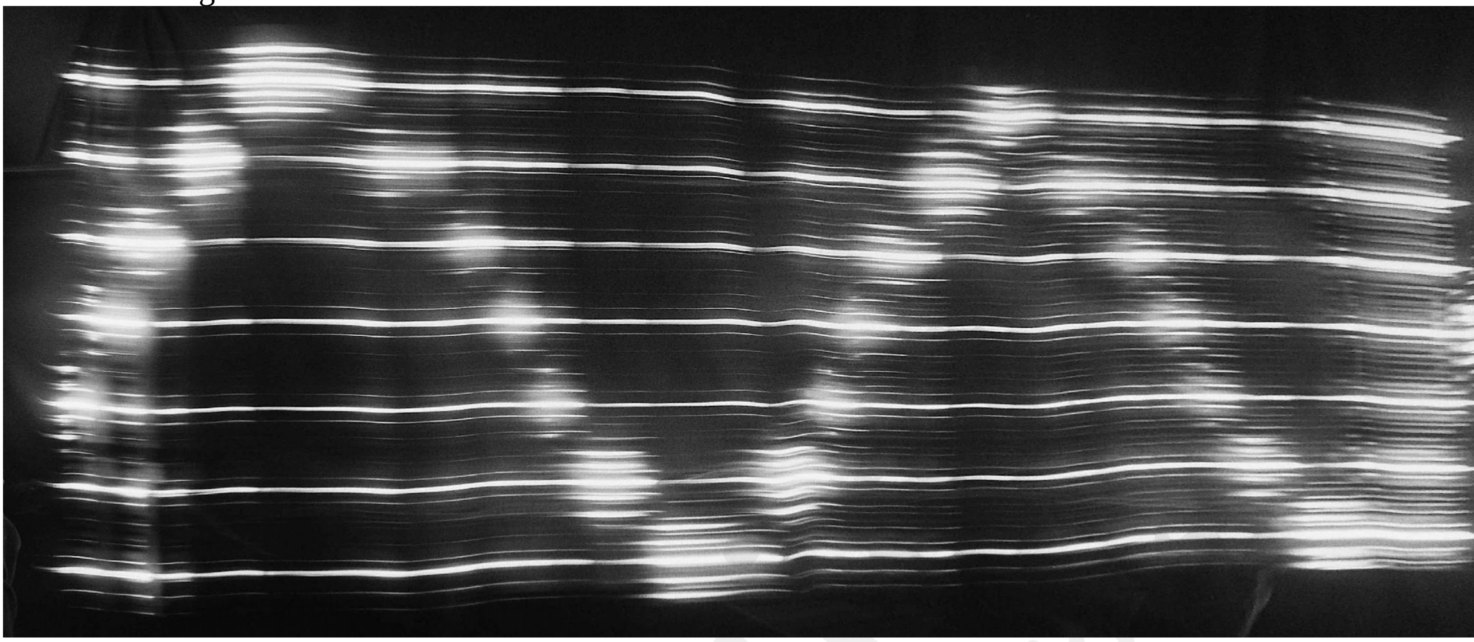

Figure 2. SWIM, an early spatial computer for shared interactive eXtended Reality (XR) [7,22].

rotary SWIM is able to display a 2D representation of the otherwise invisible rotating electromagnetic (EM) fields inside electric motors as shown in Fig 3. In this case the alignment operates at the speed of rotation of the motor, with highly accurate and instantaneous alignment down to a very small fraction of a degree of rotation of the motor. One of the real benefits of SWIM is that many people can view the live real-time spatial computing environment it creates, without the need for any special eyewear or special devices of any kind. This makes SWIM very useful for classroom teaching, as shown in Fig 4 where students are each taught how to build a SWIM and a motorized SWIM.

There has been a recent explosion of interest and research in DC-polyphase motor control in electric vehicles, power-assist bicycles, self-driving cars, electric mobility, and assistive devices. FOC (Field-Oriented Control) of electric motors is taught at University of Toronto, MIT, and Stanford University using spatial computing. See Fig 5 and 6.

3 Teaching the work of Edith Clarke using SWIM

In the 1920s, Edith Clarke, from MIT, invented a clever way of representing 3-phase electrical power as a complex-valued in-phase and quadrature signal plus a total signal. Her work forms the basis of space vector modulation in modern electric vehicles and DC-polyphase motors in general. At MIT, Stanford University, and University of Toronto, and elsewhere, we have been teaching this fundamental work using SWIM.

A Fourier analysis of the ODrive waveforms yields approximately the following:

$$V_a = A(cos(2\pi(t - p)s) - 0.20408cos(6\pi(t - p)s)) + 5.496$$

where A=5.95 is the amplitude/volt; p=0.0185 is the phase; s=23.9 is the scale, as shown in Fig 7. Based on this data analysis, we have created the SWIMulator™ which is a simulation of the SWIM spatial computer. See Fig 8 and 9.

4 Mind Over Motor

Additionally, the SWIM may be programmed to display brain wave patterns (alpha, beta, delta, and theta brain waves), through the use of the Muse-S. See Fig 10.

SWIM makes visible many otherwise invisible phenomena regarding physical systems as well as health and wellbeing. Openness in health and health-care is of growing importance [23], especially in the context of infodemiology

Figure 3. Photograph of SWIM attached to 3-phase motor, 3600 RPM (Revolutions Per Minute), i.e. 2-pole, 1-horsepower motor. Each of the three colors (red, green, and blue) of the SWIM is responsive to a different one of the three phases.

Figure 4. SWIM is a spatial computer that works well for teaching concepts like electric machines in classroom settings, where large numbers of people can view the spatialized content without the need for any special eyewear.
Here we see the 3 phases of six pole pairs of an electric 3-phase motor.

Figure 5. Audiovisual spatial computing used to teach principles of DC-polyphase motor control for micromobility. Here six loudspeakers are arranged spatially and their connection to the motor matches the spatial alignment, e.g. the far speaker is Phase A, and the near speaker is the negative of Phase A, i.e. Phase -A, and the other two pairs are connected likewise to Phase ±B and Phase ±C.

Thus one can hear the rotating magnetic field of the motor as a rotating trinaural soundfield in perfect spatial alignment with the magnetic field. One can also see it upon the SWIM.

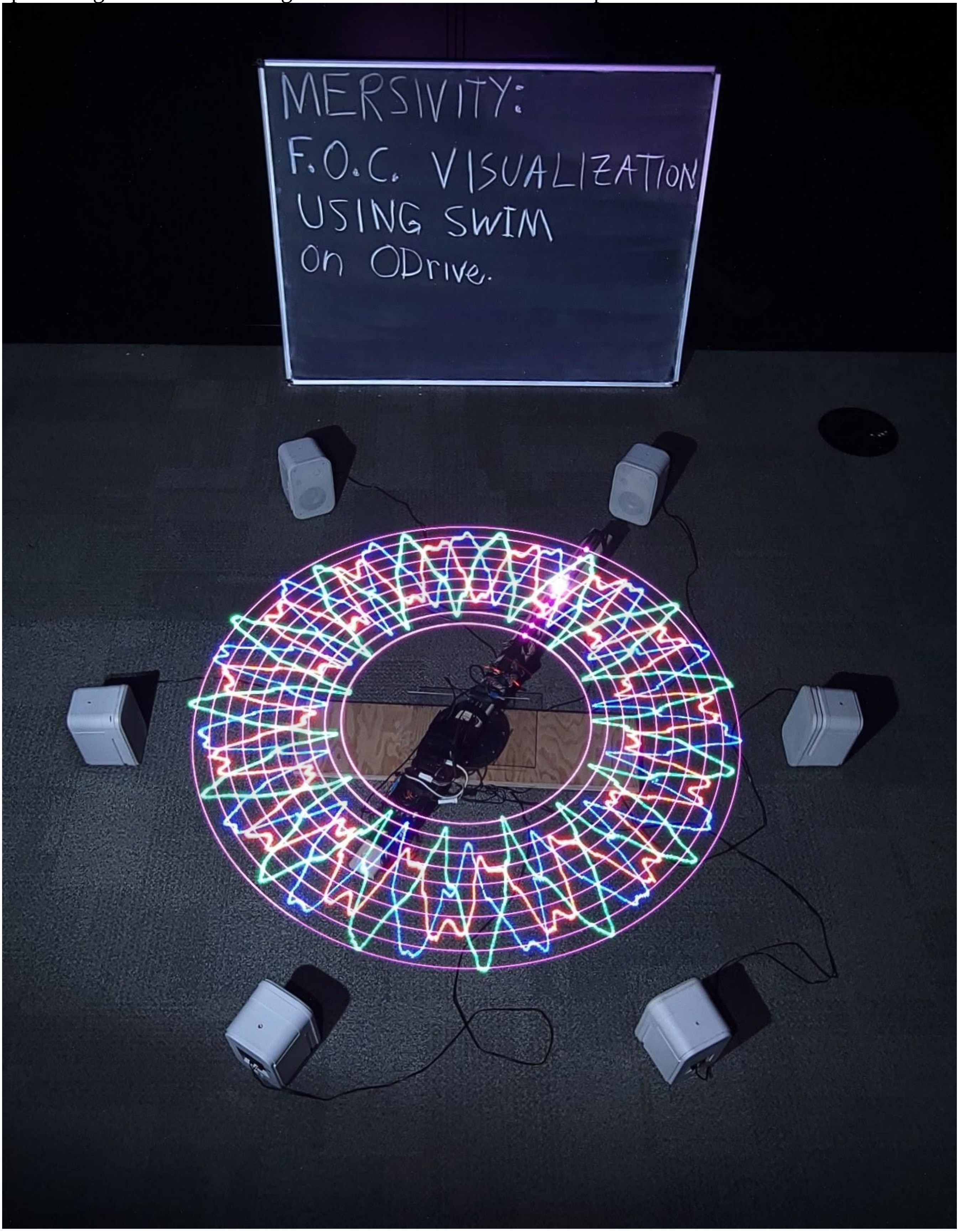

Figure 6. Visualization of a phase control defect in the DC-3phase motor’s FOC (Field Oriented Control) waveforms. SWIM shows this data in perfect spatial alignment with the rotating magnetic

field.

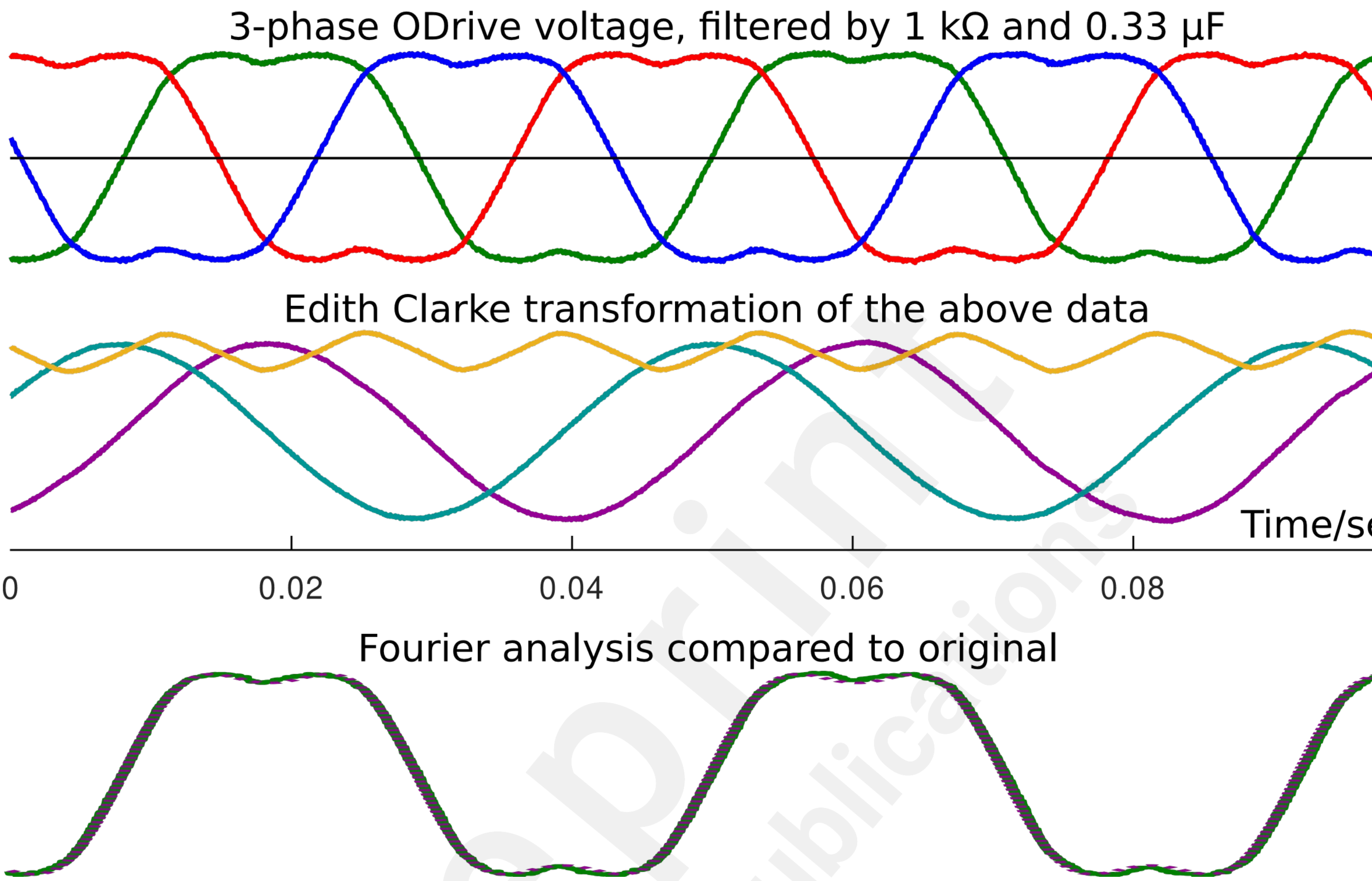

Figure 7. Edith Clarke transformational analysis (top two plots, showing 3 phases) and Fourier analysis (bottom plots: for clarity, only 1 of the 3 phases is shown here) of ODrive DC-3phase motor.

1
$$P = 30$$

2
$$A_1 = \cos(\pi P t) - 0.20408 \cos(3\pi P t) + 2$$

3
$$A_2 = \cos(\pi P t - 120o) - 0.20408 \cos(3(\pi P t - 120o)) -$$

4
$$A_3 = \cos(\pi P t - 240o) - 0.20408 \cos(3(\pi P t - 240o)) -$$

5
$$\left(A_1 \cos(2\pi t), A_1 \sin(2\pi t)\right)$$
$$0 \leq t \leq 1$$

6
$$\left(A_2 \cos(2\pi t), A_2 \sin(2\pi t)\right)$$
$$0 \leq t \leq 1$$

7
$$\left(A_3 \cos(2\pi t), A_3 \sin(2\pi t)\right)$$
$$0 \leq t \leq 1$$

8
$$o = \frac{\pi}{180}$$

Figure 8. SWIMulator™ = SWIM simulator equations based on Fourier series analysis of the ODrive motor in operation with the botwheels used for the power-assist walker rollator.

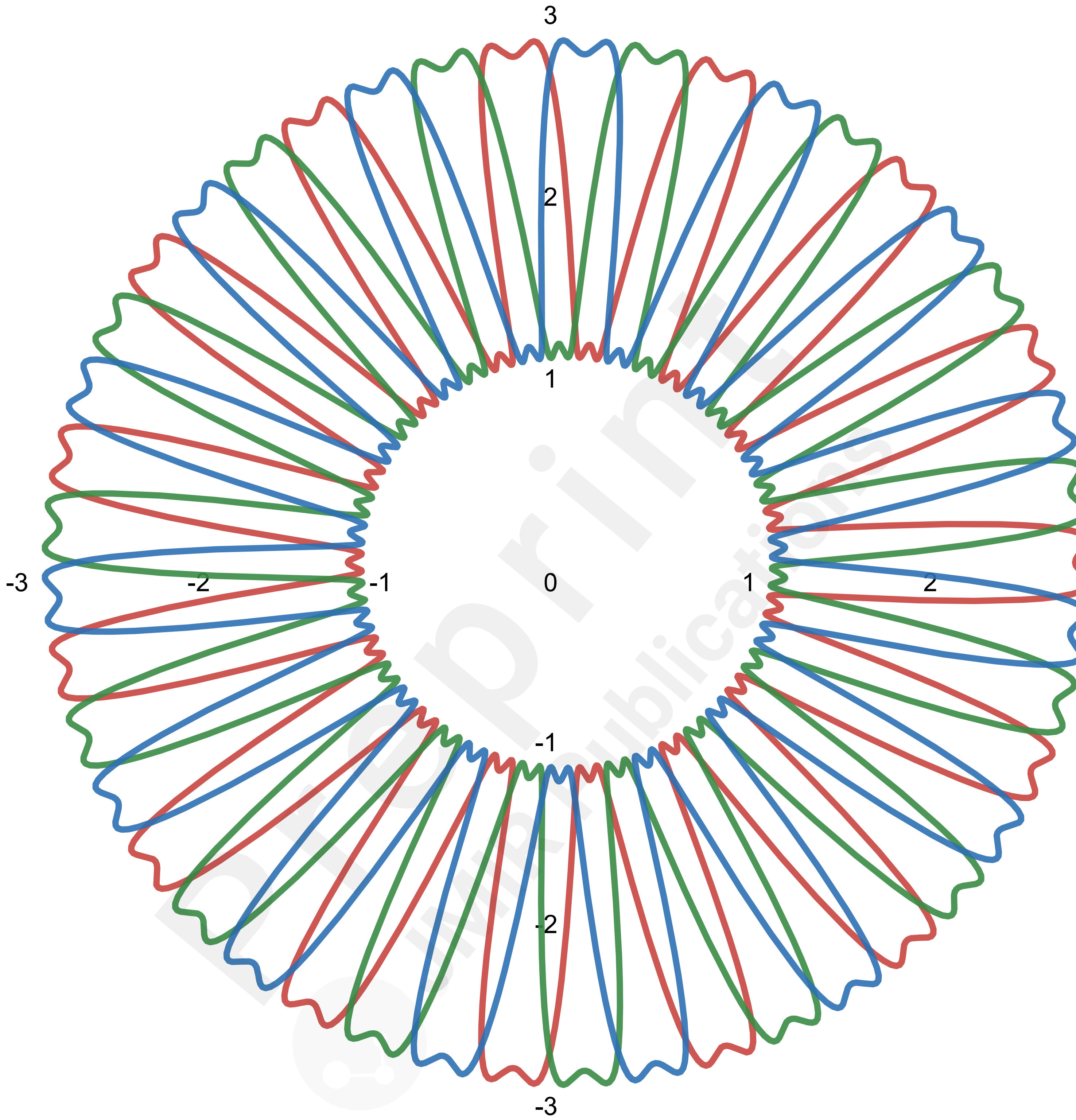

Figure 9. SWIMulator™ spatial computer simulation.

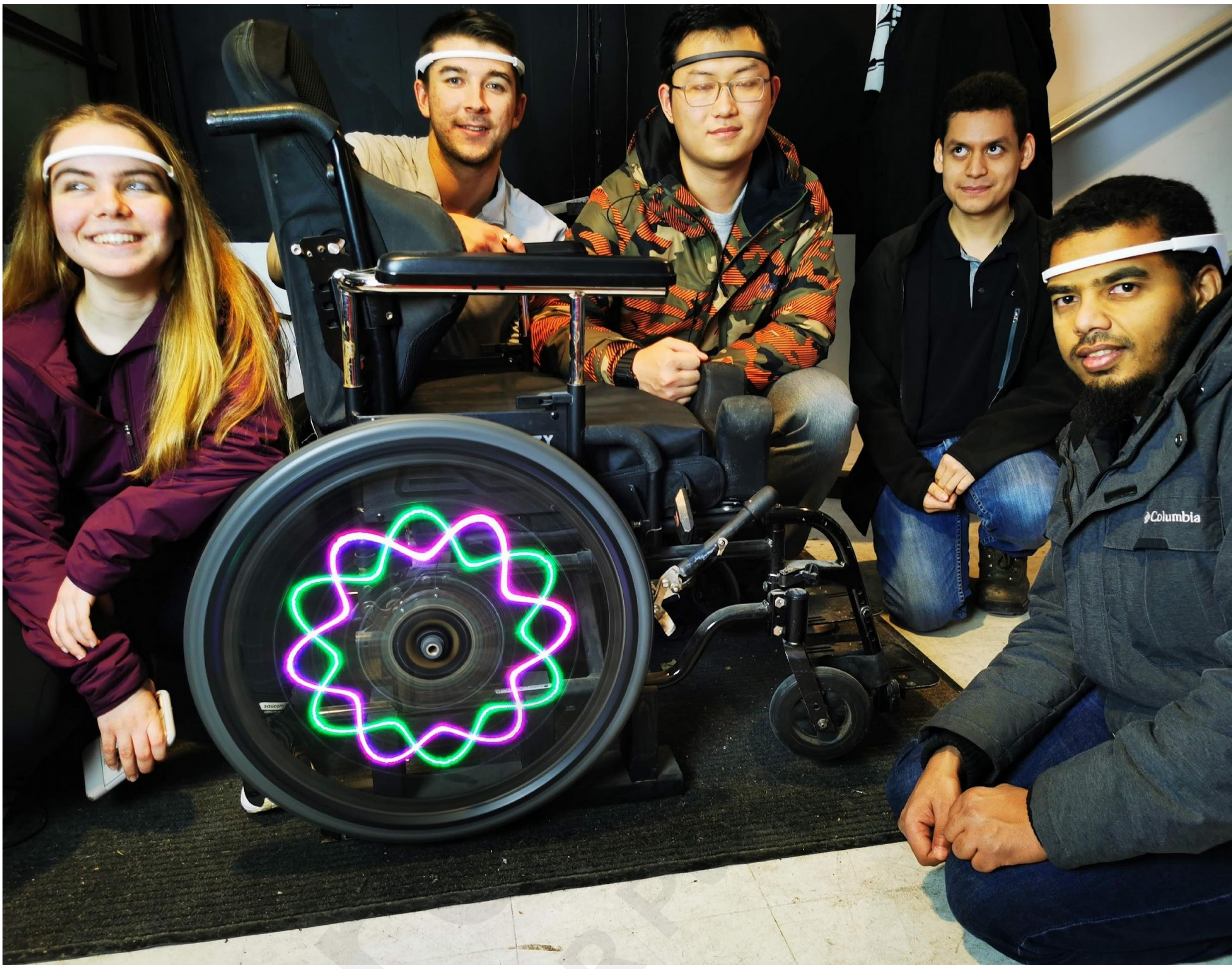

Figure 10. Mind-Over-Motor: Brain-controlled wheelchair with SWIM spatial computer as a closed-loop biofeedback system.

[24] and technologies like SWIM help facilitate free open visualization of health data and data sousveillance [25] (self-tracking) situated in spatial alignment with the human body or with aspects of connections to the human body such as the “Mind Over Motor” project.

4.1 InteraXon Muse brain-sensing headband

The muse headband is a brain-computer interface (BCI) that allows for communication between the brain and an external device. With the introduction of the Muse headband in May 2014, the difficulties of obtaining brainwave data outside of a clinical setting were bypassed. A compact electroencephalography (EEG) system, allowed for the detection of Delta (1-4 Hz), Theta (4-7 Hz), Alpha (7-12 Hz), and Beta (12-40 Hz) brainwave frequencies as shown in Fig 11. Three reference EEG sensors along with four integrated sensors resting on the forehead and behind the ears allow for the capture of faint electrical fluctuations produced by brain activity. [26] These analog signals at a microvolt scale are then converted to digital signals and processed through amplification and noise filtering.

The four sensors, operating at a default sampling rate of 220 HZ, record the EEG data and stream it via Bluetooth after it has been compressed using Golomb encoding followed by further quantization. [26] The Muse-S used in this paper utilizes the same EEG sensing techniques and functionalities as the Muse. The peripheral features and differences such as improved battery life are considered non-essential for the context of this paper.

4.2 Use of Rotary SWIM to Visualize Meditation

The Muse-S is used as a wearable device to assist with mindfulness. To provide feedback it uses electroencephalography signals to detect any brainwaves patterns produced by the brain. There are four main frequencies produced by human EEG readings: Delta (1-4 Hz), Theta (4-7 Hz), Alpha (7-12 Hz), and Beta (12-40 Hz). Delta waves are most prominent during deep sleep and even present during comas, theta waves are most commonly observed during a state of deep meditation, light sleep, and daydreaming, alpha waves indicate conscious relaxation, such as being awake with eyes closed, and beta waves show concentration, such as being focus on solving a difficult task. [27] [28]

This technology enhances their meditation practice by helping them to improve focus, relaxation and mindfulness as shown in Fig 12. By attaching a SWIM to an ODrive Pro motor, a 2D plane for displaying wave forms is created when rotated at high frequencies. Data is read from the Muse S via a python script, processed into values that can be accepted by the ODrive, and saved into a text file. The ODrive then reads the saved values from the text file, and uses them as the inputs to control the motor velocity. The ODrive can read any of the four EEG bands based on the user's selection, and therefore based-on the band it's selected, the different components of brain activity can be reflected in real-time. A larger positive value means the motor spins counter-clockwise with higher velocity, and a large negative value means spinning clockwise at a high velocity.

The EEG signals from the Muse-S is transmitted via muse-lsl [29] to a computer. A python script consolidates the EEG signal, then wirelessly communicates to the ESP32 microcontroller to illuminate the corresponding LEDs on the SWIM. One end of the SWIM is mounted on top of the ODrive's motor, so as the motor spins according the user's brainwaves, all four bands of the user's brainwaves are also visualized in real-time.

Additionally, when used with the sound system pictured in Fig 5 and 6, we implement trinaural beats (an extension of the well-known binaural beats [30] phenomenon) as a form of audiovisual spatial computing with biofeedback, allowing users to meditate while concentrating on the motor, and willfully adjusting the motor's speed and direction.

5 Freehicle: Vehicles of freedom for persons with disabilities

Much of the early work in eXtended Reality and spatial computing connects directly to the physical world in terms of a walker that could help people with disabilities to navigate the world and enhance their sense of freedom - the freehicle [2]. A proof-of-concept freehicle is illustrated in Fig 13.

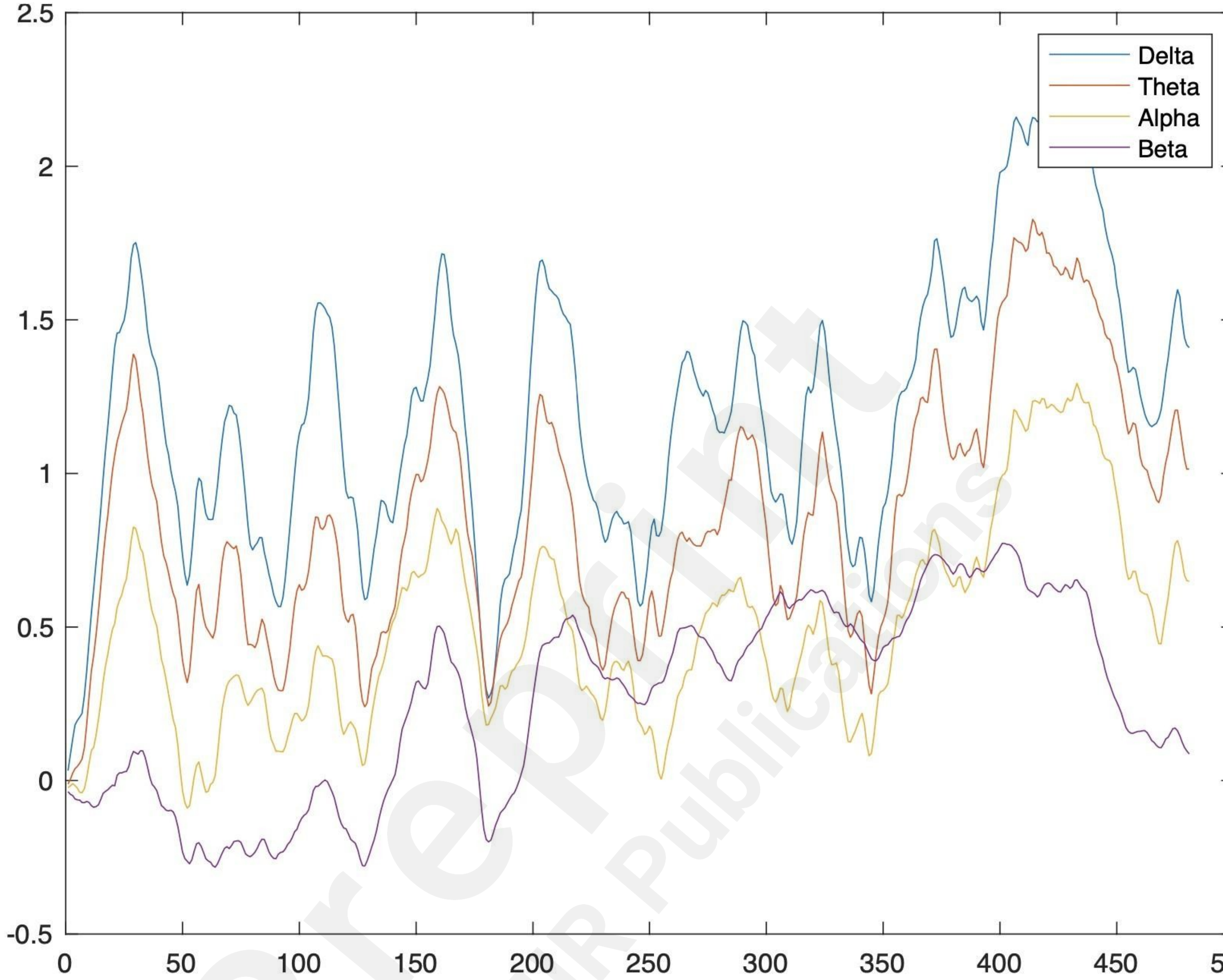

Figure 11. EEG streaming from the Muse S

Figure 12. Meditation using the visual Brain-Wave Rotary SWIM

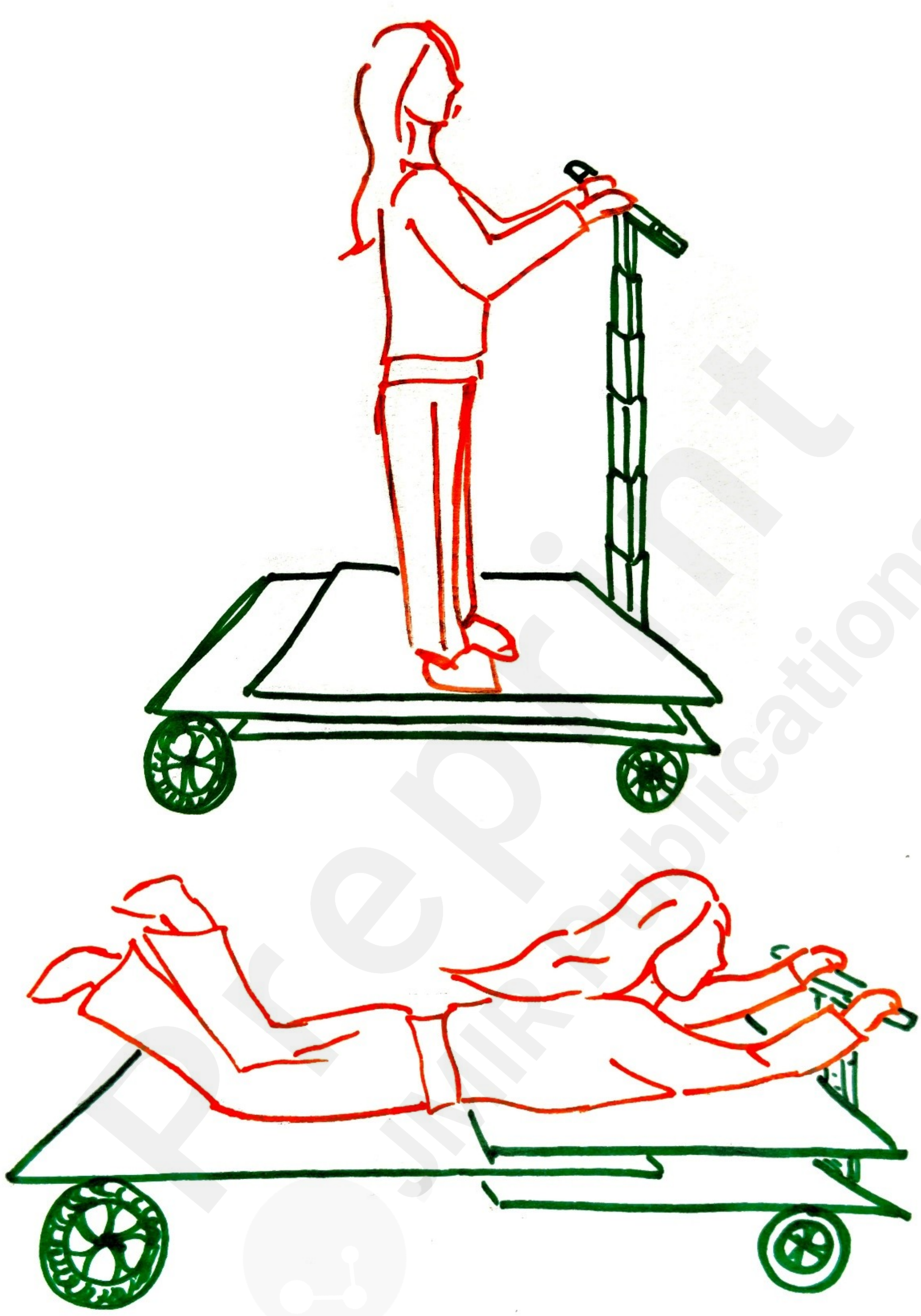

Figure 13. Micromobility for persons with spinal injury that problema
sitting. Here a person can be in a standing, prone, or supine position. T
Freehicle [2] reconfigures itself to accept standing (shortened freehicle
high handlebars) or prone/supine (lengthened freehicle with retracted
handlebars) riders.

-
-

-

5.1 Powerwalker

The Powerwalker™ is a form of Freehicle that takes the form of a motorized self-driving rollator walker that use artificial intelligence, computer vision, and DC-3phase motor control to assist persons with disabilities. It can fetc groceries, replace a seeing-eye-dog by providing vision+wayfinding, and provide spinal support for persons wit back injuries. Additionally, it constantly builds 3D maps of the spaces it visits, and these can be shared amon users to create the world's first comprehensive 3D indoor database for persons with disabilities.

The Powerwalker makes daily tasks such as grocery shopping and navigating on a sidewalk more accessible fo elderly people and people with disabilities. The Powerwalker is a motorized spatial computer that can and assi users out of difficult situations such as tight turns. It also performs simple tasks like obstacle avoidance indoors, o sidewalks, and on roads. In addition, the Powerwalker uses computer vision to detect objects such as commo grocery items for visually impaired users at a grocery store. Combined with Mind-Over-Motor described in 3, th form of our Freehicle concept can also be controlled with EEG signals which introduces more freedom-o movement and accessibility. We designed the Powerwalker and other Freehicles to be automated guided vehicle consisting of four main modules: perception; mapping and localization; planning; and actuation. These modules ar interfaced using ROS (Robot Operating System).

For perception, an RGB-D camera such as the Intel Realsense D435i [31] is used to provide 3-channel colo images and a 3D point cloud generated by the IR (infrared) dot pattern emitter. The RGB images are streamed at frequency of 30 Hz for object recognition and stereo visual SLAM (Simultaneous Localization and Mapping), an the depth information is used to produce a point cloud map of the environment. The camera model used also has a IMU (Inertial Measurement Unit) to measure the acceleration of the camera frame which is for localizing th Freehicle as well as controlling the motors in assistive mode. As illustrated in Fig 17, it recognizes common objec such as people and grocery items using deep learning-based computer vision techniques such as YOLOv5 [32 Coupled with navigation, this feature can help people with disabilities such as the visually impaired and those wit spinal injuries to easily find items in a grocery store quickly and independently.

When a Freehicle user navigates through a place where GPS is inaccurate or unavailable, such as an indoo environment, it is important to localize and map the surroundings so that the user can be guided to target location via an obstacle-free path. Therefore, we use SLAM to obtain the user's location and map the environme simultaneously. With loop closure, the user can explore an indoor environment such as a grocery store or art galle more extensively and freely. We have conducted field trials in various grocery stores as shown in Fig 15. Fo SLAM, we use RTABMap (Real-Time Appearance-Based Mapping) [33] as a strong baseline algorithm. It is a RGB-D, stereo, and LiDAR graph-based SLAM algorithm using incremental appearance-based loop closu detection. In our case, we use RGB visual information for feature matching, depth information for point cloud ma building, and fuse the built-in IMU (Inertial Measurement Unit) data to improve odometry. When a loop closure detected based on matching features from an incoming frame to a previous frame, the accumulated drift i odometry trajectory and the corresponding point cloud maps are minimized by imposing an additional constraint o the optimization problem. Fig 16 shows a sample trajectory and 3D map produced by walking in a grocery stor The blue dots represent the time-based state estimate of the camera, and the colored 3D point cloud map contai details of the store such as counters and products. This information is very useful for users to navigate through cluttered indoor environment such as a grocery store.

The 3D point cloud map is converted to data types useful for route planning, route optimization, and navigatio such as 3D voxel grids and 2D occupancy maps. For example, using a 2D occupancy grid, an optimal, collisio free path from the current position to the target position is calculated using optimal planners such as informe RRT* [34] or A* [35].

High-level commands from the planning module interface with the low-level actuation signals of th differential wheel vehicle model controlled by ODrive.

Figure 14. Girder Suspension

5.2 Mechanical Design

The Powerwalker design focused on three key factors: modularity, independent suspension, and 4-axis steerin Modularity was prioritized to easily replace arm modules. Modularity also allowed various designs to be easil tested to pinpoint key issues that were easily addressed with design iterations. Independent suspension on each arr module was selected for the walker due to the various terrains the walker would be subjected to, including roug ground, and soft ground such as beaches. The design provides increased agility for navigating in tight spaces, an uneven ground and allows precise turning. Lastly, for the suspension, girder suspension was chosen for its practica combination of packing size and streamlined configuration. The girder suspension (See Fig 14) is inherently spac efficient while keeping the overall structural integrity, which allows operation in confined spaces.

5.3 Odrive velocity or position control

The ODrive DC-3Phase Botwheel motor was used for the power-assisted rollator walker that will be described i Section 4.1. The SWIM and spatial computing in general was used in the design of the motor control, as well as i the computer vision and visualization of the control systems for it.

Power is proportional to the product of angular velocity and torque. In the assist mode the velocity is depende on the user, The system was programmed based on the desire to have the system behave such that the more th walker is pushed, causing the wheels (and motor shafts) to turn (input velocity), the higher the output power of th ODrive motors. The torque is generated in one direction as directional current is applied to the motor winding Torque is proportional to the current. Therefore the current is increased or decreased to achieve a desired torqu that results in a desired velocity or position, as part of a current control loop. We favour the use of a PIIIDD controller to account for the fact that acceleration is proportional to force which is proportional to torque which proportional to current, i.e. that which we control, whereas when we wish to maintain positional control we're o by two derivatives [6].

Figure 15. Powerwalker: Computer vision control of ODrive 3-phase motors.

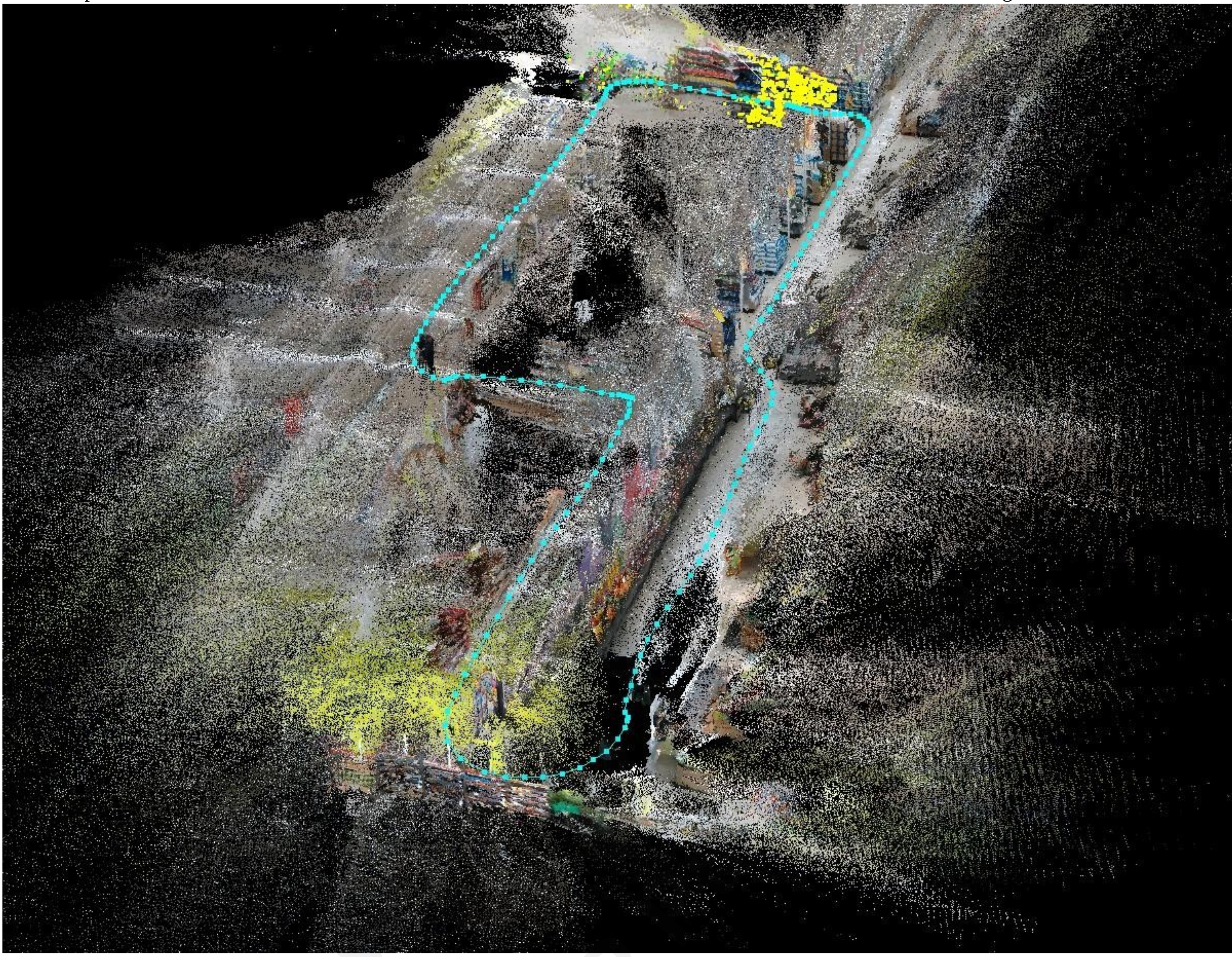

Figure 16. Map and odometry example in a grocery store with loop closure.

Figure 17. Object recognition in a grocery store.

6 Future work

6.1 The future of Freehicles

A swarm of Powerwalkers can map out various spaces like grocery stores, which can be shared along with rating of store accessibility. The mapping capabilities of the walkers can also be improved by RGB-D cameras of highe qualities and larger field of view.

Another aspect of the Freehicle / Powerwalker we are developing is its ability to work on land, water, and ai Presently the Freehicle can carry an inflatable vessel that inflates from the Freehicles power supply, and the vesse can then carry the Freehicle including the hydraulic walker / physiotherapy machine (hydraulophone) an teaching / outreach laboratory ("Hydraulikos research lab" aboard the vessel which all fits within th Powerwalker). Part of this work involves teaching, outreach, and visual art by way of SWIMs attached to th Freehicle. For example, an art installation (S. Mann) entitled "Denatured Water(front)" highlights the lack of saf access for swimmers and paddlers along our waterfronts. The Mochoid is carried by the Freehicle while it display a "NO SWIMMING" or "poison" symbol, which is accompanied by the "serving" (for display only) of denature food and beverages, so that patrons can see but not taste servings, akin to the way in which our waterfront park allow patrons up-close access but only to see but not touch (or swim or paddle in) the water. See Fig 18

6.2 Integral Kinesiology for Fitness

Integral Kinesiology refers to the use of time integrals of position for fitness purposes [36].

Whereas traditional exercise metrics include velocity and acceleration, our approach focuses on integratin instead of differentiating position. This allows us to report not only raw strength, but also precision.

The user attempts to perform a simple exercise, like push ups or pull ups, and keeping the absement score a low as possible. The score indicates how precisely the exercise was performed around a reference point, which ca be calibrated by the user [37].

We have developed proof of concept mobile applications that allow the user to use their devices to measur absement with respect to a calibrated point. The applications contain several features that are designed to stimulat the user visually and aurally during training. For example, a song selected by the user will be played out of pitch the current position is far from the equilibrium position. We also provide similar cues through background color o the application.

6.3 Biofeedback and Integral Kinesiology Based Golf Swing Training

The use of integral kinesiology is to be further explored in depth by integrating digital and analog IMUs (Inerti measurement units) into a golf club and the user to track the motion of a golf swing. The path of the swing is the compared to pro-athlete golfers, giving the absement away from the reference pro-golfer swing. During the swin any deviance from the swing path is communicated to the user with haptic feedback, which allows users to bett understand where the swing deviates most. Furthermore, the Muse-S and the attached SWIM enable th visualization of one's Alpha, Beta, Theta, and Delta brain waves as shown in Fig 20. This could be leveraged t better induce a state of flow during play through mindfulness.

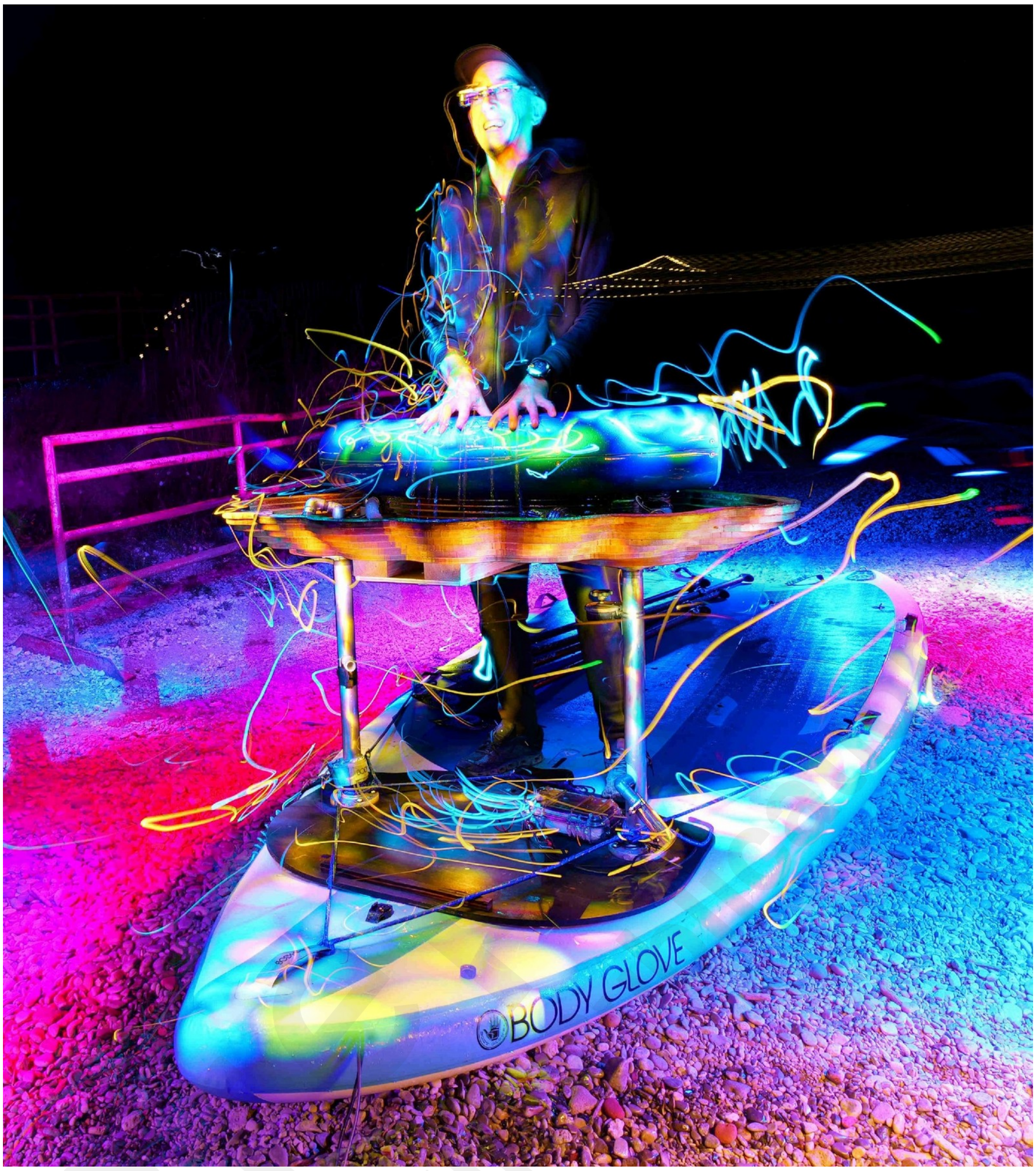

Figure 18. Hydraulikos research vessel takes the form of a 7-person inflatable paddleboard, lab equipment, etc. that transports the physiotherapy/water-therapy machine (hydraulophone) Powerwalker. E
of these can transport the other, i.e. across land or water. Top photograp
the S. Mann and R. Godshaw team.

(a) Vertical integral kinesiology training

(b) Flat integral kinesiology training: eg. wobble board

(c) Simple absemen calculation app

Figure 19. Three proof of concept ideas for Absement-based training companion app

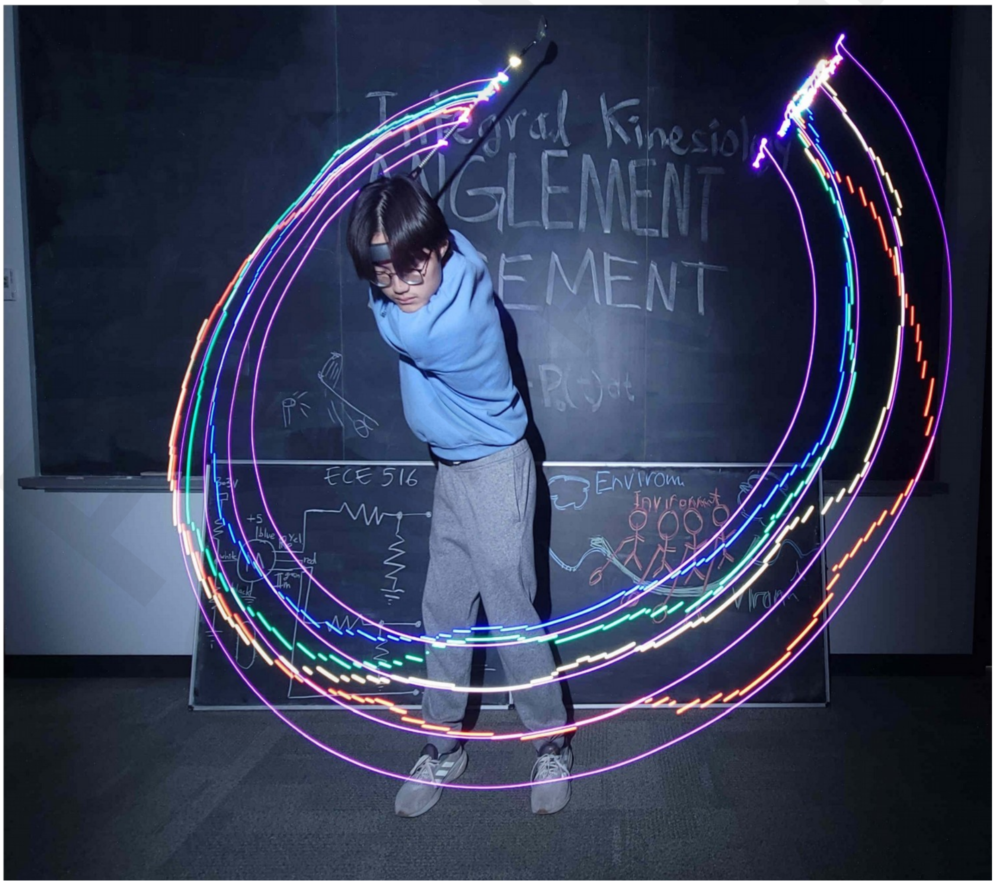

Figure 20. Photograph of brainwave-based golf swing analysis with S.W.I.M

6.4 Integral Kinesiology and Harmonization in Dragon Boating

Another application to be investigated is the application of integral kinesiology within dragon boating. B implementing IMUs into the paddles of a dragon boating team and synchronizing them to find deviances c absements the team can acquire a metric for rowing harmonization. The IMUs are used to track the rotational dat of each paddle which is then cross referenced for synchronization and absement checking. The metric generate can be used to measure the efficiency of the team and the individuals within the team that deviates from th synchronization. Furthermore, by further integrating the SWIM and Muse-S with the position data of the paddl teams can acquire visual data regarding performance within flow state as well as a visual display for specific area of absement as shown in Fig 21.

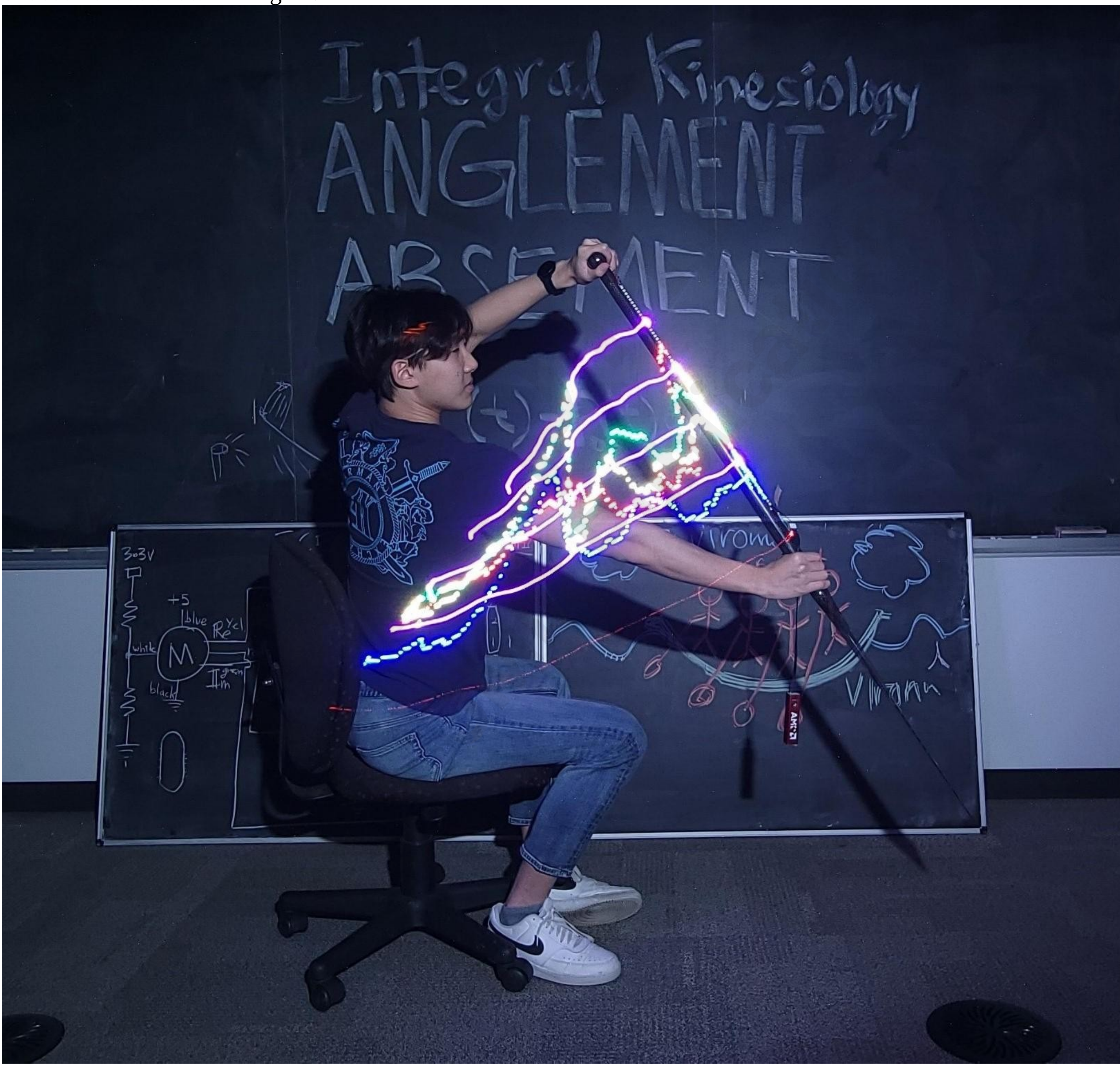

Figure 21. Photograph of the brainwave-based dragonboat paddle rowing analysis with S.W.I.M.

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