Brain/Mind Games: Inclusive health and wellbeing for people of all abilities

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***Abstract*—We present devices, system architecture, and pipeline for EEG (ElectroEncephaloGram) gamification to help with health and wellbeing for people of all abilities. Firstly, we provide a simple low-power ESP32-based Internet of Things [1], [2], [3] (IoT) capture device for EEG and other data directly from devices such as the InteraXon Muse™and Muse2™or Neurosky Mindwave™. The device eliminates the need to have a smartphone to use technologies like the Muse or Mindwave that otherwise require a smartphone. This makes technologies accessible to people who have challenges using smartphones, and also facilitates health care interventions and data logging in places such as retreats or spa facilities where cellphone use would be disruptive. Secondly, we create a series of games that encourage the development of assistive technologies. One such game is "MoBrain" which is a meditation competition based on mind-controlled motors, which we hope will lead to the development of wheelchair + mobility technologies for quadriplegics. Another game is "Mind Flow" in which brainwave-controlled water pumps provide increased flow when a player's mind is in a state-of-flow.**

I. Background and related work

Electronic media, such as games, have been designed as a means for health intervention[4], [5]. Such interventions can be customized, e.g. use of photographs of a child's home, clothes, etc., in game design for health intervention[6].

Virtual reality, augmented reality, and blended reality have also been used for game design[7], [8], including serious game design for therapy [9].

Brain-sensing technologies show great promise for immersive games [10], assessing flow in games [11], and healthcare intervention such as relaxation training to treat ADHD [12].

A. Brain-sensing technology

Electroencephalography (EEG) is the capture of electrical brain activity, which ranges from about 10 to 100 μV as measured on the scalp surface. EEG devices also pick up many artifacts, the largest of which is typically muscle artifacts, often around 10 mV. Blinking and jaw clenching events are noted by the device and are usually fairly short duration.

Regarding EEG, for the purpose of this paper we will focus only on alpha and beta waves. Alpha waves have a frequency between 7.5 and 13 Hz, emanating from posterior regions of the head, being higher in amplitude on the dominant side. It appears when closing the eyes and relaxing, and usually disappears when opening the eyes or alerting by any mechanism (thinking, calculating), although, with proper training, it is possible to maintain high alpha wave activity while concentrating. Alpha wave activity is the major rhythm seen in normal relaxed adults.

Beta waves are "fast" activity with a frequency of more than 13 Hz, and emanate frontally from both sides. It is the dominant rhythm in persons who are alert or anxious or have their eyes open [13].

In this paper we will use brainwaves to control various IoT (Internet of Things) devices in the context of physical computing.

B. Internet of Things

The Internet of Things [2], [3] (IoT) has grown tremendously in recent years. For a good summary of this development, see [1] and the earlier version of the paper on arXiv [14].

C. Physical Computing

Physical Computing [15] is the "seamless integration of computing with the physical world via sensors and actuators" [15]. It exists at the intersection of electrical engineering, computer science, mechanical engineering, robotics, and embedded systems for:

> "handmade art, design or DIY hobby projects that use sensors and microcontrollers to translate analog input to a software system, and/or control electro-mechanical devices such as motors, servos, lighting or other hardware." – https://en.wikipedia.org/wiki/Physical_computing

D. Physical Meditation

Physical meditation, physical mindfulness, or "computational telekinesis" is the application of physical computing to brain-computer interfaces. Examples include a radio controlled car that can be operated by a brain-computer interfaces [16]. This work by Dudley, and others, is obviously fun and playful, but it is also practical and useful because it inspires other developments such as brain-computer interfaces for mobility. It also provides a broader context for important work such as technologies that allow quadriplegics to operate wheelchairs using brainwaves [17].

E. Physical Metaphors

A physical metaphor makes what is normally only a metaphor into a physical reality. We draw great inspiration from Lisa Park's performance art in using brainwaves to control vibrations in pools of water [18]. This is an example of a physical metaphor in which the "stillness" metaphor of a clear mind is made physical in the pools of water. Another example of a physical metaphor is the Bright Ideas which makes physical the metaphor we often find in cartoon drawings where a light bulb appears over someone's head when they think of an idea. The physical metaphor in Bright Ideas is an actual real light bulb that lights up when the brain-sensing headband and machine learning algorithm detects that the wearer has thought of a new idea [19]. Bright Ideas is a fun playful project that helps to raise awareness of important research in brain health, such as work being done to characterize brain activity during creative problem solving [20].

II. Mind over motor for state-of-flow

We build on other work in Physical Computing, Physical Meditation, and Physical Metaphors to create some new game concepts that we hope will raise awareness of, and get people thinking creatively about, physical and mental health and wellbeing for people of all abilities.

We produced a series of games, which we call flowgames. Flowgames are games in which participants compete by getting themselves into the state of mental flow, and staying in the state-of-flow.

> Flow is the sense of inspired freedom that comes when one is lost in an activity, allowing time, duty and worry to melt away. For writers, words pour out in a continuous, creative stream... – Susan Perry, Writer's Digest [21]

The mental state-of-flow has been well-researched [22], [23], and we wanted to embody the double-entendre of a Physical Metaphor on flow, so we built a system in which a water pump was driven by a speed controller in such a way that the pump increased its speed as players went into a deeper state of flow. The simplest embodiment of this game involves two pumps at opposite ends of a small pool in which two players, facing each other, wear a Muse EEG headset and each control a water pump that causes water to flow toward the other player. The goal of the game is to "push" a floating object toward an opponent. The winner is the one who first pushes the object to the other player, using hydraulic flow from the water pump.

Each pump's speed is controlled by an output from a spectral analysis in which the speed of the pump is directly controlled by the product of energy in the alpha band and energy in the beta band of brainwave frequencies. In this way, a state of mental flow (simultaneous high alpha and high beta, i.e. simultaneous relaxation and concentration) produces a high quantity of water flow in the pump.

Expanding upon the richness of Physical Metaphors, we then decided to perform the multiplication in physical devices rather than software.

In particular, we created two physical systems, one called the *Concentrator*, that provided physical feedback to indicate beta wave activity, and the other called the *Relaxer*, that provided physical feedback to indicate alpha wave activity.

Since we wanted a Physical Metaphor in each case, we used a magnifying glass to "concentrate" the sun's (or other light source's) rays onto a fireproof brick with a high-heat photocell detecting the degree of "concentration". We used beta wave activity levels to adjust the focus of the lens, so that the sun's rays came to a point on the photocell when the user was highly concentrated. When the user was less concentrated, the lens went out-of-focus and the sun's spot broadened so that most of the energy missed the photocell.

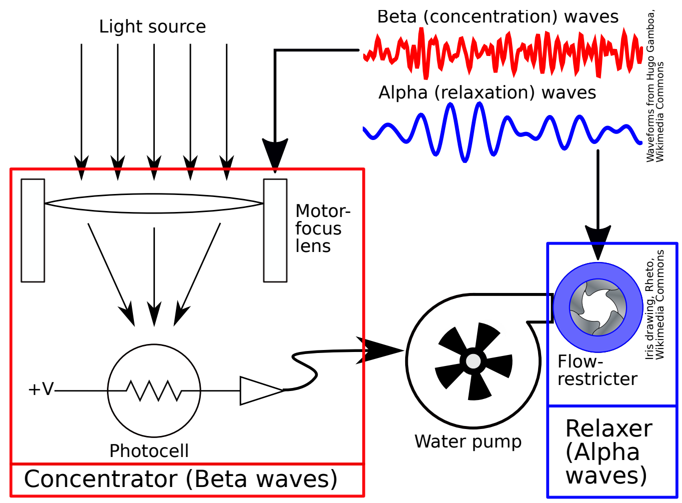

Fig. 1. The *Physical Metaphors* for Flowgames: (1) Beta waves are strongest when a user is concentrating. So we constructed a physical metaphor using a lens to *concentrate* the sun's rays to a single point on a heat-resistant photocell mounted to a flameproof block. (2) The photocell controls a water pump, so that the water pump runs more strongly when the user is concentrating. (3) In order for the water to exit from the water pump, the user must relax, because there is a naturally-closed restrictor that only opens in the presence of high alpha wave activity (relaxation). In this way, (1) mental concentration causes concentration of the sun's rays that the user can clearly observe; (2) A state of physical water flow is only achieved when there is a state of mental flow through relaxer (3).

A water pump was driven by a buffered output of the photocell so as to pump more water when the user was more concentrated.

For the relaxation metaphor, we used an iris that opened when the user was relaxed and closed when the user was not relaxed. This function is similar to the iris of the human eye, in which the muscles must relax in order for the iris to open [24]. A similar muscular process is involved in urination, in which the sphincter muscles must relax in order to allow urine to flow [25].

In our system, we first had the iris in the lens, so that the user had to both relax to let the lens open up, and also concentrate to let the sun's rays come to a point on the photocell.

However, we found that when the iris was closed, the user was unable to see the spot size of the concentrator, so we moved the iris to the output of the water pump, as a restrictor of flow.

Thus the user had to concentrate the sun's rays and relax the flow restrictor, at the same time, in order to get water flow. See Fig 1.

As an added element of purpose, we connected the water pumps to hydraulophones (water-based musical instruments) so that players could control the flow of water in a creative endeavour (creating music). See Fig 2.

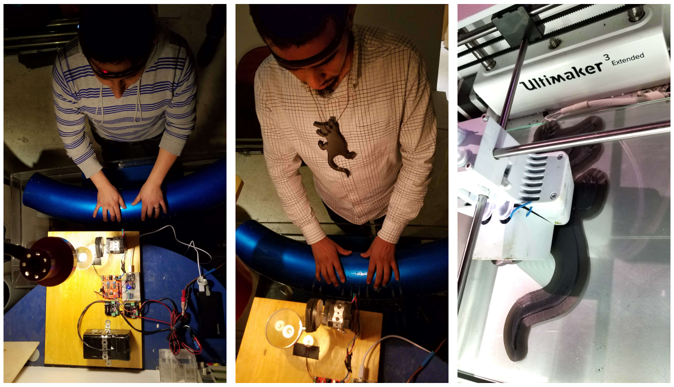

Fig. 2. Flow games: Participant Diego competes against participant Tamer. In order to eliminate the distraction of cellphones and cellphone applications from the meditation process, we developed our own neckwork wearable computer, in the shape of a crocodile. The neckworn computer repeatedly tries to establish a wireless connection to the Muse headset and serve the data to the game cloud. The crocodile is a metaphor for a voracious appetite for data that establishes a tenacious connection, while leaving the user completely free to stay in the state-of-flow without being distracted by technical details.

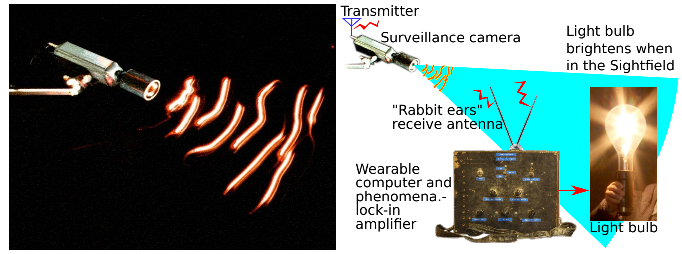

Fig. 3. Meta-veillance (meta-vision): Using video feedback to see a camera's capacity to "see". A wearable computer and videographic lock-in amplifier was designed specifically to lock in on extremely weak television signals which are amplified to drive a light source. Here the light bulb goes from a dim red glow to a brilliant white whenever it enters the camera's field-of-view, and then the bulb brightness drops off again when it exits the camera's field of view. Waving it back and forth in a dark room reveals to the human eye, as well as to photographic film (picture at left) the camera's capacity to sense. The glow from the light bulb lags behind the actual physical phenomenon. Thus as we sweep back-and-forth, odd numbered sweeps (1st, 3rd, 5th, and 7th, and 9th) appear near the top of the camera's field of view, whereas even sweeps (2, 4, 6, 8) appear near the bottom [46].

III. Sousveillant Technology

Finally, we introduce the concept of sousveillant technology, to build on the concept of veillance games [26].

Sur**veillance** (overslight) [27], [28] is an established research and business practice. The word "surveillance" ("oversight") is more than 200 years old [29], from French "sur" meaning "over" or "from above" and "veillance" meaning "watching".

Sous**veillance** (undersight) is a much newer concept [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], where the French prefix "sous" means "under" or "from below" (as in words like "sous-chef").

Metaveillance is the sensing of sensors and sensing their capacity to sense, and has also emerged as a recent area of research [42]. Meta is a Greek prefix that means "beyond". For example, a meta conversation is a conversation about conversations, and meta data is data about data. Metaveillance is the veillance of veillance, and more generally, metaveillance is the sensing of sensors and the sensing of their capacity to sense.

Examples of metaveillance include the photography of cameras and microphones to reveal their capacity to sense [43], [44], [45]. See Fig. 3

The Sequential Wave Imprinting Machine (S.W.I.M.) is a linear array of light sources, sequentialized through a wearable computer system with a lock-in amplifier for phenomenological augmented reality (to see real-world phenomena) [44], [45].

See Fig. 4 and 5.

IV. Sousveillant motors

We introduce the concept of sousveillant motors, i.e. motors which reveal their inner workings. In order to do this, we apply the SWIM technology to motors. A new way of understanding electric motors is facilitated with one or more rotating SWIMs.

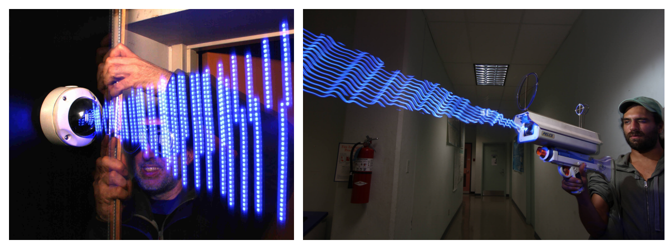

Fig. 4. LED-based version of SWIM: A linear array of light sources allows us to see otherwise invisible phenomena, such as the sightfield (metaveillance) of a surveillance camera or other vision sensor. using the methodology of [47]. Here we also see gamification of metaveillance.

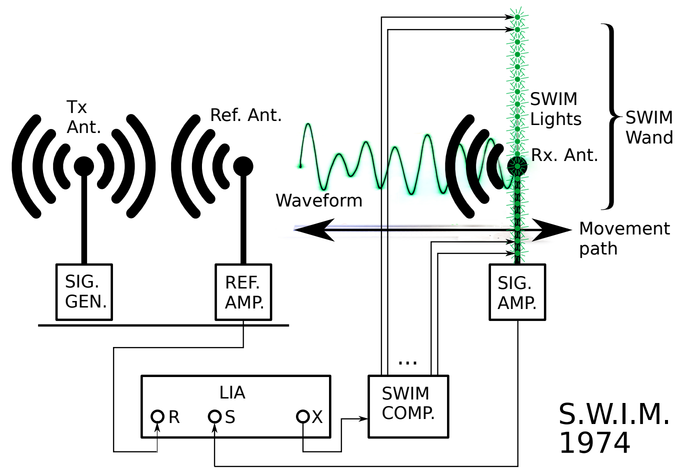

Fig. 5. The SWIM (Sequential Wave Imprinting Machine), invented in the 1970s, is a linear array of light sources that moves through space to make visible otherwise invisible phenomena such as electromagnetic fields, sound waves, and meta-phenomena (e.g. to sense sensors and sense their capacity to sense). A sensor or meta-sensor is attached to a linear array of lights (SWIM LIGHTS) and moves with it. The sensor feeds the signal input of a lock-in amplifier. The reference input to the lock-in amplifier comes from a reference sensor fixed in the environment (not moving), near the phenomenon being studied.

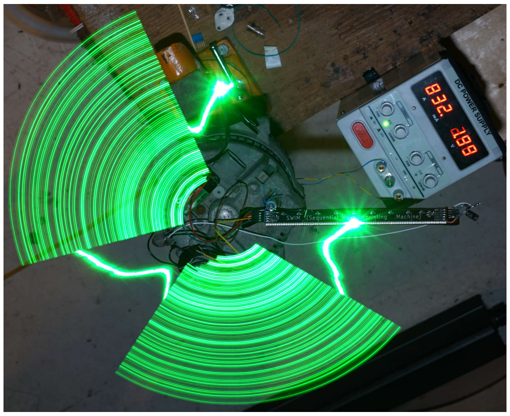

Fig. 6. An array of 100 LEDs (Light Emitting Diodes) is set in rotary motion by the motor. The LEDs are controlled by a SWIM (Sequential Wave Imprinting Machine) [42].

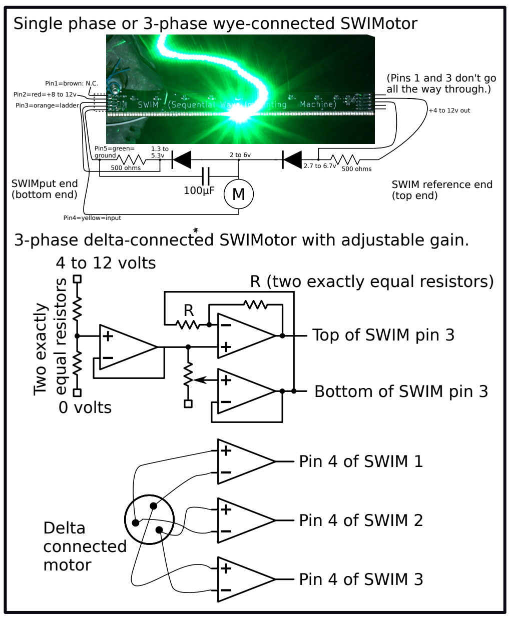

Fig. 7. Electrical wiring for the SWIM connected to the motor windings.

The result is that a human observer can directly observe the rotating magnetic field in a motor.

First the SWIM is spun with the motor, as shown in Fig. 6

Secondly, the SWIM is connected differentially to the electrical winding of the motor. In the case of a polyphase motor, a separate SWIM is used for each phase. For example, for a 3-phase motor, three SWIMs are positioned at 120 degree angles, such as to rotate together. The wiring is shown in Fig. 7.

The SWIMs are mounted to the shaft of a motor on a fixed object and the entire body of the motor is rotated, together with the SWIMs attached to it.

As the motor spins, the rotating magnetic field become visible, as shown in Fig. 8.

With a three-phase motor, three SWIMs are mounted at 120 degree angles so that they can spin with the motor's body, while showing the electricity (voltage or amperage), i.e. the rotating magnetic field in the motor. Because the motor itself is rotating with the rotating magnetic field, the motion is canceled. To understand this effect, consider coordinates attached to the shaft of the motor as it spins. You would be rotating together with the rotating magnetic field, and thus, from your perspective, the rotating magnetic field would appear stationary. Since the shaft of the motor is fixed to an object in the room, and its body is turning, we can regard the situation as if the entire room were spinning with the motor's shaft, and therefore a person standing in the room observes the situation in coordinates in which the speed of magnetic field rotation is exactly zero.

Fig. 8. A rotating SWIM allows us to see the rotating magnetic field in an electric motor. For the study of motors, we constructed a linear array of 100 LEDs to attach to the body of a motor. The array is connected to one of the motor's "stator" coils while the role of rotor and stator are reversed (i.e. the "stator" spins with the SWIM, while the "rotor" remains fixed in a vice on a workbench.

For the study of 3-phase motors, we constructed three SWIMs, one made from 100 red LEDs, another from 100 green LEDs, and a third SWIM made from 100 blue LEDs. We mounted these at 120 degree angles on a flat surface, perpendicular to the motor's shaft, but attached to the motor's body to rotate with the body of the motor. See Fig. 7 and 9.

V. MIND-CONTROLLED SOUSVEILLANT MOTOR

Finally, we implemented a neurofeedback system in which mindfulness drives the rotation of a motor with a SWIM, so that the user can see and understand the rotating magnetic field in the motor while directly affecting it through brain activity. See Fig. 10.

We constructed a number of wheelchair sculptures based on this principle. We then used these in various forms of game play in which players meditate and apply mindfulness to the control of the electric motors that drive the wheels of the wheelchairs, as shown in Fig 11

This system can be extended to a multiplayer interactive art installation, e.g. where multiple players' brainwaves compete

Fig. 9. The rotating magnetic field in a three phase motor is made visible with three rotating SWIMs. Here we see a variety of field strengths, as the field decays toward zero.

for control of a single motor, or where multiple players control multiple motors or other devices.

The system architecture is based on the principle of human-in-the-loop intelligence, also known as Humanistic Intelligence (HI) [48], as illustrated in Fig. 12.

The overall sysetm architecture is illustrated in Fig. 13 showing the following layers:

1) Embeded devices layer that includes the ESP32-based wearable computer in the shape of a crocodile. The crocodile is paired over Bluetooth (BLE or classic) with an EEG device, eliminating the need for a smartphone or other similar device. A motor controller that is connected to a physical device, e.g., the wheelchair or water pump, can be used in various game scenarios.
2) On-premises game servers layer that represents a hub for all collected real-time data. The data is used to command a motor controller according to the game logic.
3) Cloud data pipeline that collects all game events at scale, aggregates real-time scores and provides global game statistics. The pipeline also stores historical data for future analysis.

The architecture was built for flexibility and scalability (to include also large-scale gaming events). Horizontal scaling is achieved by assigning each group of players to a game server. The number of servers can be increased as more players join. The cloud data pipeline is an open system where demand increases if there is concurrent events at different venues. The elasticity of the cloud-based architecture allows compute power to be acquired and released as demand fluctuates.

Fig. 10. Motor mindfulness. Top image: participant not in the state of flow, motor not turning. Next image: participant's brainwaves causing the motor to turn, while it also reveals its internal rotating magnetic field. Here we can see the field rotating around the 72 stator slots of this two-pole three-phase motor. Photograph taken with electronic flash. Typically, however, the experience takes place in a dark room with the lights off, as shown in the photographs on the bottom row, for various electric field currents and motor speeds as controlled by neurofeedback.

Fig. 11. Wheelchair sculpture shown here being controlled by brain-sensing headwear (Neurosky). Multiple players compete to calm the electrical signals fed to the motor, and provide purposeful rotary drive. On this wheel there are six SWIMs (Sequential Wave Imprinting Machines), which allow others to see the rotating magnetic field in the motor, and thus infer some aspects of the participant's brainwaves.

The crocodile enables the machine, e.g. wheelchair, to sense the human by monitoring a player's EEG brain signals. In this implementation, each crocodile is linked to one Muse device by its Universally Unique Identifier (UUID). This one-to-one relationship is to ensure that each connection can be reliability established and maintained with minimum distribution in the data flow. New generations of Muse EEG are Bluetooth Low Energy (BLE) devices that expose data via a BLE service with multiple characteristics. Each characteristic represents a single data type that can be streamed from the Muse to the connected logger. For example, all 5 EEG channels, accelerometer, gyroscope and heart rate data are declared as separate characteristics. Additionally, there is another control characteristic that is used to command the Muse to start/stop streaming the data that the logger subscribed to receive. Data may be used for studies in brain health and wellness.

In this architecture, data can be stored in multiple locations for redundancy and flexibility of deployment. The crocodile has an SD Card. Similarly the game server have a larger storage capacity. Data transmission is also flexible: the crocodile

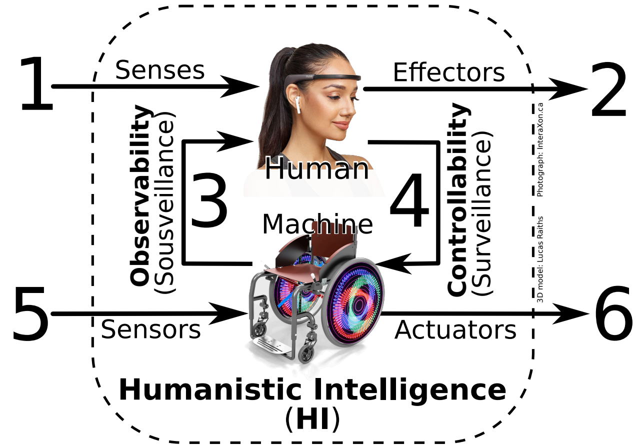

Fig. 12. Human-in-the-loop intelligence, also known as Humanistic Intelligence (HI) is a form of human-machine interaction in which intelligence arises by having the human being in the feedback loop of the computational process [48]. 1. Humans have Senses (e.g. sight, hearing, etc., depending on ability), and 2. Effectors (e.g. hands, legs, etc., depending on ability). These senses and effectors allow the human to operate a machine through the ability to sense the machine (3. Observability) and affect the machine (4. Controllability). 5. Machines have Sensors and 6. Actuators, which allow them to be sensed by the human (3. Sousveillance) and to sense the human (4. Surveillance).

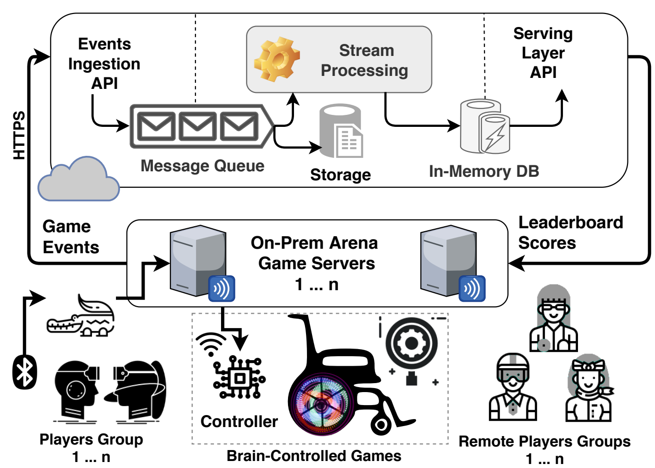

Fig. 13. System architecture. Each player wears an EEG device paired with a control device (crocodile-shaped wearable computer). The crocodile tenaciously keeps trying to re-connect if ever the connection is dropped. It consumes EEG data over Bluetooth, then sends the data to a game server. The game server commands a motor controller over WiFi to do actions according to the game logic. Game events are uploaded in real-time to a cloud data pipeline to aggregate data and calculate global game statistics such as scores and leaderboard.

can upload data directly to a cloud server or can send it to an on-premises server inside the gaming arena, for example during a gaming event or a show. For a large-scale gaming event, this architecture can scale horizontally by adding more game servers to each group of participants.

In the current experimental setup, we used User Datagram Protocol (UDP) for communication between crocodiles and game servers for speed and low latency. The communication between the game server and the motor controller was first over HTTP (Hypertext Transfer Protocol), but we changed to UDP because it allows the game server to keep sending the data even when the motor controller is not running (which leads to connection timeout in the HTTP case). However, the architecture is protocol agnostic. Other protocols such as MQTT can be used. The decision of the appropriate protocol is a function of the scale of the deployment and the required latency and desired throughput.

The software running on the game server can be implemented with a message-based *actor model* [49] to scale as the number of concurrent users increases. Additionally, each player can be represented by a single persistent actor to maintain the game state of the player which makes the code easier to understand and maintain.

VI. Motor/Mind Games for people of all abilities

When a sousveillant motor (i.e. a motor equipped with SWIM) is set in motion, the rotating magnetic field is stretched across time, as illustrated in Fig. 14.

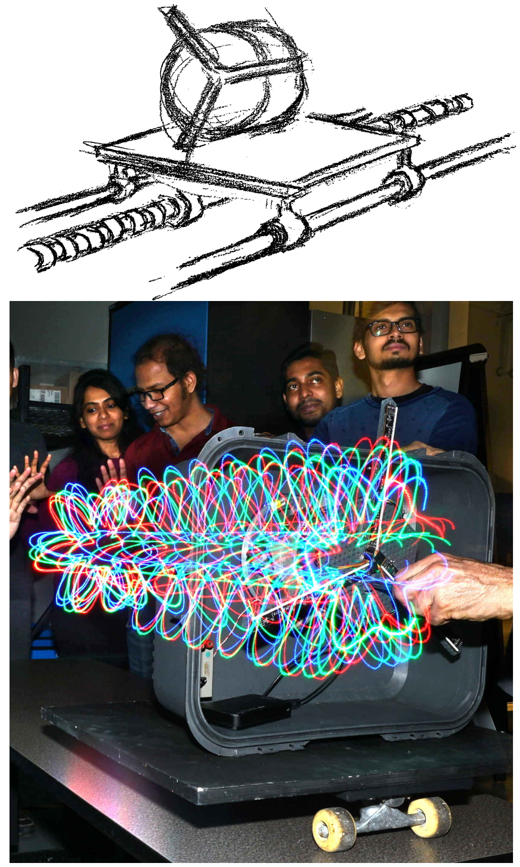

Fig. 14. Sousveillant electric motors in motion trace out a pattern which makes visible the otherwise invisible relationships of the powertrain driving the motor: concept sketch for three SWIMs on a 3-phase motor-in-motion [redacted]photograph of an experimental miniature vehicle made for teaching and testing purposes.

It is our hope that the fun and merriment of games will help get more people interested in addressing issues of mobility for people of all abilities. For example, we might expand our games toward the space of mobility scooters. Accordingly, we have outfitted a number of mobility devices with SWIMs and other devices for biofeedback-based sensing. The SWIM in motion also creates a trace or record of the powertrain function as it moves through space.

See Fig. 15

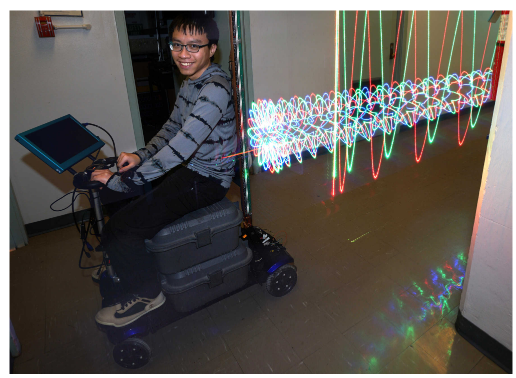

Fig. 15. Mobility scooter equipped with SWIMs for teaching purposes.

The vehicle can also carry cargo in self-driving or wagon (following behind a pedestrian) mode, and is equipped with sousveillant (self-revealing) systems and technologies.

VII. Future possibilities

We're working on a mind-controlled wheelchair or hoverboard that has just one single spherical wheel that floats (hovers) on a cushion of magnetic flux, so that it can go in any direction. By approaching this project as a game, we're building small "toy" prototypes as quick low-risk, low-budget experiments for students to competitively explore, using gamification as a way to stimulate exploration of technologies that might someday help people of all abilities.

Acknowledgments

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