Enhancing the Realism of Driving Simulators using Galvanic Vestibular Stimulation Motion Cueing

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Abstract

This paper explains what Galvanic Vestibular Stimulation is and justifies why integrating this technology with the driving simulator could significantly improve driving realism through pseudo motion cueing on a static simulator and further enhance sustained motion cueing on the dynamic simulator. The effectiveness of vestibular stimulation was optimised by experimentation with different waveforms, frequencies and amplitudes. Stimulation discomfort proved to be subject on a wide variety of factors including skin and electrode impedance, frequency and amplitude of stimulation and rapid changes in stimulation polarity. All these issues were addressed with appropriate solutions to mitigate these undesired effects.

Contents

1 Introduction

1.1 Context of Investigation

The Static and Dynamic Advanced Vehicle Driving Simulators are core products at AB Dynamics and have been designed to reduce new vehicle development timescales and costs by allowing meaningful testing far earlier in the vehicle development process. The simulator can be used across a breadth of applications, including: vehicle dynamics, ADAS and autonomous systems, durability, hardware-in-the-loop, software-in-the-loop and driver monitoring.

To ensure these simulated tests are as close to real life vehicle tests, ABD have developed exceptional realism on the dynamic simulator when cornering or braking. This is due to the well-tuned motion cueing that lets the driver experience six degrees of freedom – x, y, z, roll, yaw and pitch. However, due to the axes limits of the platform axes, there is a lack of sustained motion cueing where the driver experiences prolonged acceleration, see Sustained Motion Cueing Tests.

Two systems have currently been tested to address this issue - active seatbelts and the Cranfield G-Seat, where pneumatic actuators in the seat are used to imitate the pressures of high-velocity driving. Both implementations were evaluated in the [1]. Evident on page 15, the evaluation sheet shows that the active seat and active belt are currently key weaknesses to the Simulator and will need significant development before achieving realistic and comfortable motion cueing. Thus additional sustained motion cueing technologies are welcome and could be implemented in addition to the current system, offering motion cueing that the platform is not able to compensate for. The static simulator currently has no instantaneous or sustained motion cueing.

1.2 Background of Galvanic Vestibular Stimulation

The vestibular system is the sensory system responsible for providing information to the brain about motion, head position and spatial orientation, and can be thought as the accelerometer and inertial measurement unit of the human body. It is involved with motor functions that allow compensatory movements, in response to self-induced or external forces, to aid balance and stabilization.

Galvanic vestibular stimulation, or GVS, is a type of Transcranial Stimulation, conventionally Transcranial Direct Current Stimulation or tDCS. It works by stimulating, with a small current, the vestibular nerve, located in the inner ear underneath the mastoid processes. As explained in the vestibular model developed by Fitzpatrick 2004 [2], electrical current of the inner ear can induce a response from the otolith, located in saccule, and the semicircular canal. Due to the bi-lateral symmetry of the vestibular organs, the vectorial summation of stimulation on the vestibular organs induces 2 axes head rotation, roll and pitch, corresponding to the direction of this vector.

1.2.1 GVS based on Fitzpatrick's Model

Further investigation into GVS by Aoyama et Al. 2015 [4] found that the third axis rotation, yaw, could be induced by opposite directional anteroposterior stimulation (ODAS) using four electrodes on the temples and mastoids.

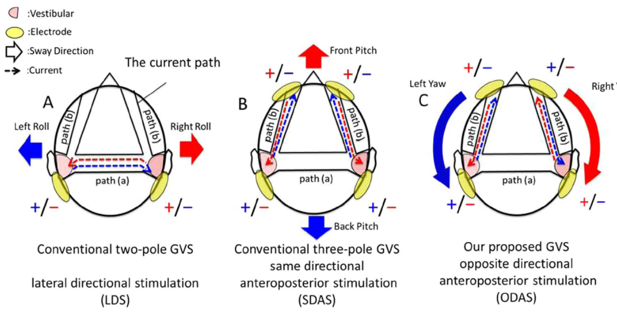

Figure 1: Current paths of GVS inducing roll, pitch and yaw head movements

This stimulation is derived from Fitzpatrick's model but was adjusted to counter for inconsistencies with SDAS.
From the hypothesised head responses, this stimulation was tested on participants using two isolated current stimulators, with a DC stimulation of 3mA. The results showed that ODAS was as strong sensation as LDAS and SDAS with all three stimulations inducing a head angle change with statistical significance of $p<0.01$. It should be noted that LDS, SDAS and ODAS were tested independently and if used with a driving stimulator, two stimulators in this configuration would not work. If there is a potential difference between the mastoids during LDS, then a subsequent potential difference between the temples would have to be greater for ODAS, which would likely cause phosphenes - where current passes through the optic nerve. There is no mention about this phenomenon in the research paper.

1.2.2 Oculo-Vestibular Recopuling Stimulation Model

Cevette et Al. 2012 [3] used a novel method of GVS, named Oculo-Vestibular Recopuling, OVR, to induce three axis rotation to mitigate simulator sickness (flight simulators, driving simulators and other virtual, immersive environments). When synchronising the speed and direction of a moving visual cue with GVS, induced simulator sickness was significantly reduced.

vMocion, a start-up that applied GVS research from Mayo Clinic created an algorithm that uses GVS to stimulate about three axes based on the Cevette et Al. study. The vMocion platform converts scenes from movies or gaming into three-dimensional movement data and using a patented algorithm to convert this to a three-dimensional motion experience using real time GVS [6]. vMocion targeted the gaming, entertainment and VR industries to add motion to visual cues, however Mayo Clinic, where they conducted the GVS research, also partnered with the US department of defense for use in flight simulators.

vMocion is no longer an active business and it is unclear why they did not pursue the product further, however their patent is still active [7].

A later study, Groth et Al. 2022[?], investigated how OVR GVS stimulation could be used to mitigate cyber sickness in a virtual reality environment.

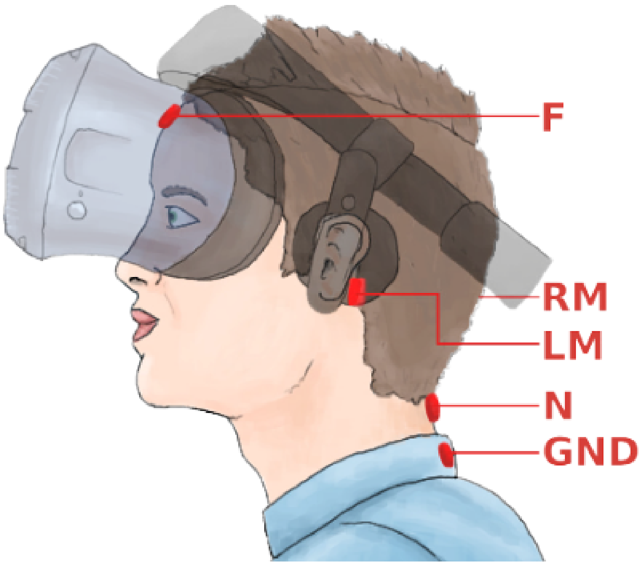

Figure 2: GVS using the Oculo-Vestibular Recopuling Stimulation Model

Electrodes were placed on the upper mastoid processes, the forehead and the nape of the neck, in addition to a ground electrode at the base of the neck.

Intended Motion	Current Flow Direction
yaw right	LM to RM
yaw left	RM to LM
pitch forward	RM to F || LM to F
pitch backward	F to RM || F to LM
roll right	N to LM || RM to N
roll left	LM to N || N to RM

Figure 3: Roll, pitch and yaw were induced by the following omnidirectional tDCS.

The study investigated three conditions - a control condition, strongest axis condition and interpolated condition where intermediate angles are stimulated by combined currents of the respective Euler angle components (yaw, pitch, roll). The results showed that the control was the most sickness inducing with 31.9% terminating the experiment instead of 25.5% for the other two GVS conditions due to discomfort. It was stated that "GVS was able to drastically reduce nausea, especially in men, after similar baseline results in SHAM". The Interpolated GVS condition showed to be more effective than the Strongest Axis GVS condition.

The equations for the interpolated stimulation were as follows:

1.3 Transcranial Direct Current Stimulation (tDCS)

DC waveforms are not charged balanced and will cause electrophoretic transport of ions over time [14]. This effect is of great importance with deep brain stimulation, DBS, to avoid tissue damage. For non-invasive stimulation, there is no evidence that tDCS can trigger tissue damage. However, a build up of ions in the nerve can contribute to discomfort when polarity of the electrodes switch and there is a fast depolarisation at the electrodes.

To counter charge build up is stimulating waveforms which are charge balanced. Hofmann et Al. 2011 [9] experimented with different waveforms to counter this effect and found that charge-balanced tACS resulted in an improvement of up to 50% for both the activation of resting neurons and the entrainment of bursting neurons.

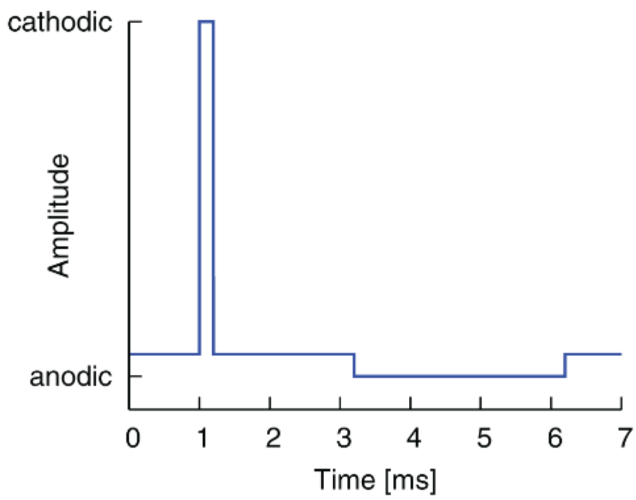

Figure 4: Anodal Compensated Cathodal Stimulation to Maintain Charge Balance [9]

By stimulating gently in the opposite direction for a prolonged time during pulse stimulation, a charge balance can be maintained, whilst the large pulse triggers a nerve response. This waveform was tested using LDS but did not improve the comfort of tACS. The paper did state that this waveform was particularly suited for DBS, where a mild but effective stimulation is of great importance and perhaps is unfit for GVS.

Unfortunately polarity switching cannot be mitigated as bi-directional stimulation is required due to the direction of the roll, pitch an yaw vectors. Ramping up or down the current slowly when switching polarity will improve the rapid depolarisation effect, however it is at a compromise to the latency and realism of the motion cueing. For example, performing a snap oversteer whilst on the simulator will prove either uncomfortable if not ramped, or unrealistic if ramped.

1.4 Transcranial Alternating Current Stimulation (tACS)

AC stimulation is often used to induce specific nerve responses, especially ones that modulate neural activity. Palmer et Al. 1986 [10] found that using high frequency tACS, above approximately 1kHz, an AC component of cochlear response is dominated by a DC response. Since the vestibular nerve is the other part of the vestibulocochlear nerve, high frequency tACS could likely induce a similar DC response in this nerve.

Higher frequency tACS, conventionally above 100Hz, has shown to reduce the impedance between electrodes, due to capacitance reactance. At increasing frequency, current can pass through the deeper tissue, in addition to the skin surface. This enables lower voltage stimulation for the same current amplitude, thereby lowering the charge build up due to the skin's capacitance. Fertonani et Al. 2015 [8] states that tACS evoked sensations are strictly related to the frequency of stimulation and in the range of 8-20Hz, phosphene perception, a side effect of several types of neurostimulation, is significantly higher.
An active patent for systems, devices and methods of GVS [11] uses amplitude and frequency modulation, where the carrier frequency can range from 3-10kHz, to lower the impedance whilst stimulating the vestibular nerve.

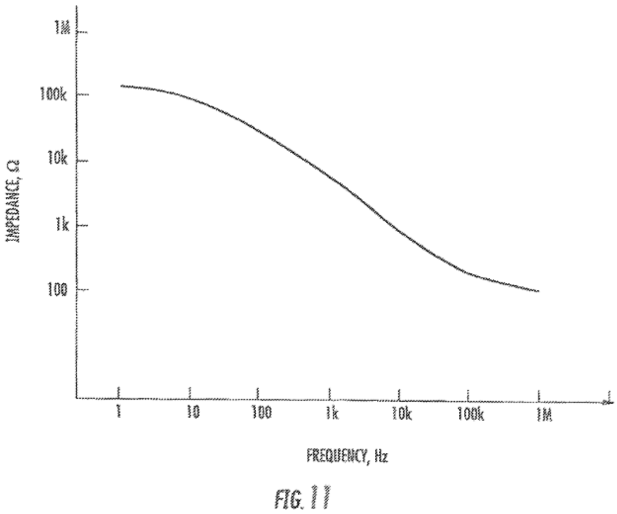

Figure 5: The Relationship between Frequency of the Carrier Signal and the Impedance of the Skin [11]

By increasing the frequency during stimulation, a lower stimulation voltage can be used to achieve the same nerve response whilst improving stimulation comfort and lowering the charge build up during unbalanced stimulation waveforms.

2 Improving the Comfort of GVS

tDCS and tACS induce sensations that are often uncomfortable, and at the very least distracting. Fertonani et Al. 2015 [8] analysed a large number of stimulation sessions to identify the factors affecting tDCS discomfort. The following sensations were identified and used to quantify comfort: Itchiness, Pain, Burning, Heat, Pinching, Iron taste, Fatigue and Discomfort. The factors contributing to these undesired sensations will be examined over this section.

2.1 Electrode Interface

The type of electrode used greatly affects stimulation sensations and was found to be the most significant factor for tDCS sensations. It is important to to obtain the lowest electrode-to-skin impedance to diminish the voltage required to perform stimulation. Electrodes inserted into a saline soaked foam pad proves to be a comfortable electrode medium. BrainPatch have identified that the correct foam-pads are important - they must have low impedance and good water retention over a long period. The optimum saline concentration should be between 15-140mM. Electro-conductive gel can also be used to improve scalp contact to maintain the current distribution uniformity, high viscosity gel is reportedly less effective. Elastic bands can also be used to ensure good contact with the skin.

If mounting the electrodes is a concern, adhesive electrodes can work. Anecdotal evidence from self-testing has revealed that TENS electrodes are significantly more comfortable than Silver-Silver-Chloride electrodes.

In addition, the size of the electrode has shown to have a large effect. [8] found that larger 25-30cm^2 electrodes were statistically less comfortable than 16cm^2 or smaller (p<0.033).

2.1.1 Other Factors

Other factors effecting stimulation comfort include:

1. Stimulation at the anode is more comfortable than the cathodal electrode. Unfortunately this effect cannot be mitigated due to polarity switching.

2. Humidity and oiliness of skin. As stated in [16], sweat gland activity and skin hydration, has a significant effect on electrode–skin impedance". Dry skin increases the skin impedance significantly so it is important to keep the skin at the electrodes humid, by ensuring there is sufficient water in the conductive foam. By adding a conductive gel between the electrode and the skin, impedance can be further reduced.

3. Time of Day - often found that stimulation in evenings are more comfortable, this could be due to increased skin moisture, in addition to the lowering of cortisol and increase in melatonin.

3 Design and Implementation of GVS on the Driving Simulator

BrainPatch, a Brain Computer Interface Company who specialise in neurostimulation, including GVS, have provided AB Dynamics with two isolated current stimulators as well as an SDK, written in C++ to interface with the stimulator. In addition, they have provided consultation and documentation on how to conduct GVS safely. This has enabled the subsequent research and development of GVS with the Driving Simulator, without whom ABD could not conduct this study.

3.1 Description of the Stimulator's Hardware

The battery powered stimulator is programmed with a microcontroller, allowing for low-level modifications and additional circuitry to be added if necessary. A 12-bit DAC is used to update the stimulator's electrode outputs. The stimulator also has WiFi capabilities allowing for high UDP stream rates for real-time wireless stimulation updates from the driving environment and synchronisation with other stimulators.

3.2 Overall Design Methodology

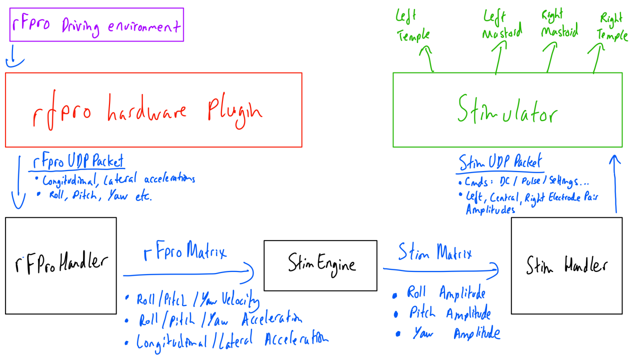

Figure 6: Firmware Structure of the GVS-Driving Simulator Interface

All firmware is available locally [12].

1. The driving simulation software rFpro will be run on a static simulator with the aVDS Hardware Plugin.

2. The plugin will send real-time vehicle physics data (rotation angles, velocities and accelerations) over UDP to a server or PC running rFProHandler.

3. rFProHandler creates a socket and waits for the machine running rFpro to bind on the port.
4. rFproHandler then sorts incoming UDP packages into a structure named rFProMatrix.
5. The StimEngine Class receives the matrix and returns a corresponding structure containing Roll, Pitch and Yaw Stimulation Amplitudes, named StimMatrix. The conversions are calculated as follows, where data from the Cartesian Plane, lateral and longitudinal accelerations were assumed to have similar motion cueing effects to their Euler Angle counterparts, roll and pitch.

$$Roll\,Motion\,Cue \equiv \ddot{\gamma} + \ddot{y}(1 - \frac{\gamma^2}{2}) + g\gamma \quad (1)$$

where γ is roll, $\ddot{y}$ is lateral acceleration, and the second and third term contain cosine and sine approximations and g is the gravitational constant.

$$Pitch\,Motion\,Cue \equiv \ddot{\beta} + \ddot{x}(1 - \frac{\beta^2}{2}) + g\beta \quad (2)$$

where β is pitch and $\ddot{x}$ is longitudinal acceleration.

$$Yaw\,Motion\,Cue \equiv \ddot{\alpha} \quad (3)$$

where α is yaw.

Maximum values (calculated during most extreme driving) from the simulated vehicle are used to map the equivalent motion cues to a maximum stimulation amplitude of 4095 (the 12-bit DAC maximum). These values are then stored to the StimMatrix structure.
6. The StimHandler Class is responsible for communicating with the Stimulator. It creates a socket for the stimulator to bind and sends commands to set comfort level, waveform frequency etc. It also controls what mode the stimulator is set to. It receives the new matrix and converts it to electrode pair amplitudes which will be sent with a command instruction to the stimulator, and updated in real-time from the live rFpro data.
7. The Stimulator receives the UDP packet, follows the commands, outputting the latest value to the stimulator's DAC. It controls the frequency, waveform, amplitude and target electrodes for the stimulation.

3.3 Amplitude-Modulated Pulse Vestibular Stimulation

To simultaneously stimulate more than one axis rotation at a time whilst preventing cross stimulation, vestibular AC stimulation was investigated. A constant frequency square wave was used as a carrier signal whilst amplitude modulation controlled the intensity of stimulation.

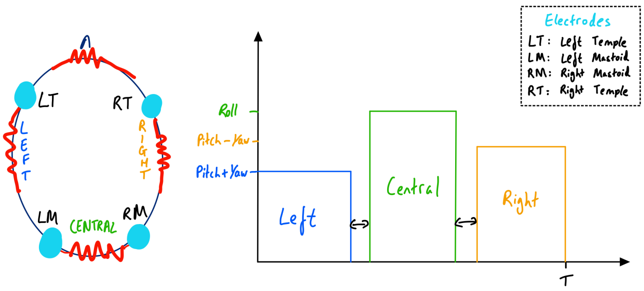

Figure 7: Pulse Waveform - Stimulating the Left, Central and Right Electrode Pair Individually

Stimulation occurs sequentially - stimulating the left, then central, then right pair of electrodes in quick secession and repeating this cycle. This prevents any cross stimulation since the stimulator is only sinking current across one electrode pair at a time.

Pulse stimulation uses a timer interrupt to precisely switch electrode pairs and their corresponding amplitudes at high frequencies. The electrode pair switches were controlled using optically isolated solid-state relays [13]. The maximum switching frequency, limited by the LED turn on time, t_{on}, was approximately 7.5kHz, resulting in a pulse stimulation of 2.5kHz at 30% duty cycle for each electrode pair.

Initial testing showed that, due to the capacitance of the skin, pulse stimulation was smoothed to the extent that it behaved like DC on the surface level of the skin. This indicates that the desired sensationary effect will likely be achieved with pulse stimulation with the benefit of preventing cross stimulation.

4 Conclusions

Unfortunately the study could not be carried out due to health and safety approval in addition to the liability aspects that were not able to be approved in time. The design and method of this study is available in the appendix, see 6. The key takeaways from those who tried GVS were as follows:

Conventional LDS stimulation, described in section 1.2.1 was most effective for Roll, with little lag. However, for pitch and yaw the results were not particularly convincing, perhaps due to the stimulation of the optic nerve as the bi-product of the potential difference across the temples.

The stimulation tingling was greatly improved with conductive foam and saline solution electrodes. This is also most suitable for a product electrode median as they are reusable and could be integrated into the VR headset or headphones.

Using pulse stimulation, described in section 3.3 greatly improved comfort and prevented unwanted cross stimulation at high frequencies. From approximately 500Hz this was more comfortable than DC stimulation and improved with increasing frequency up to the tested 10kHz. The effectiveness of the stimulation was still evident in roll with LDS. However pulse stimulation still has little research in the neuroscience community and is thus likely a lot more difficult to obtain approval in a commercial product.

The stimulation profile from Groth et Al., described in section 1.2.2, was most effective for pitch and yaw, especially when trying the offline demos. However there was some "biological lag" when quickly changing directions. One hypothesis for this problem is that there is charge build up in the tissue of the skin and when you switch motion cueing, i.e. brake suddenly, the electrodes switch (anode to cathode, cathode to anode) and the charge build up on the skin will take time to propagate to the new electrode polarity. This could also induce the tingling discomfort which was quite prominent. However, this could also be a response due to the inaccuracies in the vestibular model. In the current state, this problem is not suited for the driving simulation market, as instantaneous motion cueing is critical for feedback. There is still potential for the autonomous vehicle market to combat car sickness since the cues do not need to be as responsive. If this problem can be solved, then it reopens the simulation and gaming market.

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5 Appendix

5.1 Sustained Motion Cueing Tests

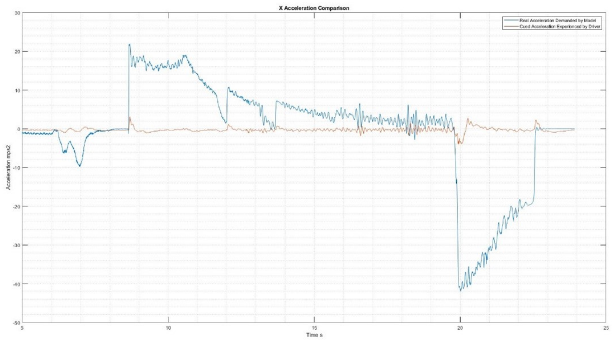

Figure 8: X-axis Motion Cueing (Accelerating and Braking)

It is evident that an acceleration on the vestibular model does not correlate to an acceleration experienced by the driver. The high pass filter blocks motion cueing below 0.6Hz, hence due to its low frequencies, the majority of the longitudinal acceleration modelled in this test is attenuated. The small correlation that is passed through is scaled with a low gain of 14% and does not yield a significant effect on the driver's acceleration. The Y-axis test is equivalent to this, with large forces modelled in cornering that do not correspond to the lateral forces that should be exerted on the driver.

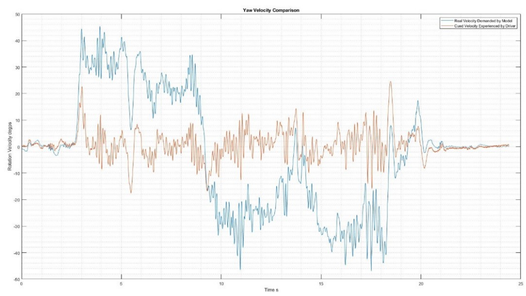

Figure 9: Yaw Motion Cueing (Cornering)

With a gain of 95%, there is correlation between the vestibular model and what the driver experiences. However, after entering the first corner, 3 seconds into the test, the motion cueing does not sustain the rotation, and its offset returns to zero, diverging from the model. This is of course due to the physical limits of the platform.

5.2 Additional Stimulator Circuitry

5.2.1 High Frequency Galvanically Isolated Electrode Switching Circuit

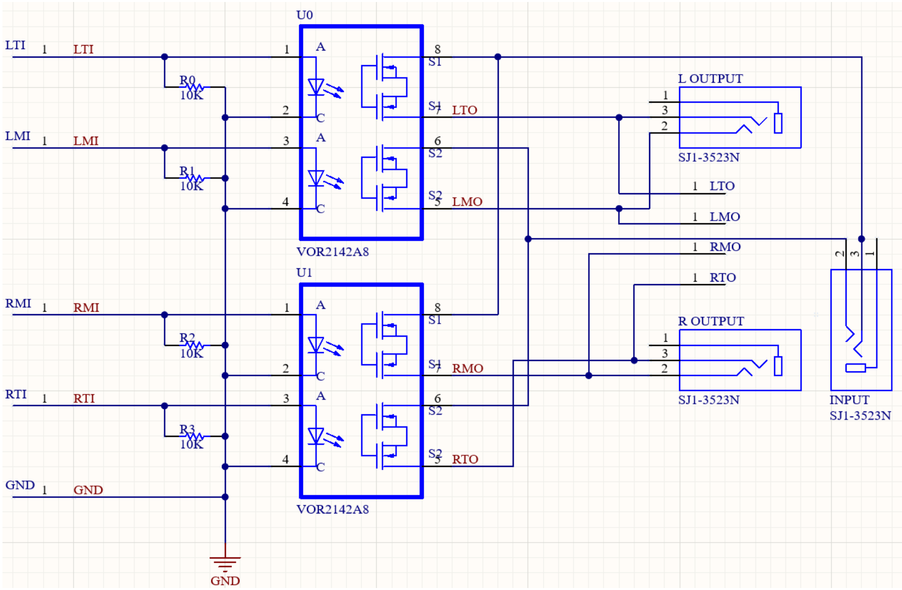

Figure 10: Solid-state Galvanically Isolated Optocouplers switch the stimulation to the three electrode pairs. Microcontroller outputs not displayed.

6 Experimental Design and Method

An experiment conducted internally at AB Dynamics will be carried out to determine the effectiveness, practicality and subject variability of Oculo-Vestibular Recoupling Galvanic Vestibular Stimulation in a simulated driving environment.

The objective of the study was to obtain qualitative and quantitative feedback on the effectiveness, benefits and drawbacks of GVS. This is a preliminary informal experiment and not a randomised control trial. No placebo group will be used.

6.1 Subjects

There were x number of subjects, x men and x women. The median age was x, with a range of (21-x). All were employees of AB Dynamics, with x% of those who had previously driven a vehicle simulator.

6.2 Procedure

1. **Preliminary Briefing** - Each participant completed the health questionnaire and signed the consent form, see Appendix x and x respectively. Participants would read through the briefing, and answer the preliminary questionnaire, see Appendix x and Appendix x respectively.

2. **Preliminary Driving** - Each participant drove for 5 minutes without virtual reality or stimulation to familiarise themselves with the driving simulator.

3. **Virtual Reality Driving** - Immediately after, the subjects would put on the Virtual Reality headset and drive for an additional 5 minutes.

4. **Preparation for Stimulation** - After a 10 minute break, the participants were prepped for stimulation by placing the electrode array on their head, see section 6.3 for more details.

5. **Calibration** - The researcher performed a calibration of the participant's individual galvanic stimulation level. This involved stimulating a step input at increasingly larger current levels between each electrode pair until a discomfort was felt. This ensured that they would be stimulated with the maximum current to optimise effectiveness whilst not being in discomfort.

6. **OVR GVS with Virtual Reality Driving** The participant then began driving in VR whilst being stimulated with real-time three axis stimulation based on the Oculo-Vestibular Re-coupling Stimulation Model, detailed in section 1.2.2.

7. **Post-Experimental Questionnaire** Immediately after the stimulation, the participants must complete the Post-Experimental questionnaire, in addition to a discussion of their experience.

6.3 Apparatus and Setup

- The AB Dynamics static driving stimulator was used with the rFpro driving environment.

- A comfort dial, in addition to an Emergency stop button, was mounted to the driving simulator to ensure the participant was always in control of their stimulation intensity.

- The stimulator was provided by BrainPatch, see section 3 for specifications. Additional circuitry for isolated electrode switching in four-pole configuration was also added, see section 5.2.1.

- A Pimax 8K Virtual reality headset was used to ensure complete immersivity.

- A 3d printed headset was used to house the electrodes and could be worn with the VR headset. The electrodes used TENS conductive pad with a conductive sponge. The sponge was soaked in a saline solution with a concentration of 150mM in addition to conductive gel at the electrode locations. Spacers and elastic bands were used to ensure a good contact and accurate fit for each participant.

6.4 Precautions and Safety Measures

1. All stimulations were limited to 2mA in current. This is limit is controlled by a hardware limiting diode, in addition to software limits controlling the stimulation current output. Conventionally, studies and clinical applications of GVS use a stimulation up to 5mA [15], this study is well in range with this guideline.

2. The stimulation duration will be limited to fifteen minutes.

3. If the participant wishes to stop the stimulation early, the e-Stop button located next to the steering wheel of the simulator could be used to immediately stop the stimulation in addition to its other stop tasks.

4. Prior to the study, participants must sign a consent form detailing the risks, see Appendix x. All participants volunteered to conduct the study on their own accord.

5. Participants completed a health questionnaire prior to starting the study, see Appendix x.

6. Participants are allowed to leave the study at any time.