A Closed-Loop AR-based BCI for Real-World System Control

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Abstract - Both Augmented Reality (AR) and Brain-Computer Interfaces (BCI) have drawn a lot of attention in recent applications. These two new technologies will significantly impact and develop interactions between human and intelligent agents. While there are several studies already conducted in the control of devices using AR based, steady state visually evoked potentials (SSVEP) control systems in a lab environment, this study seeks to implement a portable, closed-loop, AR-based BCI to assess the feasibility of controlling a physical device through SSVEP. This portable, closed-loop AR-based BCI provides users with the unique opportunity to simultaneously interact with the surrounding environment and control autonomous agents with an 88% accuracy. The potential benefits of this application include reduced restrictions on handicapped individuals or concurrent control of multiple devices through a single AR interface. Ultimately, we hope this outcome can bridge the BCI field with further real-world, practical applications.

Keywords— Portable Brain-Computer Interface, Augmented Reality, Steady State Visually Evoked Potential, Real-World

I. INTRODUCTION

Several studies into the field of consumer-based Brain-Computer Interface (BCI) and Augmented Reality (AR)-based BCI's have been conducted over recent years as the availability and stability of consumer-grade AR systems become more prevalent [1, 2, 3]. While these studies progress to a more stable state and demonstrate their application, there remains a large barrier that must be overcome before transitioning this technology into a readily available system that can be used to control agents such as robots in a consumer or commercial environment.

This barrier consists of several stable conditions provided by testing in a controlled laboratory environment that are not present in the real world. In most testing of this technology, the components are wired together to provide real-time communication between all devices. Similarly, studies infrequently require users to assess their physical surrounding before interacting with the BCI.

II. BACKGROUND

The implementation of a user interface for steady state visually evoked potentials (SSVEP) systems in an AR interface provide several unique challenges that must be overcome when considering the dynamic environment in which they must operate. Additionally, when removing the wired connection between components of a control system such as this, various challenges arise that impede the system's performance and reliability. To investigate the feasibility of implementing such a system we integrated a Microsoft HoloLens, electroencephalograph (EEG) and mobile SSVEP analysis server to control a TurtleBot 3 in response to visual stimuli.

Furthermore, while a trial-based approach to SSVEP analysis provides a robust assessment, it increases the likelihood of incorrect movement as each trial results must result in an action delivered to the TurtleBot. Considering this, an alternative was devised that provided the user with flickering stimuli and only commanded the robot once a high threshold of certainty was achieved. In this solution, the user only commands the robot when they are interacting with the stimulus rather than aligning with the schedule imposed by the pre-defined trials. While alleviating some of the stressors induced by a trial based SSVEP analysis, this solution was carefully considered as extended exposure to SSVEP stimuli is known to cause fatigue. [4]

III. RELATED WORK

The field of system control is one that is constantly evolving and adapting to leverage and develop new technologies. Many existing projects have developed systems that leverage BCI's & alternate system feedback (such as AR/ Virtual Reality (VR)) to reduce the restrictions imposed by traditional systems for control, ultimately providing an alternative to the resolution sought by utilising SSVEP over AR.

A. Practical AR/VR BCI applications

As SSVEP requires the delivery of a flickering visual stimulus, traditional systems are often bound to static screens such as a desktop PC [5]. Delivering this content over AR provides a unique opportunity for mobility but incurs several pitfalls that are to be investigated. For example, studies on the effects of stimulus positioning when in an AR-based BCI showed that stimuli must be delivered over a longer period to match the same accuracy as a static screen when specifically positioned [6]. Differing stimuli (positioning, frequency, colour, etc.) in this context could be further researched or analysed through the implementation of this system to determine performance and accuracy, particularly when compared to traditional media.

While research into the performance and accuracy of an AR-based BCI control system is important, the practical feasibility should also be considered. An example of such an application has been developed where commands were issued to a robot via brain analysis [7]. The study demonstrates the niche issues encountered when considering an AR-based system, such as stimulus anchoring and orientation. The results from this study are to be further leveraged in this application while extending the research by introducing a closed loop testing environment for rapid analysis.

B. SSVEP based AR BCI's

Some of the early research into AR, such as the feasibility study performed by Faller et. al, demonstrated the capability and effectiveness of SSVEP stimuli on an augmented reality display [8]. This study presented the participant with a navigation task in a fully virtual environment super-imposed over the real-world room. This study intends to extend this concept by providing a similar navigation task leveraging real world devices, in this case, the TurtleBot. By interacting with real-world objects, we can not only demonstrate the usefulness of an augmented reality display but assess the feasibility of assessing one's real-world environment before returning to the augmented reality interface.

Putze, Weis, Vortmann & Schultz (2019) further approach our goal by overlaying controls for a smart home in augmented reality [9]. This system provided users with the ability to control home appliances such as music players or lights with an augmented reality interface overlayed against physical stimuli. While this study more accurately combines real world effects with a virtual interface, the stimuli remain stationary in the user's vision and the closed loop application has a high latency as the user must wait for the appliance to update, make a judgement, and then correct if necessary. Our study aims to assess a more rapid closed loop that requires the user to move their focus to follow a target while EEG data is assessed. As such, we can more comprehensively assess the performance of an AR control system in the real world where the user may have to follow a device such as a drone.

Several studies have now extended upon the work of static AR interfaces that leverage SSVEP as a control system. Most of these systems provide several targets that allow the user to manipulate a semi-autonomous agent and require them to perform at task. One example, designed by Ke et. al. (2020), provides the user with a robot arm with several articulation points [10]. Participants were then asked to move an object from one location to another. The limitation of many of these studies are two-fold. Most do not require the user to move their body or head limiting noise that may be introduced in a more natural environment. They are low speed and provide no real-time feedback for correctness.

This study attempts to overcome these limitations to further assess mobility by requiring the participant to track the robot while making rapid decisions regarding the direction of the device. As we are aware of the only available path to the destination, we can assess every trial while ensuring the user still has the capability to engage with a feedback loop that affects their real-world surroundings.

IV. METHODOLOGY

By considering alternative control systems, existing studies and AR systems, several significant design challenges arose that were considered for the development of this system. The primary concerns included stimuli placement, mobile SSVEP analysis and the system with which stimuli were presented to the user.

A. *System Architecture*

The final development of the system was divided into four distinct components: TurtleBot control, interface development, acquisition/analysis of EEG data, and inter-component communication. To facilitate this approach to development, a closed-loop, AR-based BCI was built (as shown in Figure 1) that clearly outlined communication requirements for each component.

This architecture exemplifies some of the benefits that may apply to practical scenarios. For example, this system could be modified to control an unmanned aerial vehicle (UAV) used for bushfire reconnaissance or mitigation. While utilising this system, the controller could perceive their surroundings in real-time and receive input from their commanders without lag or the need to remove goggles, as would be the case in a VR or traditional, screen-based control systems. Additionally, the system provides the user with hands-free control facilitating multitasking which may become vital in a life-threatening situation such as a bushfire.

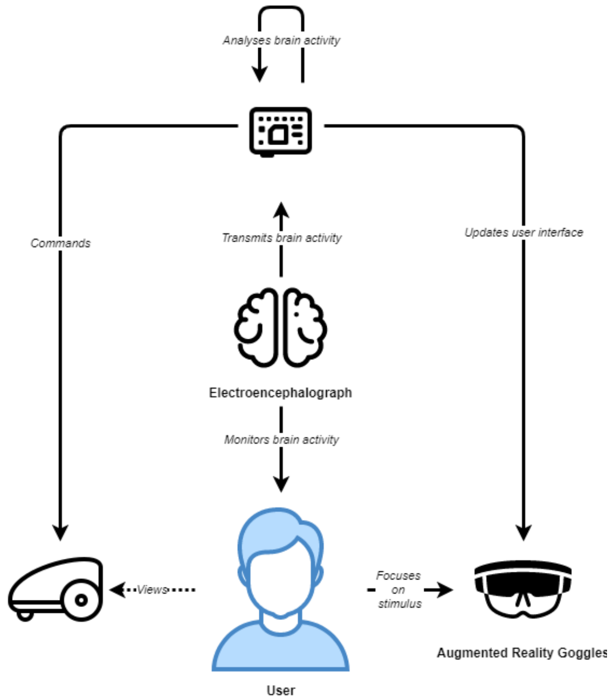

Figure 1: System Architecture: The participant views the TurtleBot & AR environment through the HoloLens while their brain signals are recorded by a wireless EEG. Data from the HoloLens & EEG are sent to a mobile server and translated to movement actions transmitted to the TurtleBot.

B. *Turtlebot Control*

The TurtleBot 3 was selected as the robot hardware to be controlled through a simple interface that would allow the user to move the device either left or right. The user was instructed to focus on either a left or right arrow while the server analysed the interaction and delivered a command across a wireless network connection. To simplify the API exposed for the robot's control, a basic Python server was implemented. This server exposed two HTTP endpoints "/left" and "/right" that queued actions for the device to perform. This queuing system was necessary as there was no direct communication from the robot back to the EEG analysis server. Without the queuing system, the EEG server may have been able to deliver a command to the robot while still performing a previous task which would have ultimately led to unexpected results.

C. *Experimental Paradigm*

To validate the user's ability to consistently control the robot, an AR scenario was developed where a participant was responsible for delivering a series of left or right commands through an SSVEP paradigm to reach a goal. As in Figure 2, a series of nine, labelled, linear destinations were presented in front of the TurtleBot within the users extended vision. At the beginning of each trial a number corresponding to a destination was displayed in augmented reality. The user was then responsible for determining the robot's current location relative to the target and focusing on a left or right SSVEP stimuli to move the robot and ultimately reach the destination. As the Turtlebot only moved one position per SSVEP stimuli, the participant was asked to remain focused on a single direction for several iterations. For example, when moving from Target 5 to Target 7, the user would focus right to move to Target 6 and remaining focused on the right stimuli to move to Target 7. Once the Turtlebot reached the destination, a new destination was calculated to using the existing movements (including errors) to ensure an even distribution of left and right instructions. While the user remained seated during the experiment they were encouraged to turn or move as necessary to view targets or the TurtleBot.

Left and right stimuli were arrows occupying a real-world space of approximately 30cm and flickering at 11 & 13 Hz (Ref Figure. 2). Each stimulus alternated between transparent and white. To ensure a consistent flicker frequency the HoloLens' refresh rate was monitoring during the development phase to ensure a consistent 60Hz was maintained. Flickers were then implemented using a basic sin wave against the time since launch where positive values resulted in a visible stimulus. As in Figure 3, each stimulus flickered for 5 seconds with a rest period of 3 second to allow the robot to move and the participant to re-assess the device's new location. This length was based on a high success rate during initial testing and previous studies [11]. Three electrodes (O1, O2 & Oz) were actively monitored and assessed using a canonical correlation analysis (CCA) remotely. Approximately 70 destinations were presented to the user resulting in an average experiment length of 30 minutes.

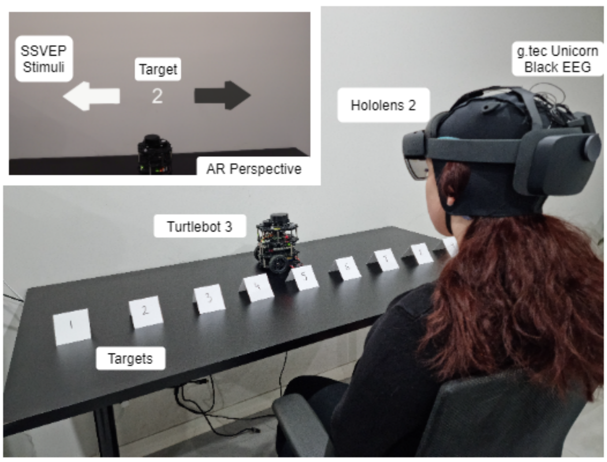

Figure 2: The experimental setup: the participant is fitted with a wireless EEG & HoloLens 2. In their immediate vision are 9 physical targets and a TurtleBot capable of moving to each target. Within the AR environment (top-left) the participant is shown a target destination and two SSVEP stimulus (left & right) to move the TurtleBot.

D. Stimuli Placement and User Interface

The most significant benefit of this technology combination is the user's increased ability to move and interact with their surroundings. The solution presents the user with an SSVEP stimuli anchored in a physical AR environment. This interface allows the user to move around the stimuli rather than having them constantly present, as is the case with a heads-up display style interface. This provides the user with the ability to remove focus from the stimuli and interact with their environment unobstructed. Alternatively, the user can also focus on a stimulus from a unique perspective of their choosing which further improves this interaction. While this approach provides several benefits it also introduces challenges with positioning stimuli in an AR environment that must be addressed.

Stimuli placement became a significant consideration in development as issues began to arise with overlaps in the AR space. The application was able to circumvent this behaviour through a combination of Unity's collision system and manual control of the stimuli. In the final design, stimuli would not overlap with real world objects and users had the capability to move the stimuli to improve their ability to gain an unobstructed and clear view of the full interface. Stimuli placement could be easily expanded to interact with the environment in more complex ways such as object tracking or anchoring on points of interest.

E. Subjects

Three participants aged 22-25 (one female, two BCI naive) free of neurological disorders or medication that might negatively affect the EEG participated in this study. Due to COVID restrictions, the number of participants is limited in the current study. All participants provided written consent prior to the experiment and verbally received explanations of the nature and purpose of the experiment. The procedure was reviewed and approved by UTS Human Research Ethics Committee (ETH20-5371).

F. Data Acquisition

To determine the user's intended action, data was streamed over a Bluetooth Low Energy (BLE) connection from the EEG to a remote server. This server was responsible for both the analysis of incoming data as well as distributing commands to the device under control. The system leveraged the g.tec Unicorn Black EEG which provides a pre-built interface for the Lab Streaming Layer (LSL).

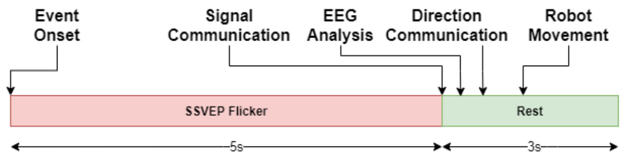

Figure 3: Trial breakdown: The first 5 seconds are used to show the left & right SSVEP flicker. Data from this 5 second period is then communicated to the analysis server via BLE, cleaned and analysed. If the analysis resulted in a direction, it is then communicated to the TurtleBot & HoloLens along with the new destination if necessary. Following this the TurtleBot moves in the corresponding direction. Over this 3 second period of no flicker, users can familiarize with the Robot's new location and the required destination.

To simplify inter-component communications, the software suite OpenVibe was leveraged with a configuration including a basic Butterworth filter (1Hz – 40Hz & 0.5dB band pass ripple) and filtering of EEG channels to improve signal quality and, ultimately, the accuracy of the analysis. As in previous studies, electrodes O1, O2 & Oz in the occipital region were selected as they have been recently assessed as providing the most significant response to the SSVEP stimuli [12]. As in Figure 3, incoming data was separated into 5 second epochs, divided by markers generated by the HoloLens' Unity application and then delivered to the server. Each epoch was then translated into a left or right API call through a custom Python script utilising SciKit's CCA analysis tools.

A significant limitation of the HoloLens' ability to effectively deliver a stable SSVEP stimulus was the lack of LSL support. While there is substantial support for LSL implementation in Unity, once transpiled to the Universal Windows Platform (UWP) required by the HoloLens several .NET APIs are no longer supported, which currently precludes the use of any open-source LSL libraries available for Unity. As such, OpenVibe's TCP marker interface was leveraged to notify the commencement of SSVEP trials.

As in Figure 4, communications between the EEG and OpenVibe interface travelled over several layers. Initially, the EEG is connected to the pre-built LSL interface developed by g.tec running on a .NET application. This LSL server is hosted on the same device as the OpenVibe server which requires Bluetooth for communications. The LSL then communicates with an OpenVibe acquisition server to further standardise the data's interface.

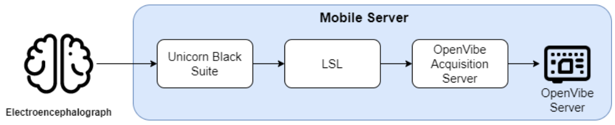

Figure 4: EEG data pipeline: Data is transmitted from the EEG to the mobile server via Bluetooth Low Energy (BLE). Once on the device, signals are normalized by the Unicorn Black Suite and exposed to an LSL stream. An OpenVibe acquisition server accesses the LSL stream in combination with TCP markers transmitted from the HoloLens and provides them to the OpenVibe Server for final processing.

G. *Brain Dynamic Analysis*

To ensure the system is robust and practical while mobile, interactions between components were discrete, standardised, and wireless. As such the clients, including the robot, analysis server and EEG, communicate wirelessly over several transports including TCP and HTTP. Each interface is standardised and capable of recovery to ensure a dropped connection does not impede the user's ability for continuous control. SSVEP trials were implemented on the HoloLens client and communicated to a distinct analysis system alongside a stream of brain data from the EEG. Each stable trial resulted in a movement direction which was then delivered to the robot accordingly. The Python analysis script was largely adapted from open-source SSVEP analysis systems with minor variations to accommodate differences in the hardware requirements. The most significant impact on system performance was any disturbance to the EEG electrode's positioning, commonly caused by a test subject's movement. This movement introduced significant noise that was not effectively handled by the existing mitigation techniques. If the user was moving more drastically than a basic head turn the EEG analysis fell well below the baseline accuracy, often to the point of failure. Similarly, changes to brightness and background of the test environment had a notable impact on performance. As white was identified as the most stable stimuli colour, an increase in brightness or whiteness of the background both reduced EEG performance and significantly reduced the user's ability to identify a stimulus.

The system's interface provided the user with two SSVEP stimuli, one left arrow and a right arrow. These stimuli flickered at 11 and 13Hz to prevent any possible overlap in resonant frequencies. Additionally, each arrow flickered between transparent and white, as this contrast resulted in the most promising results during preliminary testing in variable lighting conditions. The presentation of white stimuli was particularly effective in low light environments, however, subject to some decreases in performance against white backgrounds. This interface was developed in Unity and transpiled into an UWP application which is natively supported by the HoloLens 1 and 2.

Throughout validation procedures, it became apparent that the HoloLens' ability to consistently deliver a stable framerate significantly lowered as the device reached low battery. While not validated, this impact on performance was assumed to be a repercussion of resource throttling to further preserve battery life.

H. *Performance Evaluation*

Considering the experimental paradigm in Figure 2, it becomes clear that the correct direction can be discerned at any given point in time. If the destination is a lower number than the current position left is required and right for the inverse. This experimental setup facilitated a secondary level of validation by assessing each movement rather than the participants ability to reach some destination as is the case in several similar studies. Through this design we can assess whether the system enabled movement to the correct destination as well as a SSVEP analysis accuracy on a per-trial basis. In the final experimental design, accuracy is defined as a correctness of direction. 183 out of 183 movements in the correct direction will result in 100% accuracy. The F-score is calculated to index the BCI performance.

While complex, the system's communication interactions over a local network connection were able to facilitate near real-time performance. The most resource intensive operation was identified as the EEG analysis performed by the server on receiving each chunk of data. This process introduced a latency that was accommodated by increasing the length of rest between SSVEP trials to three seconds. This increased time provided the server with an opportunity to perform the analysis and distribute a response. Additionally, this time allocated a moment for the robot's movement while providing the user with an opportunity to validate the movement's direction and re-focus on the SSVEP stimuli.

V. RESULTS

To determine accuracy, we performed a guided study with three participants. The experiment for each participant lasted 30 minutes with 8 second trials (5 seconds stimuli / 3 second rest) resulting in approximately 185 trials per participant when accounting for baseline EEG readings at the beginning and end of each experiment and non-assessed epochs. The number of destinations for each experiment differs as the destinations are randomly generated which results in different movement count required to reach each destination. A breakdown of events throughout this trial is highlighted in Figure 3. Differing from several similar studies [9, 10], accuracy for this study was determined on a per-trial basis as the experimental setup facilitated the calculation of the correct direction at any given point in time. However, an assumption here was made that the participant could determine the correct direction. Given the opportunity for familiarisation before the active trials, no participants made an error in this assessment. To limit the possibility of any bias in terms of stimuli accuracy (e.g., left stimuli was more effectively assessed than the right) destinations were generated such that the ratio of left to right movements was as close to even as possible.

On a per trial assessment, participants averaged an accuracy of 88% with one user participant capable of 100% accuracy over the course of the experiment as shown in Table I. Assessing accuracy in relation to a participant's capability to move the TurtleBot to the target destination resulted in 100% accuracy as no situation arose where a participant was incapable of reaching the requested destination. Across all experiments, BCI performance achieved an F-score of 0.86. Considering this accuracy and F-score, users can use this AR-based SSVEP system to control robot in real environment, rather than lab environment.

Table I. The SSVEP performance

	Number of Destinations	Number of SSVEP	Correct SSVEP	Acc.	F Score
S1	69	191	155	81%	0.81
S2	75	183	183	100%	1.00
S3	70	188	157	84%	0.77
Avg	71	187	165	88%	0.86

It is worth to highlight that participants were provided with an opportunity to familiarise with the navigation system prior to each experiment. During this period, no participants made errors related to the necessary direction of the Turtlebot, e.g., moving left when right was required. Furthermore, no participants reported errors following the experiment procedure. Taking this into considering, we can assume that errors made were caused by inaccurate analyses of EEG data. The more detail is discussed in the following section.

VI. DISCUSSION

While some areas for improvement were noted, the outcomes identified fundamentally confirmed the practicality of applying an SSVEP based EEG interface delivered over AR in a real-world environment. This was demonstrated through the production of a fully functional control system for an autonomous agent (robot) over a wireless network connection. The interface provided several benefits to the end-user, largely regarding the ability to multitask while interacting with the system. Additionally, the augmented reality interface provides a standardised platform capable of hugely dynamic interfaces.

A. Accuracy

As noted in Table 1, one participant was capable of 100% accuracy. The key difference between this participant and those with lower accuracies was a lack of hair. Taking this into consideration, it is possible that the participants hair may have impeded the device's ability to record a stable EEG signal. As in Figure 5, the hybrid electrodes provided with the g.tec Unicorn Black BCI do try to reach through the hair, however, this is limited to a depth of about 1cm. Hair longer than this may prevent the electrode from reaching the scalp. Furthermore, as the electrodes are embedded in the hair it is possible that they are more prone to movement when compared to those that sit above the hair which may further lead to unstable signals.

While no standardised, subjective analysis was performed, several participants mentioned minor aches around specific electrodes upon completing the experiment. Those specific electrodes were fitted under the HoloLens' head strap which likely resulted in abnormal pressure to the electrode. In addition to discomfort, this contact was possibly a source of poor signal quality as head movement during the experiment resulted in friction between the electrode and HoloLens. In a practical application of this technology, electrode placement should be carefully considered to not only improve user comfort but potentially improve signal quality by reducing movement caused by the head strap. Alternatively, a custom mount for the HoloLens could be developed to more firmly and comfortably fit electrodes to the scalp.

Figure 5: Electrodes supplied with the g.tec Unicorn Black BCI may have had some impact on the EEG signal stability in participants with long hair.

Furthermore, at no point did a participant's stimuli overlap with an object is their environment. This demonstrated the efficacy of the collision-based stimuli placement system developed for this application. In a production environment, this would ensure that the stimuli did not overlap with the changing environment while the user was moving.

B. Practical Applications

The most significant issue was the introduction of signal noise while the user was moving. This is of particular concern as one of the most marketable improvements over a traditional control system is the ability to work in the field. A potential solution to this issue would be a more robust signal filtering system capable of detecting the underlying waveforms delivered by the EEG. While simpler than the alternatives, this mitigation technique may be less robust especially considering subject difference in brain dynamics [13].

Further examining mobility, an issue that must be considered is the system's diminishing ability to communicate with clients as the user distances themselves from host (the mobile server in this application). Considering this problem, as well as the possibility of distributing a local network from the EEG server, it becomes clear that the device should be powered in a mobile context. The introduction of an independently powered, remote server such as this also introduces the possibility of a more consistent power source for the other devices available in a local vicinity. One benefit of the current solution is the existing wireless transmission which would allow the host to be attached to any networked device. In the testing environment, the system was able to leverage the local area network, averaging gigabit transmission rates. If moved to more realistic, consumer environments it is unlikely the device will be continuously within a network that meets this specification. To overcome this limitation, the system's host could act as a gateway for any external communication required, such as integrations or updates. The introduction of this subnet would further facilitate the system's initialisation, as the host could more confidently identify and communicate with any networked client.

When considering signal latency, the most significant instability was the Bluetooth communications required by the g.tec Unicorn. These latencies were periodically identified by the OpenVibe acquisition server that introduced device drift above the expected tolerance of two milliseconds. Once started, this drift often reached values above 500 milliseconds and was resolved only by re-establishing a Bluetooth connection.

The Unity application transpiled to a performant UWP app and deployed to HoloLens in combination with a mobile analysis server & BLE EEG processing provides a clear benefit and improvement over existing BCI's developed for robotic control. This system not only allows an individual to move away from the traditional fixed screen required for SSVEP stimuli but can facilitate simultaneous engagement with their surroundings through benefits provided by AR.

C. *AR Interface*

When integrating SSVEP into an augmented reality headset one concern that may arise is the presence of eye-tracking. If we can already determine the user's focus through eye-tracking what benefit does SSVEP provide?

Eye-tracking requires the user to be constantly focused on a stimulus. Should the user look away at any point they must restart the selection process. SSVEP is robust enough to overcome such distractions allowing the user to momentarily focus on a new point of interest. This is particularly important in applications where user requires flexibility to assess their surroundings. Furthermore, eye-tracking often uses pupil dilation, gaze fixation or blinking detection [14, 15, 16]. These interfaces require training making them less intuitive than an SSVEP system where the user can simply look at the stimuli. Additionally, the action of focusing on an arrow is a simple task that requires less focus than blinking or pupil dilation. This may be important in environments where the user may have to stop and focus on the selection which may distract from an important task at hand.

In addition, eye tracking, in general, is susceptible to differences in lighting conditions. For example, only specific eye-tracking systems are capable of eye tracking in low light environments. These devices are not necessarily integrated into devices like the Microsoft HoloLens meaning this device can only operate in well-lit conditions. Similarly, pupil dilation is susceptible to changes in lighting conditions. SSVEP is less affected by changes in ambient lighting as we can accommodate the intensity of the stimuli. In future, it may be possible to implement dynamic stimuli colours to improve contrast with the user's background using the Hololens' cameras. This change may further improve SSVEP's performance in relation to eye tracking.

Furthermore, information transfer rate (ITR) is a good indicator of the speed at which the user can interact with an eye-tracking or SSVEP selection system. Eye-tracking performance is largely dependent on the method of input selection meaning ITR's can vary from 50~160 bits/min [17]. Recent innovations have leveraged a combination of SSVEP & eye-tracking to produce a speller capable of 184 bits/min [18]. Furthermore, several studies into SSVEP performance have resulted in speeds of over 319 bits/min [19].

"The Midas Touch Problem" in eye-tracker is an error that occurs when a user accidentally selects an option while searching for the target. SSVEP experiences a similar issue where signals may be misinterpreted leading to an error in selection. It may therefore be possible to combine these technologies to lead to a more accurate and robust BCI. For example, instead of using either SSVEP or eye tracking for target selection, eye tracking may be used for region highlighting and SSVEP for final target selection. Such a system would not only lower the likelihood of accidental selection but may also increase the quantity of stimuli available within a finite space in the user's vision.

Finally, one minor concern is the user's ability to identify stimuli in AR. As the background behind the stimuli is dynamic it is possible for the colour to match the colour of the stimuli hindering the participant's ability to engage with the system. During preliminary testing it became apparent that a dark background provided the highest performance in SSVEP accuracy. However, when working with a white background, as in Figure 3, SSVEP accuracy was subject to some decrease. To overcome these limitations in a practical application of this technology, the AR system could define an average colour for the environment and dynamically update the interface to improve the reliability of EEG data.

VII. CONCLUSION

In this study, we designed a mobile, wireless architecture to facilitate an AR based BCI for real-time device control while allowing users to simultaneously engage with their surroundings. This system was achieved by presenting participants with an SSVEP stimulus in an AR scenario through a HoloLens while wirelessly syncing SSVEP events to a mobile server. Simultaneously, EEG data was processed and transmitted across several network layers including TCP & BLE to the same server. The EEG signals were analysed in real-time and translated to movement comments sent to a TurtleBot that participants were required to navigate to the specific destinations with 88% accuracy and minimal latency. One limitation of this study is the numbers of participants. The data captured for this experiment was largely impeded by Sydney's COVID lockdown. Once restrictions are alleviated, the team intends to include further participants to have more datasets for validation. Another limitation is the numbers of SSVEP flickers. We primarily developed a two flicker, SSVEP scenario to optimise battery life and HoloLens performance. In the further studies, we intend to implement multiple flickers to provide more freedom for robotic control.

The results show that this portable, wireless, closed loop BCI leveraging AR and SSVEP is not only feasible for practical use but highly accurate. While performant, the study revealed several areas for future work and highlighted limitations that should be considered when undertaking further applications utilising this technology stack. As such, we intend to extend this work by introducing a combination of eye tracking alongside the existing SSVEP control to improve reliability and leverage the full capability of the HoloLens 2 for more real-world BCI applications.

VIII. REFERENCES

[1] Makin, J.G., Moses, D.A. & Chang, E.F. 2020 "Machine translation of cortical activity to text with an encoder–decoder framework", Nat Neurosci 23, 575–582.

[2] Musk, E. 2019, “An integrated brain-machine interface platform with thousands of channels”, bioRxiv 10.1101/703801, 514-555.

[3] Xu, D., Songyun X., Xinzhou, X., Ya, M., Zhao, X. 2019, “Quadcopter Flight Control Using a Non-invasive Multi-Modal Brain Computer Interface”, Frontiers in Neurorobotics, 13, 1662-5218, 23.

[4] Xie, J., Xu., G., Wang, J., Li, M., Han, C., Jia, Y 2016, “Effects of Mental Load and Fatigue on Steady-State Evoked Potential Based Brain Computer Interface Tasks: A Comparison of Periodic Flickering and Motion-Reversal Based Visual Attention”, PloS one, 10, 12-71.

[5] Lin, C. T., Chiu C. Y., Singh, A. K., King J. T., Ko L., W., Lu Y. C. and Wang Y. K. 2018 "A Wireless Multifunctional SSVEP-Based Brain–Computer Interface Assistive System," in IEEE Transactions on Cognitive and Developmental Systems, vol. 11, no. 3, pp. 375-383, Sept. 2019, doi: 10.1109/TCDS.2018.2820153.

[6] Zhao, X. Liu, C., Xu, Z., Zhang, L., & Zhang, R 2020,” SSVEP Stimulus Layout Effect on Accuracy of Brain-Computer Interfaces in Augmented Reality Glasses”, IEEE Access, vol. 8, no. 10, pp. 5990-5998.

[7] Si-Mohammed, H., Petit, J., Jeunet, C., Sanz, F A., Spindler, F 2020, “Towards BCI-based Interfaces for Augmented Reality: Feasibility, Design and Evaluation. IEEE Transactions on Visualization and Computer Graphics, Institute of Electrical and Electronics Engineers”, vol. 26, no. 3, pp.1608-1621.

[8] Faller J., Allison B., Brunner B., Scherer R., Schmalstieg D., Pfurtscheller D. and Neuper C. 2017, “A feasibility study on SSVEP-based interaction with motivating and immersive virtual and augmented reality”, abs/1701.03981 .

[9] Putze F., Weiß D., Vortmann L. and Schultz T. 2019, "Augmented Reality Interface for Smart Home Control using SSVEP-BCI and Eye Gaze," IEEE International Conference on Systems, Man and Cybernetics (SMC), pp. 2812-2817.

[10] Ke Y., Liu P., An X., Song X. and Ming D. 2020, “An online SSVEP-BCI system in an optical see-through augmented reality environment”, Journal of Neural Engineering, vol. 17, no. 1, pp 16-66.

[11] Chen, S.K., Wang, Y.K., and Lin, C.T., 2020, “An SSVEP Stimuli Design using Real-time Camera View with Object Recognition”, 2020 IEEE Symposium Series on Computational Intelligence (SSCI), pp. 562-567

[12] Meng, L., Jin, J., and Wang, X. 2011, “A comparison of three electrode channels selection methods applied to SSVEP BCI”, 4th International Conference on Biomedical Engineering and Informatics (BMEI), Shanghai, 2011, pp. 584-587.

[13] Arvaneh, M., Robertson, I., Ward, T. 2014, “Subject-to-subject Adaptation to Reduce Calibration Time in Motor Imagery-Based Brain-Computer Interface”, IEE Eng Med Biol Soc, 10.1109.

[14] Microsoft 2014, Microsoft Patents Technology To Type Text Through Eye Gaze - MSPoweruser n.d., viewed 15 May 2021

[15] Access Computing 2020, Low Cost Eye Tracking for Computer Access and Speech Synthesis | AccessCSforAll n.d., viewed 15 May 2021,.

[16] Chakraborty, P., Roy, D., Zahid, Z., Rahman, S., 2019, “Eye Gaze Controlled Virtual Keyboard” 2019, International Journal of Recent Technology and Engineering, vol. 8, no. 4, pp. 3264–9.

[17] Cecotti, H., Meena, Y.K. & Prasad, G. 2018, “A multimodal virtual keyboard using eye-tracking and hand gesture detection,” Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, vol. 2018-July, Institute of Electrical and Electronics Engineers Inc., pp. 3330–3, viewed 15 May 2021.

[18] Naeem Mannan, M.M., Kamran, M.A., Kang, S., Choi, H.S. & Jeong, M.Y. 2020, “A hybrid speller design using eye tracking and SSVEP brain–computer interface,” Sensors (Switzerland), vol. 20, no. 3.

[19] Chen, X., Wang, Y., Nakanishi, M., Gao, X., Jung, T.P. & Gao, S. 2015, “High-speed spelling with a noninvasive brain-computer interface,” Proceedings of the National Academy of Sciences of the United States of America, vol. 112, no. 44, pp. E6058–67.