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IMPLEMENTING EYE MOVEMENT TRACKING FOR UAV NAVIGATION

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ABSTRACT

This paper presents a novel approach to unmanned aerial vehicle (UAV) control through electrooculography (EOG) based eye movement tracking. The research focuses on developing an interface that translates eye movements into UAV navigation commands, showcasing a unique integration of biometric technology in UAV (i.e., drone) control. To measure horizontal eye movements, we used EOG electrodes positioned near the person's eyes. Using a thresholding algorithm, eye movements are categorized as right, left, or neutral, and then converted into control signals using a finite state machine. The control signals are then sent to the UAV via an internet connection. Our experimental results demonstrate precise and efficient UAV control through EOG-based eye tracking. This approach demonstrates a new direction in human-robot interaction, and it holds potential in assistive technology for individuals with mobility or communication challenges. This study establishes a foundation for future advancements in intuitive and accessible UAV control systems.

Keywords: UAV control, EOG, Eye Movement Tracking

1. INTRODUCTION

Eye-tracking technology has a wide range of applications in areas such as Human-Computer Interaction (HCI) [1], Human-Machine Interface (HMI) [2], assistive driving [3], fatigue monitoring and attention detection [4]. The potential of this technology is especially life-changing for individuals who are severely physically impaired, such as those with Locked-In Syndrome. For these individuals, who can only control their eye movements, this technology provides a way to communicate and interact with the world, despite their challenges in controlling motor functions including verbal and physical movement [5].

In the field of eye movement measurement, four primary techniques have been widely studied: Scleral search coil, Infrared Oculography (IOG), Video Oculography (VOG), and Electrooculography (EOG). Each method presents its own advantages and limitations. Scleral Search Coil [6-7] involves wearing a contact lens embedded with a small coil. When the eye moves within a magnetic field, the coil induces a voltage proportional to the movement. This method is highly accurate and has excellent temporal resolution, making it ideal for precise eye movement studies. Its drawbacks include being invasive (as it requires wearing a contact lens), potential discomfort for the subject, and being less suitable for long-term studies.

IOG [3], uses infrared light to track eye movements. An infrared source illuminates the eye, and a camera or sensor detects the reflection from the cornea and the pupil. This method is non-invasive and offers good accuracy and resolution. However, it can be affected by eyelashes, lenses, and external light sources, and may require calibration for each use.

Similar to IOG, VOG [8], uses video images to track the movement of the eye. Advanced algorithms analyze the video to determine the position of the pupil and the vector of the gaze. VOG is versatile and non-invasive, allowing for natural eye movements without the need for physical contact. The limitations include potential errors in low light conditions and the need for sophisticated image processing algorithms, which can be computationally intensive.

EOG is based on detecting the biopotential that exists between the front and the back of the human eye. When the eyes move, this potential creates a measurable electric field, which EOG captures through electrodes placed around the eyes [9]. The primary advantage of EOG is its simplicity and relatively low cost. Being a biopotential-based method, it remains unaffected by environmental conditions such as lighting. It is effective for anyone who has control over their eyeballs, including individuals who are blind, those with conditions that obscure or alter pupil visibility, or even with closed eyes. However, it is less accurate than other methods, particularly in detailed tracking. For this reason, when precise eye gaze tracking is essential (such as determining the specific location of gaze), methods like VOG and IOG are more suitable. However, for communication purposes where general eye tracking is sufficient, EOG proves to be a better choice. Consequently, this study has opted for the EOG method due to its relevant advantages in our context.

In [10], using EOG, blink actions were detected and were used to control a wheelchair through a Graphic User Interface (GUI). The GUI system featured two speed levels for forward movement, one speed level for backward, eight directions for left and right movements and a stop function. Each of these features flashed and whenever the desired feature flashes, the user blinks to communicate his/her intention. Wheelchair control for Amyotrophic Lateral Sclerosis (ALS) individuals has been done in [2] using eye gaze tracking glasses which are video based. An HCI was designed in [5] that measured eye movements using EOG electrodes to play a game. In [11], using VOG, a GUI has been designed that allowed user to select desired manufacturing tools by blinking. In [4], using EOG, blinks (duration, amplitude, and time intervals between blinks) were mentioned and used to detect fatigue in workplace.

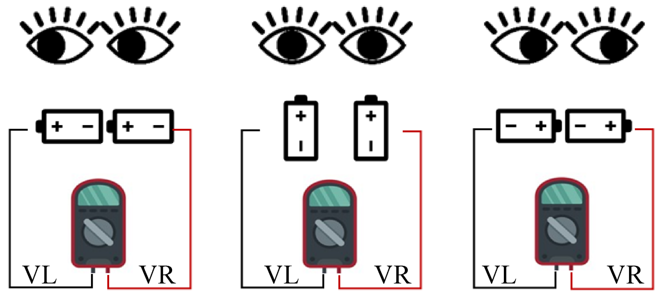
This paper aims to showcase and explore the capabilities of eye-tracking technology by introducing a new approach to robot control. The selection of controlling an Unmanned Aerial Vehicle (UAV), or drone, as a specific application serves as a practical and real manifestation of EOG technology. Nevertheless, the adaptability of this technology extends beyond just controlling UAVs; it can be utilized in various other scenarios. The implementation of the UAV control system in this project demonstrates the latest advancements in eye-tracking technology. Simultaneously, it highlights potential paths for future progress, emphasizing the extensive flexibility and diversity of this technology.

The remainder of this paper is organized as follows. Section 2 explains the method and experimental setup. The results are discussed in Section 3, followed by a conclusion in Section 4.

2. MATERIALS AND METHODS

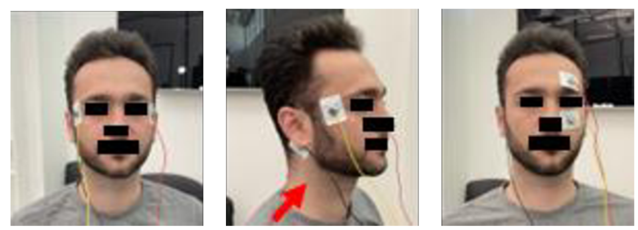
EOG, makes use of the corneoretinal potential, which is the difference in electrical potential that exists between the cornea (positive potential) and the retina (negative potential). Owing to this difference, the eye serves as an electric dipole, the orientation of which varies as the eye moves. Hence, the voltage differential on the skin surface fluctuates slightly based on the position of the eyes and can be quantified by employing electrodes affixed to specific locations on the skin. For instance, as shown in Figure 1, when the eyes move to the left, the potential at the left eye's temporal canthus increases while it decreases at the right eye, leading to a negative potential difference. The opposite occurs when the eyes move to the right. When the eyes are directed straight forward, the electrodes detect an approximate potential of zero.

EOG signals are measured by positioning silver (Ag) electrodes on the outer canthus of each eye for horizontal EOG, and above and below an eye for vertical EOG (Figure 2). The reference electrode is positioned over the mastoid region behind the ear to establish a neutral site for each electrode [12-13]. Due to their small amplitude (50-3500 mV) [14], EOG signals must be amplified before they can be appropriately analyzed.



Left gaze: VR-VL < 0 Front gaze: VR-VL≈ 0 Right gaze: VR-VL > 0

Figure 1: EOG working principle



(a) (b) (c)

Figure 2: Electrode placement for (a) horizontal eye movement measurement, (b) Reference electrode, and (c) vertical eye movement measurements.

Like any other physiological signals, EOG signals are often contaminated with noise and artifacts caused by electrode contact noise, power line interferences, intrinsic electronic device noise, motion artifacts, muscle contractions, etc. [15-16]. Hence, it is crucial to use adequate biopotential data acquisition modules or Analog Front-End (AFE) systems on the hardware side to amplify the EOG signal and minimize such artifacts in order to process the signal and obtaining reliable results. In our work described in this paper, the signals collected from EOG electrodes undergo processing and amplification using a “BioAmp EXG Pill” analog-front-end (AFE) biopotential signal-acquisition board [17].

As can be seen from the schematic of BioAmp EXG Pill board given in Figure 3, a power supply provided the necessary voltage for the TL074H Op-amp and generated a reference voltage of 2.5 V. The Driven Right Leg (DRL) circuit used in the circuit aids in minimizing common-mode noise, which could arise from various sources such as power line interference, electromagnetic radiation, the body's own bioelectric processes or skin-electrode DC offset. In essence, the DRL circuitry operates by measuring the common-mode voltage present on the inputs of the differential amplifier (the EOG signal in this case) and inverting it. This inverted signal is then fed back into the body via the “right leg” electrode. This process effectively reduces the common-mode voltage seen by the amplifier and, consequently, the influence of the common-mode noise on the measured signal. By minimizing the impact of common-mode noise, the technique allows for more precise tracking of eye movements and, in turn, more accurate control of the drone.

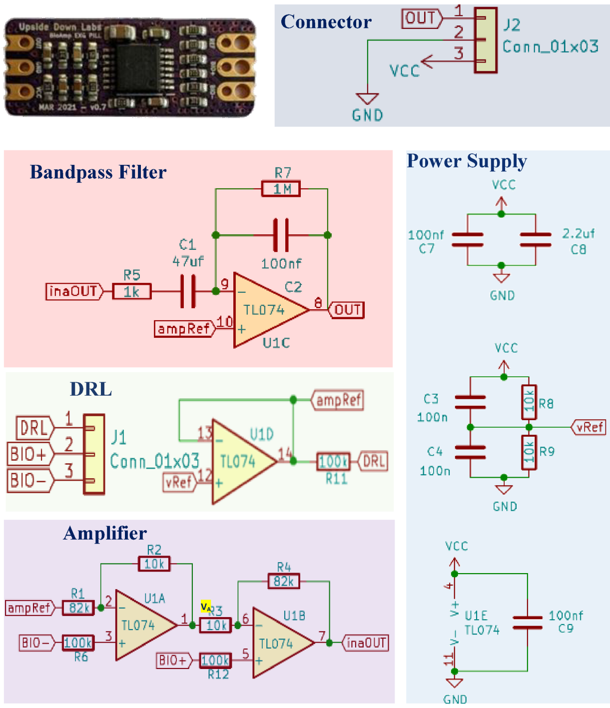


Figure 3: "BioAmp EXG Pill" analog front-end (AFE) biopotential signal-acquisition board

Based on the schematic given in Figure 3, the amplifier gain is calculated as:

$$V_{inaOUT} = 9.2(Bio^{+} - Bio^{-}) + 2.5 \tag{1}$$

Where Bio^{+} and Bio^{-} represent the channels for the positive and negative output voltages of the EOG signal, respectively. The signal-acquisition board also incorporated a bandpass filter with an inherent differentiator. Transfer function of bandpass filter is:

$$-\frac{Z_2}{Z_1} = \frac{R_7 C_1 s}{(1 + R_7 C_2 s)(R_5 C_1 s + 1)} \tag{2}$$

The upper cut-off frequency of the bandpass filter is:

$$f_u = \frac{1}{2\pi R_5 C_1} = \frac{1}{2\pi \times 47 \times 10^{-6} \times 1000} = 3.3864^{Hz} \tag{3}$$

The lower cut-off frequency of the bandpass filter is:

$$f_l = \frac{1}{2\pi R_7 C_2} = \frac{1}{2\pi \times 10^{6} \times 10^{-7}} = 1.5915^{Hz} \tag{4}$$

Bode magnitude diagram of this filter is depicted in Figure 4, illustrating a gain of 50 dB for the frequencies between 1.5915 Hz and 3.3864 Hz.

Given that each degree of horizontal rotation produces a 16mV variation in the electrodes [18], the difference potential of a full right gaze (considered to be 35°, with a neutral straight gaze defined as 0° [1]) could be calculated as:

$$V_{FRG} = Var_v \times A_{FG} \times G_{amp} \times G_{bf} \tag{5}$$

Where V_{FRG} is the difference potential of a full right gaze, Var_v is voltage variation per degree, A_{FG} is full gaze angle, G_{amp} is amplifier gain, and G_{bf} is bandpass filter gain.

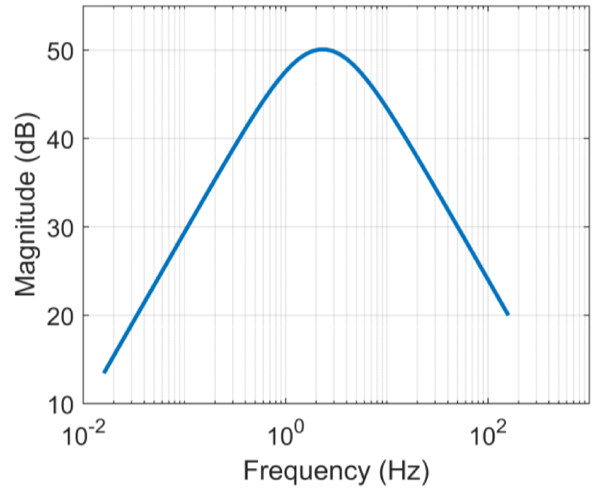


Figure 4: Bode diagram of "BioAmp EXG Pill" board

Substituting the specific design values of BioAmp EXG Pill into (5) yields an output voltage of approximately 1.6292 V using the following calculation:

$$V_{FRG} = 16 \times 10^{-6} \times 35° \times 9.2 \times 316.22 = 1.6292 \tag{6}$$

Since the neutral position of eye is mapped to 2.5 V, according to (6) the full right gaze is expected to have the potential of 4.1292 V. It is important to note that the bandpass filter utilized in this project also functions as an active differentiator [19], resulting in the output signal appearing in the form of spikes.

Following signal amplification and filtering, the analog signal needs to be digitized for processing within the computer. This is achieved by first passing the analog signal to the 10-bit analog-to-digital converter (ADC). Once digitized, the signal is then transmitted to the computer via USB serial communication at 9600 bits/sec. The computer, in turn, reads the digital information from its serial port and discerns left, right, and neutral eye movements using a finite state machine and a thresholding algorithm given in Figure 5 and Algorithm 1, respectively. Relative control commands are then generated and dispatched to the DJI Tello UAV over a Wi-Fi connection, providing control based on the person's eye movements. The hardware configuration of this project is shown in Figure 6.

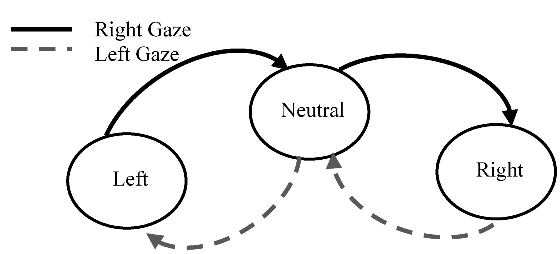


Figure 5: EOG-based UAV control State machine

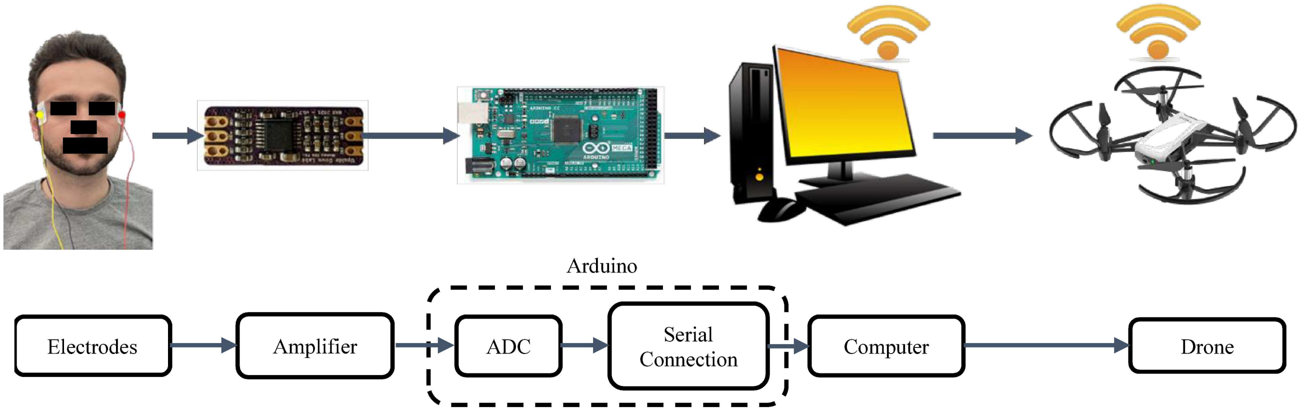


Figure 6: Hardware setup for EOG-based UAV control

3. RESULTS AND DISCUSSION

EOG signals in both horizontal and vertical directions were initially analyzed using an oscilloscope for various eye movement scenarios such as left/right gaze, up/down gaze, and blink. In Figure 7, the effects of horizontal eye movements and natural blinks on the EOG signals recorded by the horizontal electrodes are shown. As anticipated, when the eye is in a neutral position, signifying forward gaze, the readings register at 2.5 V (the reference voltage). In the case of left gaze, a negative spike from the reference voltage is observed, whereas a right eye movement results in a positive spike. The spike amplitude from the reference is approximately 1.5 V, which aligns with the value provided in (6) considering individual variations and non-ideal equipment conditions. As previously noted, the circuit's use of a differentiator renders the signals in the form of spikes instead of pulses. This means that when the eye is stationary, the reading

Algorithm 1 EOG-based Tello Drone Control

```
Connect to the drone
Initialize Right_flag, Left_flag, Trip_counter
Take off the drone
while True do
    if (data in serial buffer) then
        H_val, V_val = Serial_Read()
        if (H_val != None) then
            if (Trip_counter is even) then
                Reset Right_flag, Left_flag
                State = Neutral
            end if
            if (H_val ≥ Upper_threshold) & (Right_flag = 0) then
                Right_flag ← 1
                Reset Left_flag
                Trip_counter ← Trip_counter + 1
                State = Right
                Move the drone 50^cm to the right
            end if
            if (H_val ≤ Lower_threshold) & (Left_flag = 0) then
                Left_flag ← 1
                Reset Right_flag
                Trip_counter ← Trip_counter + 1
                State = Left
                Move the drone 50^cm to the left
            end if
        end if
    end if
end while
```

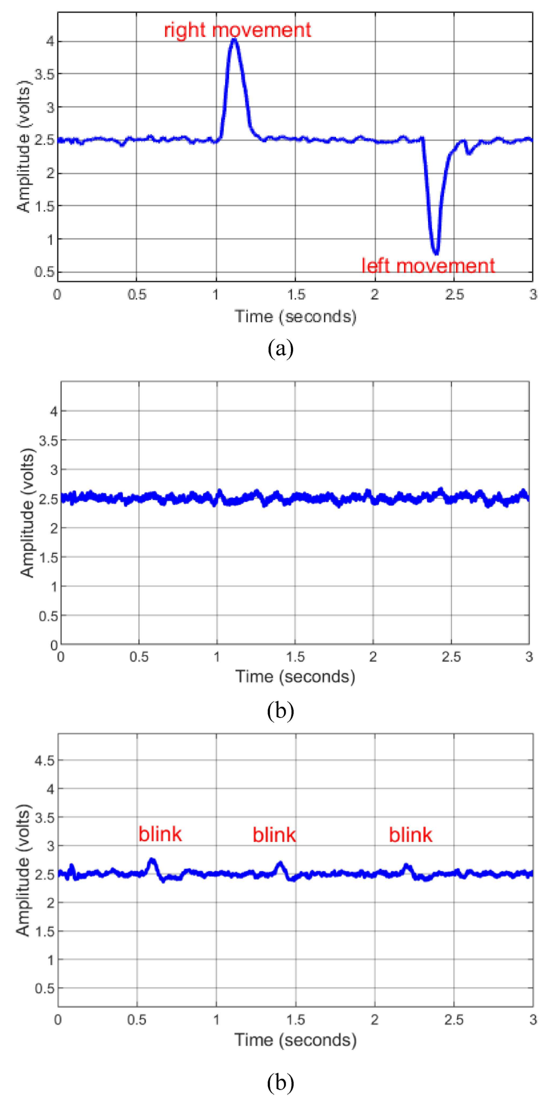
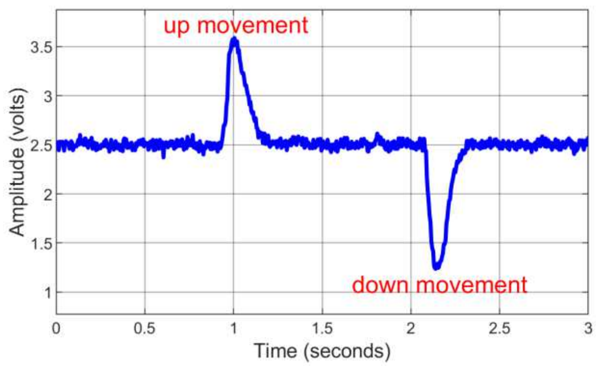


Figure 7: Horizontal EOG signal response to: (a) right and left eye movements, (b) up and down eye movements, and (c) natural blink

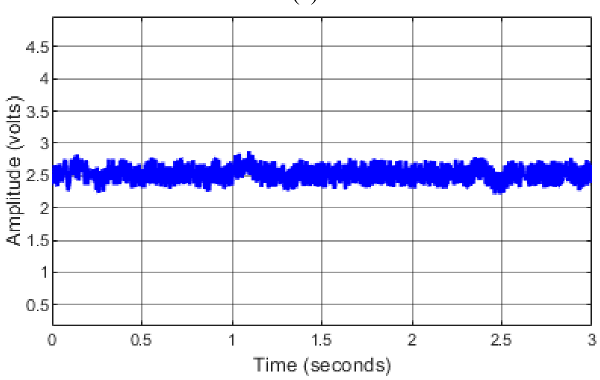
remains at the reference voltage of 2.5 V, which is identical to the neutral position. Hence the current system can effectively detect eye movement, although not eye position.

Upward and downward movements of the eyes yield no impact on readings from the horizontal electrodes. Natural blinks are manifested as a pair of positive and negative spikes, with an amplitude of approximately 0.3 V away from the reference voltage, thereby demonstrating that blinks constitute artifacts in the horizontal EOG readings. The result of vertical eye movements and blinks on the readings from the vertical electrodes is illustrated in Figure 8.

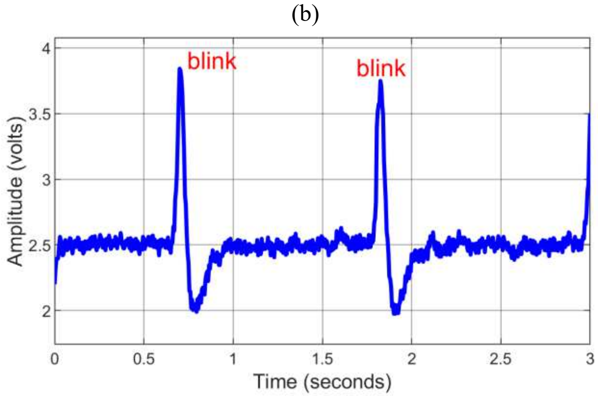
Analogous to the horizontal electrode setup, the neutral eye position, and the periods when the eye remains stationary, display a voltage of 2.5 V in the electrode readings. When the gaze ascends, a positive spike is observed with an amplitude approximately 1.1 V above the reference voltage.



(a)



(b)



(c)

Figure 8: Vertical EOG signal response to: (a) up and down eye movements, (b) right and left eye movement, and (c) natural blink

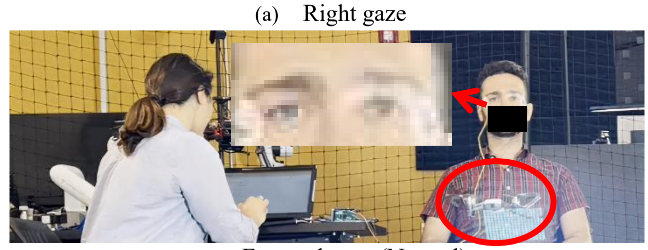
Conversely, a downward gaze generates a negative spike. It becomes evident that left and right gazes exert a negligible impact on readings from vertical electrodes. A natural blink, however, significantly affects the vertical electrodes, with the amplitude of the EOG signal surpassing that observed using the horizontal electrodes. This observation is congruent with expectations, given that blinking constitutes a vertical movement. In a similar vein, a forceful blink generates an EOG signal with an amplitude larger than that of a natural blink.

Figure 9 illustrates the system's performance, indicating that when the human subject shifts his gaze to the left, the drone correspondingly flies in the same direction. When the subject returns his eyes to a neutral position, the drone also reverts to its neutral state, and a similar pattern is observed for rightward eye movements.

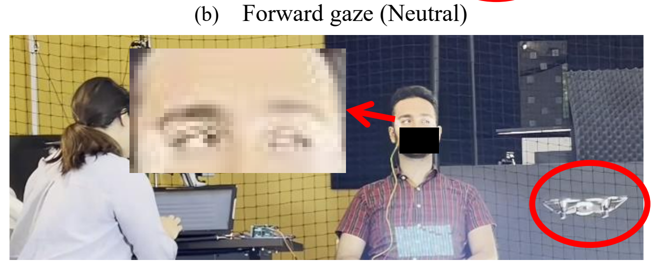
The performance of our EOG-based system suggests that it remains functional within the typical range of indoor environmental conditions. However, intense lighting that induces involuntary eye movements can impact its accuracy. The system operates effectively with individuals who have typical eye movement patterns and no ocular disorders.

Involuntary facial muscle movements may influence the accuracy of readings. External noise including electrode contact noise and power line interference affects the system but can be mitigated through signal filtering.

(a) Right gaze



(b) Forward gaze (Neutral)



(c) Left gaze

Figure 9: Correlation Between Gaze Direction and UAV Movement

4. CONCLUSION

In conclusion, this paper has presented an approach towards an intuitive human-UAV interaction paradigm, utilizing electrooculography (EOG) signals to control the movements of an UAV. The integration of dedicated hardware and software, involving a BioAmp EXG Pill module for EOG signal acquisition, a threshold algorithm and state machine for signal interpretation and UAV control, was a key aspect of this study. The performance of the system as demonstrated was found promising. The results indicated a consistent correlation between the human subject's eye movements and the corresponding UAV movements. Future research could delve into refining the processing of EOG signals with a specific focus on blink artifacts. Given the inherent complexity and variability of eye movement patterns, the application of machine learning algorithms could offer significant benefits. These algorithms could be leveraged to effectively recognize patterns of eye movements and eliminate blink artifacts from electrode readings, leading to more accurate and reliable detection of eye movements.

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