Quaternion-Based Remote Photoplethysmography for Continuous Heart Rate Monitoring

By Nicholas Basile and Maxim Kleyer

Project Advisor: Dr. Sos Agaian

Abstract

Heart rate (HR) monitoring is essential for evaluating physiological health and identifying cardiovascular problems early. Most HR monitors need skin contact, but remote photoplethysmography (rPPG) provides a non-invasive option by analyzing subtle skin color changes through video. This method, also called video plethysmography (VPG), is beneficial for people who cannot use contact-based monitors, such as those with sensitive skin or in remote monitoring situations. VPG uses consumer-grade cameras to measure heart and breathing rates without wearable devices. This enables its use in various domains, such as sports optimization, emotional communication in human-machine interaction, and driver monitoring. However, estimating HR from video accurately is challenging due to subject movement and lighting variations. This study presents a novel approach to HR measurement using quaternion algebra, an improvement over complex numbers, to exploit the relationship between RGB camera color components effectively. Our framework aims to offer continuous HR monitoring in diverse settings, such as telemedicine, fitness, and psychological assessments.

Introduction

Why Monitoring Heart Rate is Critical

According to data from the Centers for Disease Control and Prevention (CDC), heart disease is the leading cause of death for men, women, and people of most racial and ethnic groups in the United States: “one person dies every 33 seconds in the United States from cardiovascular disease” or 1 in every 5 total deaths in 2021 (“Heart Disease Facts” 1). Heart disease also costs the United States about $239.9 billion each year from 2018 to 2019, including the cost of healthcare services, medicines, and lost productivity due to death ("Heart Disease Facts" 1). There are many risk factors for heart disease, including, but not limited to, high blood pressure, high blood cholesterol, smoking, diabetes, obesity, unhealthy diet, physical inactivity, and excessive alcohol use ("Heart Disease Facts" 3). Regular heart rate (HR) monitoring can help detect cardiovascular issues at an early stage, which is crucial for timely intervention and treatment.

How to Measure Heart Rate

An individual can measure their own HR by placing the pads of the index and middle fingers on a pulse site on the body, most often the area on the neck beneath the ears. The individual counts the number of pulses felt over a minute (or felt over 30 seconds multiplied by two) ("What is Heart Rate?" 2). The best pulse sites for examination include the temporal artery (sides of forehead), facial artery (the angles of the jaws), and carotid artery (in the neck), as well as others displayed by Figure 1 ("What is Heart Rate?" 3).

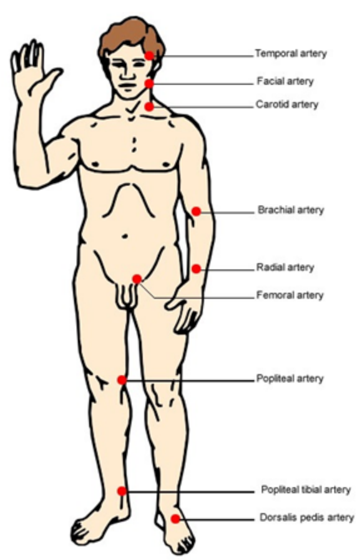


Figure 1. Mandal, A. *What is Heart Rate?* (2023)

Standard Methods of Measuring Heart Rate

In hospitals and doctors' offices, standard methods of measuring HR include the use of an electrocardiogram (ECG) or a pulse oximetry (PO) sensor, but these techniques have downsides for long term monitoring of HR. ECGs are the most accurate method of measuring HR and work by utilizing electrodes placed on the body that sense electrical activity from the heart; however, ECGs "require patients to wear adhesive gel patches or chest straps that can cause skin irritation and discomfort" (McDuff 3). The use of adhesive and wires presents great risk for babies in neonatal intensive care units (NICU) (Figure 2): wires can become tangled and cut off circulation or damage newborn skin and leave scars (Sweely 1). Like ECGs, PO sensors that attach to the fingertips or earlobes are also not ideal for long-term monitoring because they may cause pain if worn for too long (McDuff 3).

Figure 2. Sweely, B., *Camera-Based Remote Photoplethysmography for Estimation of Heart Rate using Single Board Computers* (2020)

Goal and Main Contributions

Our objective is to develop a low-cost, non-contact monitoring system utilizing quaternion-based remote photoplethysmography for continuous HR monitoring in diverse settings, such as telemedicine, fitness, and physiological assessments. Our research distinguishes itself from others by being the first of its kind to exploit the underlying relationship between red, green, and blue (RGB) color channels and the vector components—*i*, *j*, and *k*—of quaternion-algebra. The RGB color video is captured using low-cost cameras like webcams. Our system accurately measures health data from key facial areas by employing quaternion algebra, as well as other signal processing techniques, including the Fast Fourier Transform (FFT) signal enhancement method. Our novel HR monitoring system provides computer simulation results that outperform that of prior research, establishing a new benchmark in the field.

Benefits of Measuring Heart Rate with Remote Photoplethysmography

Remote photoplethysmography (rPPG), also referred to as video plethysmography (VPG), offers a simple, low-cost technique to monitor HR. VPG works by analyzing subtle skin color changes in video footage; for every heartbeat, blood circulation creates color variations in the individual's facial skin (Rahman 1). These color variations, invisible to the human eye, can be recorded through digital cameras to extract vital signs, such as HR (Sweely 5). A reliable framework that integrates VPG technology would yield many benefits. HR is not the only vital sign that VPG technology can extract, meaning that such a framework could lead to improved accuracy in monitoring other vitals, including anxiety, sleep patterns, cognitive stress (Kellman 2), blood pressure, and heart rate variability (Sweely 5). Because the system is non-contact and relies on cameras, the cost of electrodes and the restriction on motion that ECGs impose are eliminated (Kellman 2). This non-invasive method is highly beneficial for sensitive populations, such as individuals with long-term epilepsy, burn or trauma patients, sleep studies, or babies in NICUs (McDuff 3). This technology also enables long distance HR monitoring that is useful for assisting patients in remote locations where no in-person doctor is present. In scenarios where an in-person doctor visit may pose a risk, especially during flu season or the COVID-19 pandemic, telehealth visits–telecommunications technologies supporting the delivery of all kinds of medical, diagnostic and treatment-related services usually offered by doctors (Federal Communications Commission 1)–help assist patients while minimizing exposure risk to severe illness. This is significant because it helps keep vulnerable populations safe, such as the elderly or those who are immunocompromised.

Methods

Developing a New Approach to rPPG/VPG

There are various methods used by existing research that our system aims to improve upon. Existing research begins the HR monitoring process by placing a region of interest (ROI) on the individual's face using face tracking technology (Figure 3). The color channels are analyzed and averaged together to compute the HR. In our research, we place three ROIs on the subject's face during monitoring for improved accuracy (Figure 4).

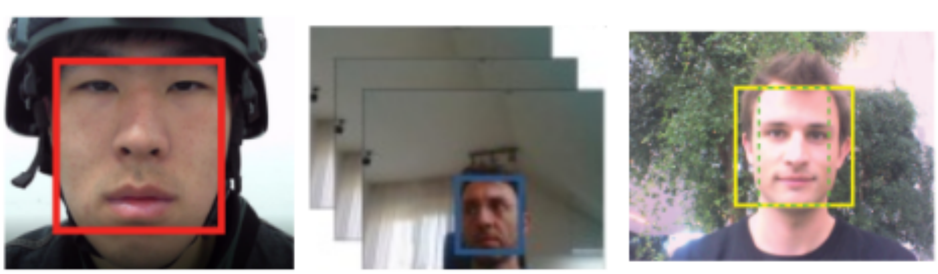


Figure 3. Singular ROI on subjects from existing research (Gao, H.) (Przybyło, J.) (Jensen, J.)

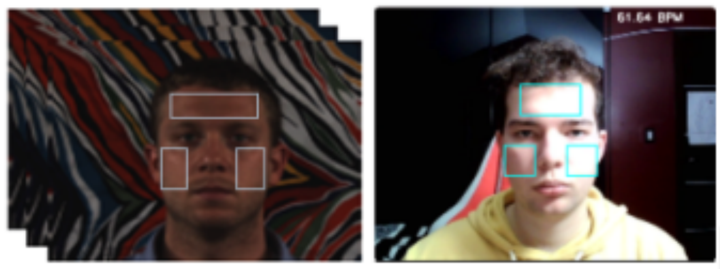


Figure 4. Three ROIs placed on subjects' faces

Similar HR monitoring research utilizes programming languages such as Java, C++, and MATLAB on Android, MacBook, and HP devices. Our system is written in Python code and only requires a laptop webcam. Our HR monitoring system is the first of its kind to utilize quaternion-based VPG.

Quaternion Number System

The quaternion number system–invented by Irish mathematician Sir William Rowan Hamilton in 1843–is an extension of complex numbers. Hamilton discovered quaternions while trying to generalize complex numbers to higher dimensions. The breakthrough came during a walk with his wife, when he suddenly realized the correct formula and famously carved it into the stone of Brougham Bridge in Dublin: $i^2 = j^2 = k^2 = -1$. This formula established the fundamental rules of quaternion algebra (Arnold et al. 1). Quaternions are composed of one real part and three imaginary parts, typically written as $q = a + bi + cj + dk$, where a, b, c, and d are real numbers, and i, j, and k are the fundamental quaternion units (Arnold et al. 35). Unlike real and complex numbers, quaternion multiplication is non-commutative, meaning that the order in which you multiply two quaternions matters (Arnold et al. 35). This property, along with their four-dimensional nature, makes quaternions particularly well-suited for applications involving rotations and three-dimensional space (Arnold et al. 1).

x	1	i	j	k
1	1	i	j	k
i	i	−1	k	−j
j	j	−k	−1	i
k	k	j	−i	−1

Color shows non-commutativity

Figure 5. Quaternion multiplication table

Sir William Rowan Hamilton

Sir William Rowan Hamilton was a prominent 19th-century mathematician and physicist who made significant contributions to algebra, optics, and classical mechanics. Born in Dublin, Ireland, at midnight between August 3 and 4, 1805, Hamilton showed prodigious talent in languages and mathematics from an early age. By the age of five, he was already proficient in Latin, Greek, and Hebrew, and before he turned twelve, he had expanded his studies to include French, Italian, Arabic, Syriac, Persian, and Sanskrit. His early education was overseen by his uncle, James Hamilton, a clergyman and educator, who recognized and nurtured William's exceptional abilities (Wilkins 2).

Hamilton entered Trinity College Dublin at the age of 18, where he quickly distinguished himself in both classical studies and mathematics. His interest in extending complex numbers to higher dimensions led to his discovery of quaternions. This work was groundbreaking because it provided a new way to describe rotations in three-dimensional space, something that had been a challenging problem for mathematicians and physicists (Wilkins 2). Hamilton's invention of quaternions was not immediately appreciated by his contemporaries, but it eventually gained recognition for its profound implications in both mathematics and physics. Today, quaternions are widely used in computer graphics, robotics, and aerospace engineering for their ability to efficiently handle three-dimensional rotations (Wilkins 4).

In many applications, particularly those involving rotations and orientations, quaternions offer significant advantages over traditional averaging methods (Wilkins 4). One major advantage is that quaternions avoid the problem of gimbal lock, a situation in which the loss of one degree of freedom occurs, typically encountered with Euler angles. Quaternions represent rotations in a way that is free from singularities, providing a smooth and continuous representation of orientation (Arnold et al. 1). Averaging rotations using Euler angles or rotation matrices can be problematic because these methods do not handle the complexities of three-dimensional rotations effectively (Arnold et al. 1). When averaging angles, there is a risk of interpolation errors and discontinuities. Quaternions, however, provide a more robust framework for interpolation, known as spherical linear interpolation (slerp). This method ensures that the interpolated rotations follow the shortest path on the four-dimensional unit sphere, resulting in smooth and accurate transitions (Arnold et al. 1) (Wilkins 4).

Furthermore, quaternions require less computational power than rotation matrices. While a rotation matrix needs nine parameters to describe a rotation, a quaternion only needs four, reducing the computational load. This efficiency makes quaternions especially useful in real-time applications such as video game development, virtual reality, and robotics, where quick and accurate calculations of rotations are crucial (Arnold et al. 1) (Wilkins 4).

New Approach: Quaternion-Based rPPG

Face Tracking & ROI's

Our quaternion-based remote photoplethysmography (rPPG) system begins with advanced face tracking using a standard webcam. This enables users to monitor their heart rate conveniently at home, without needing to visit a medical facility. The webcam captures real-time video, and face tracking algorithms identify and lock onto key facial features, ensuring consistent and accurate monitoring. This face tracking ensures the system can continuously analyze the user's face, accommodating small movements and maintaining focus on predefined regions of interest (ROIs). The system designates three specific regions of interest (ROIs) on the face: the forehead, right cheek, and left cheek. These areas are chosen because they are relatively stable and less affected by facial expressions, providing reliable data points for heart rate monitoring. By focusing on these regions, the system can extract more consistent color data, which is crucial for accurate heart rate detection. The choice of these ROIs maximizes the signal quality by minimizing noise and variations caused by facial movements.

Quaternion Usage

A unique aspect of our system is the utilization of quaternions to enhance the accuracy of color comparisons. Quaternions allow us to capture more intricate relationships between the red, green, and blue (RGB) color channels. By using quaternion mathematics, we can model the color variations in the skin more precisely, leading to improved detection of subtle changes related to blood flow and heart rate. This advanced mathematical approach provides a more robust framework for analyzing the color data from the facial ROIs. In our system, the RGB color channels are used in tandem with the i,j,k components of quaternions, enabling a comprehensive representation of color interactions. To translate the quaternion color comparisons into usable data, we calculate the quaternion modulus for each RGB channel. This process involves determining the intensity of each color channel by leveraging the quaternion representations, which encapsulate the interactions and differences between the colors. The result is a more accurate measurement of the color intensities, reflecting the subtle changes in skin color due to blood flow. This accuracy is crucial for reliable heart rate monitoring, as it ensures that the detected signals are true representations of the physiological changes.

Fast Fourier Transform

For real-time analysis of heart rate peaks, our system employs the Fast Fourier Transform (FFT), a cornerstone in signal processing. The FFT converts time-domain signals, which are the raw intensity data from the RGB channels, into frequency-domain representations. This transformation allows us to identify the dominant frequencies that correspond to the heart rate. In practice, the intensity variations captured by the webcam, which reflect blood flow changes, are subtle and mixed with noise. By applying the FFT, we can decompose these complex signals into their constituent frequencies, making it easier to detect the heart rate peaks. The FFT process involves sampling the intensity data at a fixed rate and then applying a mathematical algorithm to transform these samples into a spectrum of frequencies. Each peak in this frequency spectrum corresponds to a periodic component in the original signal, with the most significant peak typically representing the heart rate. This method is particularly effective because it isolates the periodic fluctuations caused by blood flow from other non-periodic noise, enabling precise heart rate detection even in a home environment with potential movement and lighting variations.

Alpha Values for Enhanced Accuracy

To further refine the accuracy of our system, we incorporate alpha values into the signal processing workflow. Alpha values are essentially weighting factors applied to the intensity data before and after the FFT. By adjusting these weights, we can enhance the influence of more reliable data points while minimizing the impact of noise and less relevant fluctuations. This selective weighting process ensures that the FFT results are more accurate and representative of the true physiological signals. The use of alpha values helps to smooth out the intensity variations and highlight the genuine heart rate signals. For instance, during periods of significant movement or sudden lighting changes, certain intensity readings might be disproportionately affected. By assigning lower weights (alpha values) to these outlier readings and higher weights to more consistent data points, the system can maintain a stable and accurate heart rate calculation. This step is crucial for producing reliable real-time results, as it mitigates the effects of transient noise and enhances the clarity of the heart rate peaks identified by the FFT.

Combined Heart Rate Calculation

The final step in our system involves integrating the FFT results from each individual color channel (red, green, and blue) into a single heart rate value. Each color channel provides a different perspective on the blood flow variations, with green typically offering the strongest signal due to its higher sensitivity to hemoglobin absorption. However, relying on a single channel can introduce bias or errors if that channel is affected by specific noise or lighting conditions. To create a comprehensive heart rate measurement, we combine the FFT outputs from all three channels. This multi-channel approach leverages the strengths of each color channel while compensating for their individual weaknesses. By averaging or otherwise fusing the frequency peaks detected in each channel, we obtain a more robust and reliable heart rate estimate. This combined result is less susceptible to errors and provides a more consistent measurement. The final heart rate value is then presented to the user, offering a real-time, accurate indication of their physiological state. This holistic approach ensures that the heart rate monitoring system is both precise and user-friendly, making it a valuable tool for personal health tracking without the need for specialized medical equipment.

The diagram below shows the process of our new approach incorporating Quaternion, ICA and Signal processing, as well as Fast Fourier Transform to give us the peak frequency, ultimately being the heart rate.

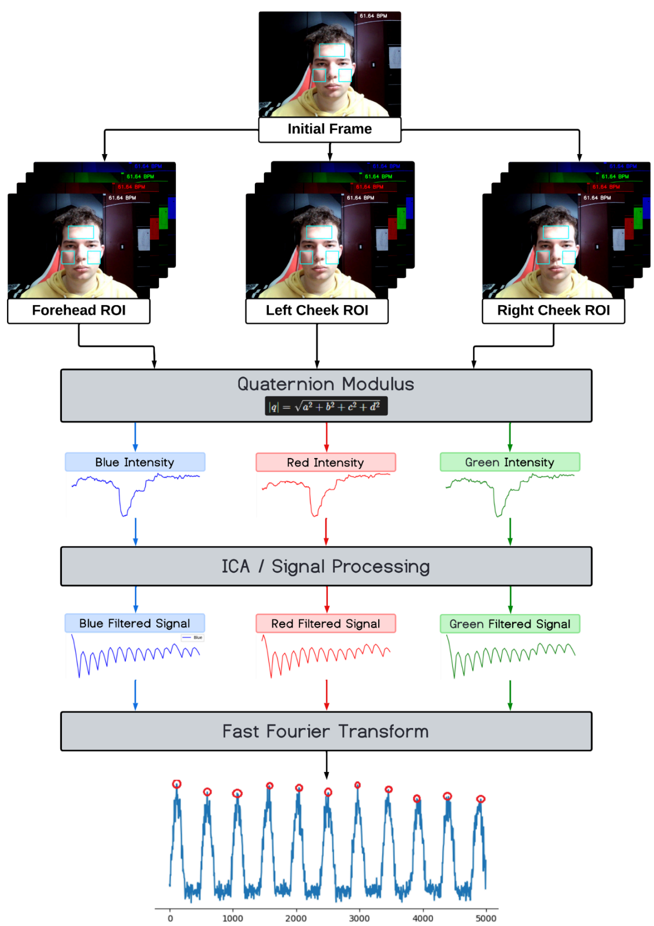


Figure 6. Diagram of the algorithm our system uses to compute HR.

Results

Results Using Varying Alpha

Experimenting with a range of alpha values, we found that α = 0.86 yielded results closest to the true heart rate (HR) values (Table 1). This optimal alpha value was determined through extensive testing and calibration. The accuracy of these results was further validated by comparing our computer simulation outcomes with the measurements obtained from a standard blood pressure machine and the traditional method of manually measuring HR by holding two fingers to the neck and counting the pulse. The comparison with these established methods underscored the reliability of the chosen alpha value, as the results were consistently within a narrow margin of error. This alignment with traditional measurement techniques confirms that the system is capable of providing accurate and dependable HR readings.

Table 1: Comparing Results from Standard Methods of Measuring HR with Computer Simulations

			α = 0.86		α = 0.80		α = 0.90		α = 1	
	BP Machine	Finger to Neck	Avg	Quan	Avg	Quan	Avg	Quan	Avg	Quan
Relaxing	58	61	60	59	38	39	80	79	102	97
Coffee	77	76	67	78	45	47	82	90	114	110
Weight Lifting	72	73	66	72	44	46	81	88	110	108

Results Measured at Varying Lengths from Subject

When measuring results at varying lengths from the subject, the quaternion model demonstrated more robust and stable outcomes compared to the simple averaging method (Table 2) (Table 3). This superior performance can be attributed to the quaternion model's ability to effectively handle the complexities and variations inherent in three-dimensional spatial data. Unlike simple averaging, which can be overly sensitive to outliers and variations in distance, the quaternion model provides a more holistic representation of the subject's orientation and movement, leading to consistent and reliable measurements across different distances. The stability of the quaternion model is particularly advantageous in scenarios where the distance between the measurement device and the subject cannot be perfectly controlled or remains variable. By leveraging the mathematical properties of quaternions, the model can maintain accuracy and coherence in its results, even when the subject moves closer or further away.

Table 2 & 3: Experimenting with Varying Lengths from Subject

3 Feet			α = 0.86		α = 0.80		α = 0.90		α = 1	
	BP Machine	Finger to Neck	Avg	Quan	Avg	Quan	Avg	Quan	Avg	Quan
Relaxing	58	61	61	62	42	47	86	85	115	112
Coffee	77	76	81	80	55	50	86	91	135	128
Weight Lifting	72	73	80	77	53	49	85	92	130	129

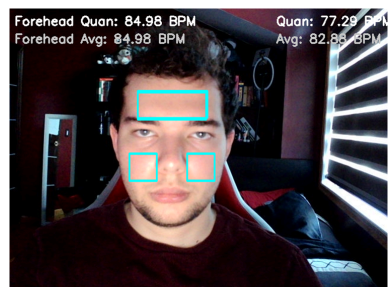
5 Feet			α = 0.86		α = 0.80		α = 0.90		α = 1	
	BP Machine	Finger to Neck	Avg	Quan	Avg	Quan	Avg	Quan	Avg	Quan
Relaxing	58	61	62	62	44	48	90	84	108	110
Coffee	77	76	82	82	55	53	88	92	140	132
Weight Lifting	72	73	83	77	53	52	90	93	132	131

Results Using One vs. Three ROIs

Utilizing three regions of interest (ROIs) significantly increased accuracy compared to standard single-ROI methods. The inclusion of multiple ROIs allows for a more comprehensive analysis of the subject, capturing a wider array of data points that contribute to a more detailed and precise measurement (Table 4). This multi-faceted approach mitigates the impact of any inconsistencies that might arise from focusing on a single area, thereby enhancing the overall robustness and reliability of the results. The use of three ROIs also plays a crucial role in reducing the influence of localized noise or artifacts present in the camera stream. In a single-ROI setup, any noise or distortion within the selected region can disproportionately affect the measurement's accuracy. However, by spreading the focus across three separate ROIs, the system can average out these anomalies, ensuring that the final results are less likely to be skewed by isolated irregularities.

Table 4: Increased Accuracy with Multiple ROIs

			α = 0.86			
	BP Machine	Finger to Neck	Avg	Quan	Avg	Quan
Relaxing	58	61	60	59	67	66
Coffee	77	76	67	78	85	85
Weight Lifting	72	73	66	72	80	77
			3 ROI		**1 ROI**	



Discussion

Measuring is considered complete after the user experiences 25 seconds of uninterrupted focus on the region of interest (ROI) outlines. This uninterrupted period ensures that the user's attention remains fixed, allowing for accurate and reliable data collection. Any distractions or disruptions during this period could compromise the validity of the measurements, necessitating a reset and the commencement of a new 25-second interval. The rationale behind this duration is to establish a consistent and stable environment for measurement, mitigating the influence of external variables that could skew the results. The selection of 25 seconds is based on preliminary observations suggesting this duration is sufficient for users to maintain focus without experiencing significant fatigue or distraction. However, this timing might require adjustment based on further studies involving a larger and more diverse participant pool. Ensuring the user remains undistracted and the ROI outlines are consistently clear is crucial for the accuracy and reliability of the measurements. This approach underscores the importance of a controlled environment in obtaining precise data.

The current results are derived from testing on a single individual, which poses significant limitations in terms of generalizability and robustness of the findings. For more rigorous testing and tuning of the system, it is imperative to involve a larger and more diverse group of participants. The inclusion of various individuals would help identify and account for individual differences in attention span, visual acuity, and response to the measurement environment. Such diversity is essential to ensure that the system performs reliably across a broad spectrum of users, providing a comprehensive understanding of its efficacy and potential areas for improvement. Furthermore, expanding the participant pool can help uncover any systematic biases or limitations inherent in the system. For instance, variations in user demographics such as age, gender, and cognitive abilities could impact the system's performance. By addressing these variables through extensive testing, the system can be fine-tuned to enhance its accuracy, reliability, and overall usability. This approach not only improves the system's robustness but also contributes to the development of a more inclusive and equitable technology.

The system has not yet been tested on individuals with darker skin tones, highlighting a critical gap in its development and evaluation process. This lack of testing is particularly concerning given that skin tone can significantly impact the performance of visual and optical systems. Different alpha values, which affect the transparency and blending of ROI outlines, might be required to ensure accurate measurements for users with darker skin tones. This adjustment is necessary to account for the varying levels of contrast and visibility that different skin tones present. To address this limitation, comprehensive testing involving individuals with a wide range of skin tones is essential. This would involve calibrating the system to optimize the alpha values and other relevant parameters, ensuring that the ROI outlines are consistently visible and effective for all users. Such testing would not only enhance the system's accuracy but also promote inclusivity by ensuring that the technology is equally effective across diverse populations. By prioritizing these adjustments, the development process can move towards creating a universally reliable and equitable measurement system.

Conclusion & Further Plans

We have developed a novel method for real-time, non-contact HR extraction using quaternion algebra applied to facial color video captured by a low-cost webcam. Our computer simulations indicate that this method outperforms most existing techniques in this domain. We plan to extend our research to explore other important physiological parameters such as respiratory rate (RR), heart rate variability (HRV), arterial blood oxygen saturation, and driver monitoring using the proposed system. The quaternion-based approach provides a significant advancement in the field of remote photoplethysmography (rPPG), allowing for more precise modeling of color variations in the skin. This precision is crucial for accurate detection of subtle changes related to blood flow and heart rate, ensuring that the system delivers reliable physiological data. By leveraging the mathematical properties of quaternions, we can capture more intricate relationships between the RGB color channels, enhancing the robustness of our measurements. In addition to heart rate monitoring, our system's potential applications in telemedicine, fitness, and psychological assessments highlight its versatility. The non-contact nature of the system makes it particularly valuable for populations that may be sensitive to traditional contact-based monitors, such as individuals with sensitive skin or those in remote monitoring situations. The ability to accurately monitor heart rate and other vital signs from a distance can transform healthcare delivery, making it more accessible and convenient for patients.

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