Real-Time ECG-monitoring in Virtual Reality

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ABSTRACT

Virtual reality (VR) enables new perspectives and approaches for interaction with a computer-generated environment, thus enhancing data science and a variety of applications. An electrocardiogram (ECG) records the heart's electrical activity, allowing insights into its behavior and identifying potential problems. Novel textile shirts with integrated ECG sensors offer convenient and continuous ECG recording. We investigate the feasibility of using such a shirt with textile sensors for real-time monitoring of an ECG signal in VR. We developed an application that wirelessly records and analyzes the ECG from a subject in real-time, visualizing both the ECG itself and the heartbeat in VR. The heartbeat is visualized on an animated, three-dimensional heart model, while the ECG signal is displayed as a time series graph. For analysis, we employ a real-time heartbeat detection algorithm. The recorded signal can be monitored live in the VR environment with a delay of less than 10 ms. Thus, the combination of smart wearables and VR demonstrates how immersive analytics facilitates real-time heart monitoring. Eventually, similar approaches can open new possibilities for training medical personnel as well as educating a broader interested audience.

Keywords: Virtual Reality, Electrocardiogram, Heart, Real-time Monitoring, Smart wearables, QRS-Detection

1. INTRODUCTION

Virtual reality (VR) enables users to interact with computer-simulated environments in an immersive manner. Apart from entertainment, it holds significant potential in various medical fields, including pre-planning neurosurgery, neurosurgical education, litigation prevention, pain management, and rehabilitation.[1]

Smart wearables, incorporating increasing technology and sensors, collect real-time data and offer beneficial functions for users. These applications provide accurate snapshots of a patient's condition, including the ability to inconspicuously record electrocardiograms (ECGs) regardless of location or activity, facilitating heart activity monitoring during daily routines.

We explore the feasibility of utilizing commercially available ECG shirts with textile sensors to visualize heart activity in real-time within VR environments. Heart activity is portrayed through a model accompanied by animation, while the ECG is depicted graphically. Users can freely navigate the virtual space, observing heart activity from multiple perspectives. ECG shirts facilitate normal activities, being cable-free and comfortable to wear, rendering them ideal for capturing realistic ECG signals during everyday tasks. Integrated with VR technology, ECG shirts enable real-time monitoring of daily activities within virtual environments.

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Medical Imaging 2024: Imaging Informatics for Healthcare, Research, and Applications,
edited by Hiroyuki Yoshida, Shandong Wu, Proc. of SPIE Vol. 12931, 1293113

2. STATE OF THE ART

In recent years, significant advancements have arisen from the progress of technologies in three-dimensional (3D) representation, including computer simulation and virtual reality (VR). In medicine, this technology proves highly valuable, enabling efficient professional training. 3D simulations of the heart have emerged as a notable topic in the medical field. Coelho et al. (2018) developed software facilitating the simulation of a 3D heart on mobile devices, allowing users to emulate ECG data and observe changes in a 3D environment. Such concepts support mobile learning, significantly impacting the scalability of education.[2] Further endeavors focus on the 3D simulation of the heart's electrical activity, as demonstrated by Sovilj et al. (2013), who implemented a 3D bidomain model of the heart using a 12-channel ECG.[3] Additionally, other studies concentrate on specific simulations for particular heart malfunctions, such as arrhythmias, as exemplified by Quester et al. (2021).[4]

These studies utilize recorded ECGs, some of which were previously analyzed. However, they lack real-time analysis, which may not be crucial for training but plays a vital role in diagnostics. The study by Llanas et al. (2018) addressed this gap by analyzing the ECG signal in real-time using a wired ECG recorder and presenting it with their interactive cardiac model activated by the R-Wave (CAVE) system. The CAVE system generates a 3D model of the heart from MRI and uses independent projections from different angles to display the 3D heart on the walls of a small simulation room.[5] Although these concepts generate a 3D simulation, partially in real-time, they lack the transition towards VR using a VR headset to immerse users in a virtual environment. Moreover, the connection with smart shirts allows for wireless recording, ensuring that patient activities are not disrupted or influenced.

An other essential component of this work is the QRS detection algorithm. It is a signal processing algorithm used to identify and locate QRS complexes in an ECG signal. The QRS complex represents the depolarization of the heart's ventricles and is the most prominent part of a heartbeat in the ECG. Various approaches for QRS detection exist, including threshold-based methods[6,7] or employing machine learning techniques.[8,9] Each algorithm has its strengths and limitations, prompting researchers to explore and develop new techniques to improve QRS detection accuracy and robustness in different scenarios. For example, Elgendi et al. 2010 introduced an algorithm that utilizes the specific morphology and frequency band of the QRS complex for detection.[10] Smigiel and Marchiniak 2017 proposed an approach using matched filters and a known template to detect the presence of QRS complexes.[11] However, a real-time analysis detection algorithm is sought. For instance, Chen et al. (2020) proposed a controlled threshold strategy using the exponential transform and proportional derivative (PD).[12] Nevertheless, the Pan-Tompkins algorithm was used in this study, which is one of the most well-known and widely used algorithms for QRS detection.[13] Originating from 1985, the Pan-Tompkins algorithm employs a threshold-based method.[14] In this study, the Pan-Tompkins algorithm was selected for QRS detection due to its suitability for real-time processing, ease of implementation, and availability of existing implementations in comparable studies.

3. MATERIAL & METHODS

We have developed a VR application consisting of multiple modules. This innovative software records ECG signals, utilizes a proven algorithm to detect heartbeats, and presents heart activity through a 3D, animated heart model and an ECG graph. Our evaluation involved examining the quality of the ECG signal and the effectiveness of the detection algorithm. Additionally, we carefully analyzed the processing time of the entire workflow, from recording to visualization, as our goal was to achieve real-time monitoring capabilities.

The following section introduces and explains the individual hardware and software components.

3.1 ECG shirt

We employ the smart shirt (Pro-Kit Hexoskin, Quebec, Canada) in our setup. This shirt consists of a vest and a module capable of real-time signal recording, which can be transmitted to an application via Bluetooth Low Energy (BLE) or stored locally on the module. When used passively, the data is uploaded to a server through a USB interface post-recording for subsequent analysis. Integrated into the smart shirt are textile sensors seamlessly woven into the fabric. Compared to conventional ECG recorders, these textile sensors enhance comfort and enable unobtrusive, interference-free, and neutral heart monitoring.

These smart shirts can record various signals, including single-channel ECG (256 Hz), heart rate (1 Hz), respiratory signals (Thorax + Abdominal: 128 Hz), and more. Notably, the shirt's battery consumption is remarkably low. According to a study by Schuler et al. 2021,[15] after nearly 9 hours of continuous recording, the shirt's battery retained 70 % of capacity.

In addition to the smart shirt, a software development kit (SDK) is available, facilitating the development of custom applications and utilization of the smart shirt's application programming interfaces (API). The SDK used in this project is provided by Hexoskin and is compatible with the Android operating system. The Android dependency requires the signal to be routed through a mobile device before reaching the VR application on appropriately equipped computer hardware.

3.2 VR-Headset and Smartphone

In our setup, the connection between the application and the smart shirt was facilitated by utilizing a Android smartphone (OnePlus Nord, OnePlus, Shenzhen, China). This smartphone served as the intermediary device for transmitting data from the smart shirt to the application.

On the VR side, our application seamlessly ran on the VR system (HTC Vive Pro, Valve Corporation, Bellevue, USA). The HTC Vive Pro package includes not only the VR headset but also two controllers, providing users with an immersive interaction experience. Additionally, the system incorporates the SteamVR Base Station 2.0, a critical component responsible for accurately tracking the user's position within the virtual environment.

The combination of the smartphone and the VR system provided a robust and reliable platform for our application, ensuring smooth connectivity with the smart shirt and delivering an immersive VR experience to users.

3.3 HexoMonitoring Application

Our HexoMonitoring application comprises three integral modules, Figure 1:

HexoClient: This Android application, developed using Kotlin and Java, serves as the interface for recording the ECG signal from the smart shirt. It establishes a connection to the smart shirt, interfaces with HexoServer, and transmits the ECG data securely.

HexoServer: Serving as the backbone of the entire system, HexoServer is a Python-based server responsible for orchestrating the connection and conducting signal analysis. It receives data packets, each containing 16 samples at a frequency of 16 Hz, resulting in the specified 256 Hz sample rate. HexoServer leverages the Pan-Tompkins algorithm (see Section 3.5) for real-time processing of the received data packets to detect heartbeats accurately.

HexoVR: Developed using Unity, HexoVR is a crucial component responsible for visualizing the heart activity in the immersive environment of virtual reality. It receives the data packets with detection flags from HexoServer and renders the ECG signal as both a dynamic heart animation and a graph for enhanced understanding..

The HexoClient module initiates the data flow by interfacing with the Smart shirt and forwarding the acquired ECG data to HexoServer for real-time analysis. Subsequently, HexoServer employs advanced signal processing techniques to detect heartbeats promptly and accurately, providing crucial insights into cardiac health. Finally, HexoVR transforms the processed data into intuitive visual representations, offering users a unique and immersive perspective on their heart activity within the virtual realm.

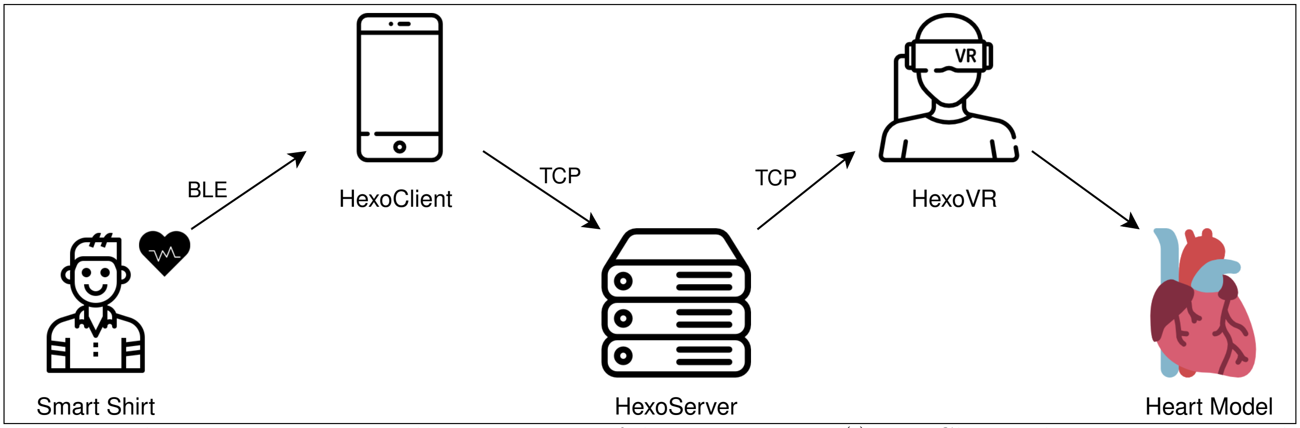


Figure 1: The HexoMonitoring application consists of three components:(i) HexoClient: This component records the ECG via Bluetooth Low Energy (BLE) from the Smart shirt.(ii) HexoServer: Running on a Desktop PC, this component detects the heartbeats.(iii) HexoVR: Also running on the same PC as HexoServer, this component visualizes the data in the VR environment.

3.4 Heart Model & Animation

The 3D heart model stands as one of the paramount features within our entire project. Numerous vendors offer ready-made 3D models online, accessible through platforms like the Unity Asset Store[16] or CG Trader.[17] These models vary in complexity and functionality, ranging from simplistic designs to intricate models equipped with animations and meticulously crafted textures, reflecting their price points.

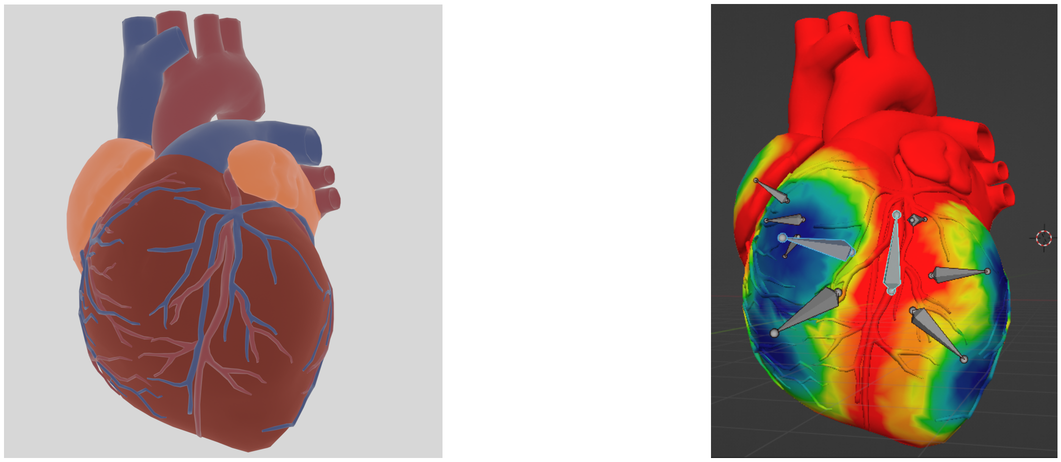
For our project, we adopted an existing heart model sourced from Open3dmodel,[18] to which we applied simple textures to facilitate the visualization of distinct components of the heart. The creation and modification of the model and its animations were undertaken using Blender (Blender Foundation, Amsterdam, Netherlands). We integrated Bones into the model. Bones are a Blender feature that can be used for the animation of objects. Specific vertices can be assigned to the Bones, so that only the individual bone needs to be moved for a motion instead of each individual vertex. With the help of Bones, animations can be easily integrated into Blender. In Figure 2, we present the model utilized for animation and their corresponding weighted maps. In the figure, the Bones are represented as pyramid-like figures with a sphere at the tip.. Each Bone is linked to vertices through a weight map, with colors denoting the strength of their relationship. As a result, surface areas move in accordance with the Bone's influence relative to the weighted maps.

Leveraging these capabilities, we developed an animation spanning 75 frames, breathing life into our 3D heart model and enhancing its visual representation.

3.5 Real-time QRS Detection

We employ the Pan-Tompkins algorithm to detect the R-peaks of the ECG in real-time. This algorithm involves low-pass and high-pass filtering to remove impurities and noise from the signal, thereby increasing the signal-to-noise ratio. According to Pan and Tompkins, a passband of 5 to 15 Hz is recommended. In the next step, the slope of the signal is calculated using a derivative filter. Subsequently, the signal is squared, and a moving window integration is applied. Squaring highlights the peaks of the slope, and the moving average window can determine the duration of the QRS complex. To identify the peaks of the integrated signal, the algorithm examines changes in the slope's direction (from positive to negative) in the signal. These points represent potential QRS complexes. Finally, these potential QRS complexes are compared with a threshold value.

Based on this concept, Sznajder and Łukowska developed a real-time QRS-detector using an Arduino-based e-health sensor platform.[19] We adopted this algorithm to process the signal from the smart shirt and indicate a heartbeat by adding a specific flag to the data packet.



(a) Heart Model

(b) Weighted Maps

Figure 2: HexoVR presents a 3D heart model and a graph in which the ECG is visualized. Based on the detected R-spikes, the animation of the heartbeat is played. The VR device automatically connects to the application, allowing for free movement in the virtual space to observe the heart activity from various perspectives. Figure 2b depicts the integrated Blender features Bones along with their corresponding weighted maps. When the bones are moved, the associated vertices move, generating the animation.

3.6 Experimental Design

We evaluated the HexoMonitoring modules using mocking techniques for individual modules. This approach allowed us to intercept the ECG signal and send known signals between some modules, enabling us to assess the functionality of each module.

3.6.1 Application

Initially, we tested the individual modules and their interaction. The ECG signal recorded by the HexoServer was qualitatively evaluated, and the signal transmission to HexoVR was verified. Finally, we evaluated all modules together to ensure that all components interact correctly and that an ECG signal is displayed in HexoVR and the heartbeat animation is played.

3.6.2 QRS Detection

To verify QRS detection, we compared the real-time Pan-Tompkins algorithm with a known algorithm from a Python library and analyzed the runtime of the detection process. In 11 one-minute intervals, the number of heartbeats was detected using both algorithms and expressed in beats-per-minute (bpm). We compared Pan-Tompkins to the library algorithm using the mean absolute error and mean relative error.

3.6.3 Real-time Analysis

Finally, we measured the runtime of each step in the application to verify real-time capabilities. We defined four time points to determine three durations: the two transmissions from HexoClient to HexoServer and from HexoServer to HexoVR, and the runtime of the signal analysis in HexoServer.

4. RESULTS

4.1 ECG Signal

In the ECG signal captured by the smart shirt, all heartbeat components are discernible. Figure 3 illustrates an original ECG signal recorded using the smart shirt. The upper graph displays an ECG recording spanning approximately 70 seconds, while the lower graph zooms in on a smaller segment (highlighted by the green rectangle) of about 3 seconds.

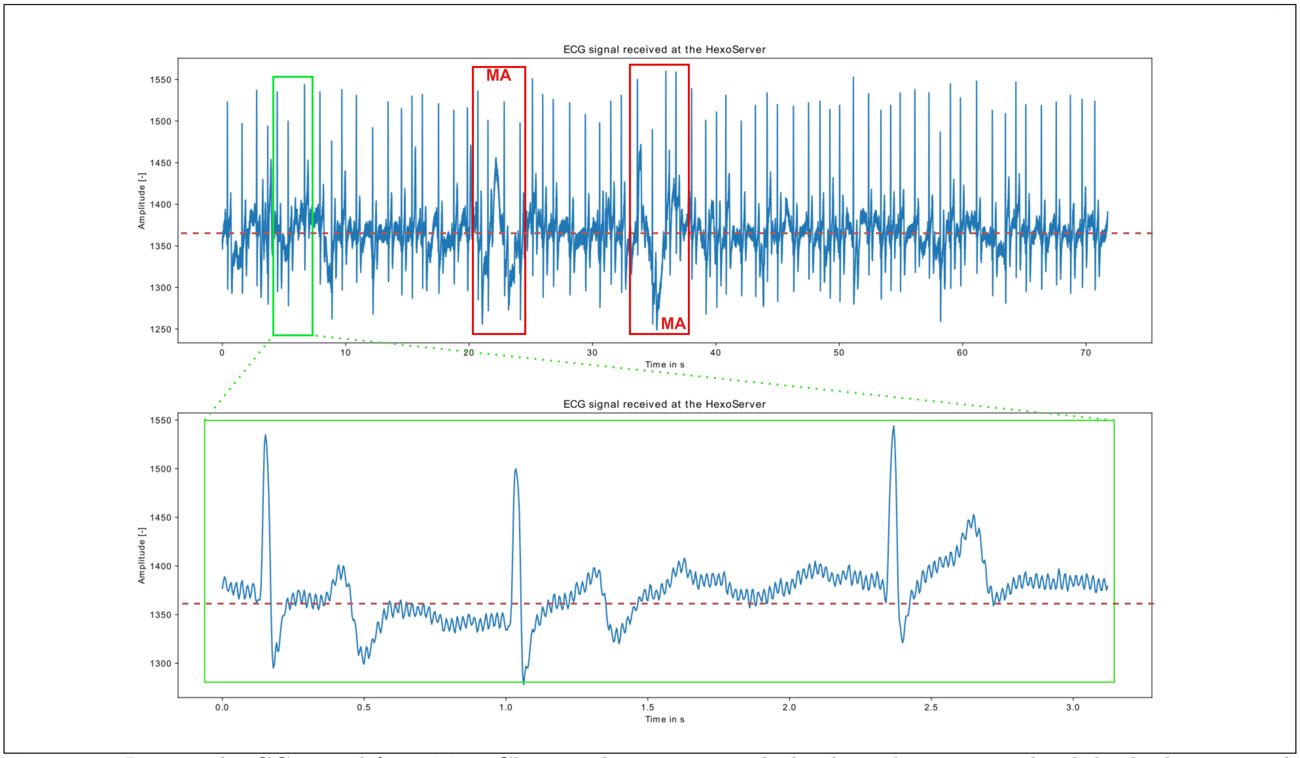


Figure 3: Received ECG signal from HexoClient. The upper graph displays the 70s signal, while the lower graph shows a 3.5s segment of the signal (marked with the green box). All components of the EKG are discernible in the signal, but there are also some artifacts present. It contains a baseline shift of around 1370 mV (red dotted line), motion artifacts (red boxes, marked with MA), and the typical 50 Hz noise.

In the upper graph, motion artifacts are evident and highlighted by the red rectangles. Additionally, it is noteworthy that the baseline falls within the range of 1350 mV to 1450 mV. Furthermore, motion artifacts persist in the signal. In the brief segment of the ECG signal, various components such as waves and peaks are observable. However, there is a noticeable 50 Hz noise present in the signal.

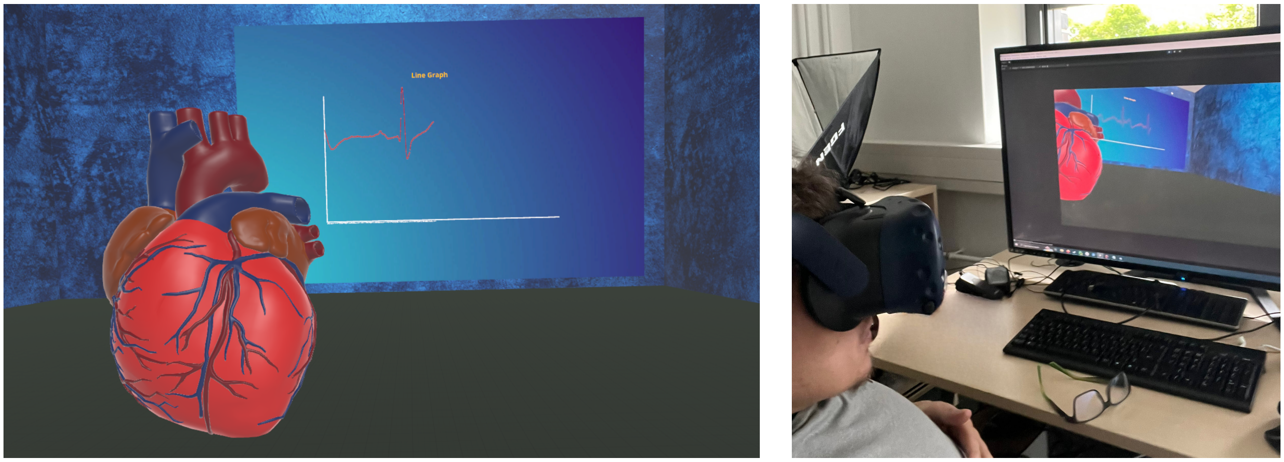
According to the manufacturer, the raw data should be output in mV. However, the measured values in Figure 3 do not correspond to the expected values of a normal EKG. Therefore, the unit and scale of the voltage axis (Y-axis) is not correct. In this study, the incorrect scaling and baseline shift did not have a significant impact on the animation and calculation of the QRS complexes and were therefore not adjusted.

4.2 HexoMonitoring

Figure 4 illustrates the usage of the application with all active modules. The participant wears the smart shirt and records the ECG in real-time. The ECG is then transmitted from the smart shirt to the HexoClient via BLE and forwarded from there to the HexoServer. The HexoServer performs real-time analysis of the ECG and forwards the signal to HexoVR. If a heartbeat is detected, the corresponding packet is flagged so that HexoVR recognizes that the animation needs to be played. HexoVR plays the animation and adjusts the playback speed by measuring the time interval between two consecutive heartbeats. This allows the participant to view the model and animation in 3D in VR. Additionally, the signal is plotted in real-time on the graph. Using the keyboard, the participant can move around the space and view the animation from different perspectives.

4.3 QRS-Detection

The real-time Pan-Tompkins algorithm exhibits a mean absolute error of 8.0 bpm with a mean relative error of 13% over 11 one-minute intervals. This suggests that the algorithm provides relatively accurate heart rate measurements. Furthermore, the algorithm's efficiency is noteworthy, as it processes a single data packet from



(a) HexoVR (b) HexoMonitoring in VR

Figure 4: HexoVR presents a 3D heart model and a graph in which the ECG is visualized. Based on the detected R-spikes, the animation of the heartbeat is played. The VR device automatically connects to the application, allowing for free movement in the virtual space to observe the heart activity from various perspectives. Figure 4a depicts the model and the graph during the application. In the graph, the end of a heartbeat is identifiable, while in the animation, the relaxation phase of the two heart chambers is also discernible. Figure 4b depicts a participant using the application. In real-time, his ECG signal is represented as an animation and on the graph while he freely navigates in VR and observes the model from different perspectives.
http://dx.doi.org/10.1117/12.3006472.1

the Hexoskin shirt in just 3.07 ms. This rapid processing time meets the real-time requirement of the application, enabling immediate visualization and analysis of heart activity within the VR environment.

4.4 Real-Time Analysis

The Figure 5 depicts the measured time points at the individual modules. From this, the time intervals $D1 - D3$ arise to determine the transmission and computation duration's.

$$D1 = T2 - T1 = \ -52.68\ ms \tag{1}$$

$$D2 = T3 - T2 = \ 3.63\ ms \tag{2}$$

$$D3 = T4 - T3 = \ 0.19\ ms \tag{3}$$

For the real-time requirement, the time intervals of data transmission and analysis were examined. During 10 transmissions from HexoServer to HexoVR, a mean duration of 0.19 ms was measured. In HexoServer, the time duration for analysis was measured to be 3.63 ms, consistent with the results of the QRS-Detection analysis.

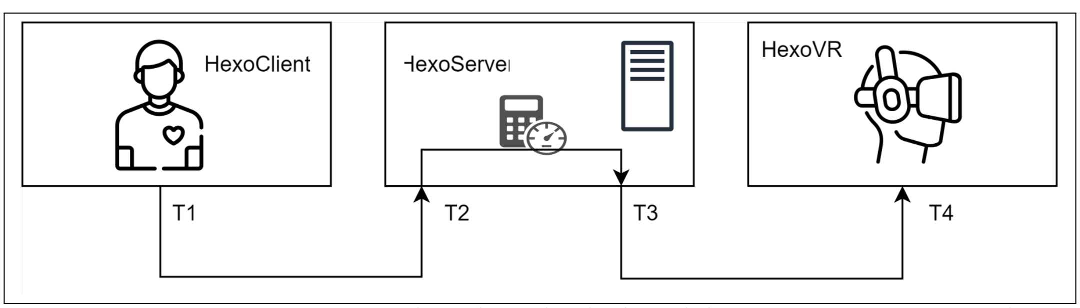


Figure 5: Time points T1 to T4 correspond to the individual modules. $T2 - T1$ represents the transmission duration from HexoClient to HexoServer. The calculation duration of the QRS detection in HexoServer is $T3 - T2$. Finally, the transmission duration from HexoServer to HexoVR is $T4 - T3$.

5. DISCUSSION

In this study, the feasibility of real-time monitoring of cardiac activity in VR using smart shirts was investigated. An application consisting of three modules, responsible for signal recording, analysis, and display of the ECG signal, was developed. The HexoClient, an Android app, receives the signal from the shirt and forwards it to the HexoServer. The HexoServer performs signal analysis and sends the signal and analysis to the HexoVR module. The module utilizes the analysis to initiate a heart animation and display the ECG signal on a graph. Users have the freedom to move around the virtual space and observe the animation from different perspectives.

The results of the application demonstrate that the concept and implementation are functional and ready for use. The application performs real-time monitoring using a heart animation and a graph representing the information of an ECG signal in real-time.

Figure 3 illustrates that a recognizable ECG signal is transmitted from the HexoClient component using the smart shirt. The mocked HexoServer can receive and process this signal. However, the 70s recording shows some motion artifacts. The received signal exhibits a baseline shift of approximately 1400 mV. This shift can be neutralized by subtracting the mean value. Motion artifacts are also a major problem because they cause interference in QRS algorithms. In this project, simple artifact filters were used to control the motion artifacts, such as amplitude thresholds. However, improved filters for these artifacts could be incorporated into future work. Finally, especially in Figure 3 with the signal segment, 50 Hz noise is present. The observed noise is likely caused by magnetically induced interference originating from the electrode leads and the body. This behavior has been observed in other studies with the smart shirts and can be remedied with a notch or bandstop filter.[15,20] These filters can be employed to eliminate specific frequencies or frequency bands from a signal. However, these filters would impact the runtime.

The quality of the QRS detection algorithm is mixed. With a relative error of 13%, the precision meets the requirements of this application adequately. Problematic for this type of algorithm are the artifacts in the ECG signal, which are not filtered in this application. Accurate filtering or alternative real-time QRS detection algorithms could significantly improve the application's performance.

The real-time requirements of the application have been met. With a complete transmission and calculation duration of approximately 5 ms, heart activity can be displayed in real-time. The time duration of data transmission from HexoClient to HexoServer could not be accurately measured due to an issue with the Android smartphone's clock, resulting in slight discrepancies compared to the atomic clock and incorrect timing. However, assuming a similar time behavior to the transmission from HexoServer to HexoVR, the total transmission and analysis time would be under 5 ms, meeting the real-time requirement.

However, we encountered a limitation during movements, as strong artifacts were introduced in the ECG signal, leading to a significant negative impact on the detection algorithm. As a result, the animations in VR became erroneous. In future research, the incorporation of effective real-time filters could be explored to mitigate these artifacts and improve the accuracy of the detection algorithm. Another potential improvement is the utilization of a multichannel ECG. For instance, the Astroskin shirt from Hexoskin provides a three-channel ECG. Incorporating this shirt would offer additional features, such as enhanced cardiac animation and increased precision of the detection algorithm. Furthermore, future work could involve upgrading the application to a standalone Unity application. If Hexoskin supports other operating systems in the future, it would be possible to remove the HexoClient and HexoServer modules. This would improve usability and reduce potential errors associated with duplicate transmissions. Currently, the management of these modules is quite complex, as they need to be individually started, and a connection must be established. Simplifying the application's setup would make it more practical for real-world use.

Previous studies utilizing shirts have already highlighted their importance in the medical field, particularly in ECG analysis. This research confirms the feasibility of real-time monitoring and suggests its potential utilization in medical personnel training, providing a non-invasive method for medical students to gain a realistic experience of heart anatomy. Additionally, these smart shirts are comfortable for users and minimally disruptive to their activities.

It opens up new possibilities for applications in medical training, research, and patient care. By addressing the artifact issue during movements and further improving the real-time processing capabilities, this technology could become an invaluable tool in the medical

6. CONCLUSION

The evaluation results demonstrate that the application is capable of performing these functionalities in real-time. The QRS detection algorithm successfully detects most of the heartbeats, allowing for the display of the user's real cardiac activity. The transmission and analysis time are estimated to be less than 10 ms, meeting the real-time requirements. Overall, the Hexoskin smart shirt exhibits significant potential when combined with virtual reality.

In conclusion, we demonstrate the technical feasibility of using VR and smart wearable technology for real-time monitoring of heart activity.

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