Computational and Structural Biotechnology Journal 24 (2024) 160–175

Contents lists available at ScienceDirect

Computational and Structural Biotechnology Journal

journal homepage: www.elsevier.com/locate/csbj

Research Article

MiVitals–***Mi****xed Reality Interface for* ***Vitals*** Monitoring: A HoloLens based prototype for healthcare practices

Syed K Tanbeer, Edward Roderick Sykes *

Centre for Mobile Innovation (CMI), Sheridan College, Oakville, Ontario, Canada

ARTICLE INFO

Keywords:
Augmented reality
HoloLens
Mixed reality
Mobile health
Visualization
Vital sign monitoring

ABSTRACT

In this paper, we introduce *MiVitals*—a Mixed Reality (MR) system designed for healthcare professionals to monitor patients in wards or clinics. We detail the design, development, and evaluation of *MiVitals*, which integrates real-time vital signs from a biosensor-equipped wearable, *Vitaliti*™. The system generates holographic visualizations, allowing healthcare professionals to interact with medical charts and information panels holographically. These visualizations display vital signs, trends, other significant physiological signals, and medical early warning scores in a comprehensive manner. We conducted a User Interface/User Experience (UI/UX) study focusing on novel holographic visualizations and interfaces that intuitively present medical information. This approach brings traditional bedside medical information to life in the real environment through non-contact 3D images, supporting rapid decision-making, vital pattern and anomaly detection, and enhancing clinicians' performance in wards. Additionally, we present findings from a usability study involving medical doctors and healthcare practitioners to assess *MiVitals*' efficacy. The System Usability Scale study yielded a score of 84, indicating that the *MiVitals* system has high usability.

1. Introduction

Monitoring vital signs such as Respiration Rate (RR), Blood Pressure (BP), Heart Rate (HR), blood oxygen saturation (SpO_2) and Body Temperature (TEMP) plays a significant role in clinical and non-clinical medical care [1]. There are multi-facet benefits of continuous monitoring of vital signs [2], such as proactively addressing clinical deterioration, reducing hospital stay duration, decreasing the mortality rate and lowering the expenditure [3,4]. Featured with the ability to continuously monitor vitals, therefore, has become crucial for vital monitoring devices and instruments.

Most conventional vital sign monitoring instruments are not suitable for continuously monitoring vitals [1]. Other significant limitations of these instruments include (i) a given instrument may not be capable of capturing all 5 vitals simultaneously [5]; (ii) they rely on direct physical contact (which may cause potential skin infection and discomfort for the patient [4]); and (iii) they may not be compatible with the underlying data capturing technology (e.g., via wireless connectivity [6]). Due to these limitations, conventional vital monitoring instruments are becoming infeasible with modern patient care demands and caregiver team requirements [6], especially for smart mobile healthcare scenarios.

Recent research has gained attention in developing wireless wearable devices to continuously monitor patient vitals, primarily to address the above issues with traditional vital sign monitoring instruments [6–8] and offer additional benefits of improved visualization of vitals. Inspired by the potentiality of effective use of wearable devices in vital sign monitoring, vendors and industries in the healthcare sector from across the globe have focused on devising such devices [9–13]. One design benefit of wearable devices is that they are simple, lightweight and easy to wear [8]. Moreover, they can be connected to a data repository and other smart devices for data analysis [8]. However, a close study on most health monitoring wearable devices reveals that none of them enable simultaneously monitoring the previously mentioned 5 vitals (i.e., RR, BP, HR, SpO_2 and TEMP). To the best of our knowledge, the only vital sign monitoring wearable device that can monitor all 5 vitals at the same time and having minimum contact with the patient's body is the *Vitaliti*™ [14] designed and developed by Cloud DX [15]. This wearable device follows an efficient and secure data communication protocol, as outlined in [16,17] - collecting the

* Corresponding author.
E-mail addresses: syed.tanbeer@sheridancollege.ca (S.K. Tanbeer), ed.sykes@sheridancollege.ca (E.R. Sykes).

https://doi.org/10.1016/j.csbj.2024.02.024
Received 30 November 2023; Received in revised form 26 February 2024; Accepted 26 February 2024
Available online 1 March 2024

Fig. 1. Cloud DX's Vitaliti^{TM} continuous vital signs monitoring wearable.

health data through its sensors, transmitting the data using wireless access point over the network, and presenting it to the selected device for processing. Fig. 1 presents the Vitaliti^{TM} continuous vital signs monitoring wearable.

Besides the reliable monitoring of vital signs, another critical component of patient care for clinicians is the ability to visualize vital data through interactive interfaces. The choice of visualization significantly influences the accuracy and ease of interpretation, assisting clinicians and other healthcare practitioners in their decision-making processes [18–21]. Inspired by these findings, augmented reality (AR)[1] and Mixed Reality (MR)[2] based computer-aided interactive technologies are gaining considerable attention in healthcare sector [22,20,23,24,21,25–28]. Between these two virtual reality technologies, MR offers a more natural interaction with the 3D environment - with it, clinicians can zoom, rotate, relocate, and pan virtual components (e.g., charts, images, text panels, clips, and animations), thereby enhancing the visualization experience of the vital signs and enabling it a prevalent option for vitals monitoring in clinical setup compared to AR.

Among mixed reality smart devices, the Microsoft HoloLens (HoloLens) [29] is an all-in-one mobile device that can connect to a wide range of potential patient wearable devices (e.g., the Vitaliti^{TM}) via wireless connectivity (e.g., Bluetooth and WiFi) [22] - making it suitable to use almost anywhere and with any data capturing device [26]. Due to this capability, the portability and the connectivity features, the HoloLens based MR applications have become popular in various sectors including healthcare, e.g., pathology/labs [24,22], surgery [26,21,27], modeling [23], and visualization [19,27,18,28,25]. Despite these successful uses, to the best of our knowledge, using HoloLens in monitoring and visualizing vital signs in clinical environments has not been the subject of any study.

Therefore, it naturally begs the question: Can a system be developed to continuously monitor all five essential patient vital signs—namely, Respiratory Rate (RR), Blood Pressure (BP), Heart Rate (HR), Oxygen Saturation (SpO_2), and Temperature (TEMP) — utilizing a single wearable device that requires minimal body contact? Moreover, can this system employ HoloLens-based Mixed Reality (MR) technology for the visualization and interaction with these vital signs, thereby facilitating the analysis of vital data, early detection of abnormalities, enhancing patient care, and minimizing the risk of health condition deterioration in both clinical and non-clinical settings? This paper aims to explore this question and propose a solution. The key contributions of our work include:

- Continuous and simultaneous capture of all five vital signs using a single wearable device, namely the Vitaliti^{TM}, making these vital signs available for visualization and analysis.
- Utilization of HoloLens-based MR technology for the visualization of vital signs and other physiological signals, incorporating interactive features for clinicians.
- Provision of detailed visualizations that include real-time detection of the current condition of each vital sign and their trends.
- Implementation of a middleware layer to facilitate seamless data transfer between the Vitaliti^{TM} and the HoloLens.
- Design and development of a prototype for the proposed system, termed *MiVitals* (**Mi**xed Reality Interface for **Vitals** Monitoring).

The remainder of this paper is organized as follows: The subsequent section provides a background on the tools, instruments, and techniques utilized for detecting, monitoring, and visualizing vital signs. We then detail our *MiVitals* prototype and its implementation in Sections 3 and 4, respectively. The findings from our study are presented in Section 5. Finally, Section 6 concludes the paper, summarizing our contributions and discussing potential future directions for this work.

2. Background and literature review

In recent years, the integration of cutting-edge technologies such as mobile health (mHealth), artificial intelligence (AI), data-driven methodologies, smart devices, and virtual reality (VR) into healthcare delivery and management processes has seen significant advancement [30,13,31,20,32,33]. This research is particularly concentrated on the monitoring of patient vital signs through the development of effective user interfaces and visualizations, leveraging Mixed Reality (MR) technology. This section offers a comprehensive review of the existing literature, focusing on the application of wearable devices in health monitoring, the visualization of vital signs, and the employment of sophisticated technologies in this context.

2.1. Use of wearable devices in health monitoring

Over recent decades, monitoring all critical patient vitals—specifically, Respiratory Rate (RR), Blood Pressure (BP), Heart Rate (HR), Oxygen Saturation (SpO_2), and Temperature (TEMP)—in a conventional clinical setting necessitated multiple specialized devices and medical equipment, such as pulse oximeters for SpO_2, nasal thermocouples for respiration studies, respiratory belts for measuring respiration rate, thermometers for body temperature, and transducers for imaging [1,5]. Moreover, these devices require direct physical contact with the patient via straps, probes, and electrodes, potentially causing health hazards and discomfort over continuous and long-term use. This is particularly problematic in ambulatory settings and for patients with sensitive conditions, including the elderly, burn victims, and premature infants [4]. Additionally, traditional monitoring methods have limitations such as

[1] The augmented reality technology creates a composite environment by overlaying digital components over real-world elements. However, it does not allow the user to interact with the digital elements.

[2] The mixed reality technology allows not only of overlaying digital components on top of real-world elements but also their interactions i.e., users can see and interact with both the digital and physical elements.

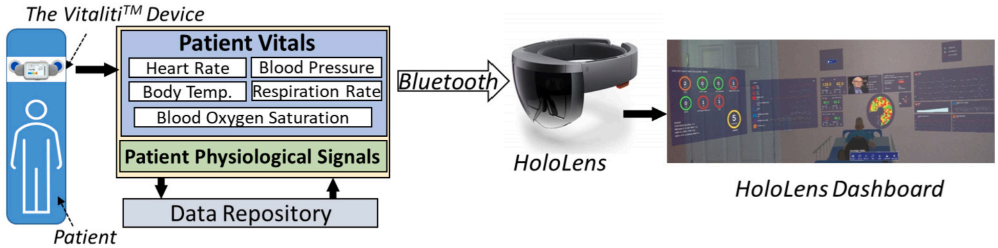

Fig. 2. High-level architecture of *MiVitals*.

delayed detection of physiological deterioration [1] and a lack of wireless data communication capabilities [6].

The limitations of traditional vital monitoring techniques, coupled with advancements in healthcare technologies, have spurred the development and adoption of wearable devices across various patient care and monitoring applications [6–13]. Enhanced battery life, improved wireless data transmission, and the proliferation of handheld devices like smartphones have facilitated the advancement of wearable health monitoring technologies [8]. This has led to the creation of innovative products by numerous manufacturers globally, such as VitalPatch by Vitalconnect [9], Spry Health Loop by Spry Health [10], EQ02 Lifemonitor by Vandrico Inc. [11], VisiMobil by Sotera Digital Health [12], and the Vitaliti™ by Cloud DX [14].

Although wearable devices vary in their attachment methods—ranging from patch-based to band and strap applications—they are designed to minimally impact the patient's lifestyle [8]. The Vitaliti™, uniquely worn on the upper chest, stands out for its flexibility and comfort, enabling uninterrupted wear even during sleep. Unlike other devices that monitor a subset of vital signs, the Vitaliti™ is specifically designed for the continuous monitoring of all five essential vitals and other physiological data [8]. In contrast, devices like Everion and EQ02 Lifemonitor cover all vitals except BP, VisiMobil is intended for static use, Spry Health Loop does not monitor TEMP, and the VitalPatch lacks BP and SpO_2 monitoring capabilities.

2.2. Use of mixed reality in health monitoring and visualization

Over the past few decades, Augmented Reality (AR) and Mixed Reality (MR) technologies have increasingly been incorporated into various healthcare domains [19]. Klinker et al. [20] introduced an AR prototype for hands-free documentation of wound treatment procedures, utilizing the HoloLens to measure wound sizes. Similarly, Chien et al. [34] demonstrated an innovative application of the HoloLens in healthcare, where medical data are superimposed onto the physical surface of a patient, allowing physicians to maintain their focus without distraction.

Significant advancements have also been observed in pathology, laboratory, and surgical fields through MR integration, streamlining procedures and enhancing operational precision [24,26,21,23]. Hanna et al. [24] showcased a HoloLens-based virtual annotation system for autopsy in anatomic pathology, facilitating correlation between pathology and radiology. Mojica et al. [27] introduced a mechanism using HoloLens output to control MRI scanners for optimized 3D MRI data acquisition. Further, MR-assisted planning for liver resection and congenital heart surgeries, alongside HoloLens-aided surgical prototypes, have been developed [26,21], with Jiang et al. [23] proposing a HoloLens-based vascular localization system to improve accuracy in perforator location identification during vascular flap transfer procedures.

The utilization of HoloLens and MR technology for 3D visualization of medical images and vital signs is gaining traction across various healthcare sectors, including surgery, patient care, and pathology [28,34,26,27]. The ability to overlay virtual 3D models onto real-world environments and interact with these models has positioned the HoloLens as a key tool in medical data visualization and analysis [22,34,23,25,27,28]. Notably, Chien et al. [34] developed a HoloLens-based MR system that projects preoperative medical images as 3D holograms within the same coordinate space as the actual patient, enhancing physician visualization capabilities. Furthermore, Mojica et al. [27] and the study by Traub et al. [28] have contributed holographic interfaces for MRI data visualization and MR-based solutions for computer-assisted minimally invasive surgeries, respectively, highlighting the intuitive and efficiency-enhancing nature of MR data visualization. Despite these advancements, the visualization and monitoring of vital signs via MR technology remain areas ripe for further research exploration.

Given the promising applications of HoloLens in healthcare, this study introduces a prototype that leverages HoloLens technology for visualizing vital signs collected by the Vitaliti™ wearable device within a 3D environment. The methodology employed to design, develop, and evaluate our *MiVitals* prototype is discussed in the following section.

3. Methodology

The primary objective of MiVitals, our proposed system, is to facilitate the capture of patient vitals and provide healthcare professionals, such as physicians and nurses, with a mixed reality experience. This experience is enriched with holographic visualizations of the patient's vitals in real time, eliminating the need for physical interaction with the devices used for capturing or monitoring these vitals. Through mixed reality user interfaces, healthcare professionals can effortlessly visualize current vital readings, observe trends in any vital sign, and assess the status of vital values (e.g., whether they are high, low, or within normal ranges). In this section, we elaborate on the comprehensive functional architecture of MiVitals and provide detailed descriptions of its constituent components.

Fig. 2 illustrates the overarching architecture of the MiVitals system, a mixed reality-based framework for the monitoring and visualization of patient vital signs. The diagram highlights the role of a wearable device, the Vitaliti™, in capturing the patient's vital signs. This device is engineered to continuously monitor a comprehensive array of vitals, including heart rate, blood pressure, respiratory rate, body temperature, and blood oxygen saturation. Additionally, it records other physiological signals such as electrocardiograms (ECG), photoplethysmography (PPG), and data from built-in accelerometer and gyroscope sensors, all in real-time. This extensive monitoring capability is supported by references to current literature and technological advancements in the field [14,35].

In our *MiVitals* system, we employed the Microsoft HoloLens 2 as our mixed reality device for delivering vital information to clinicians through a mixed reality experience. The HoloLens 2 represents the evolution of the original Microsoft HoloLens [29]. Throughout this paper, we employ the term *HoloLens* to denote the latest iteration of the device, namely, HoloLens 2.

The HoloLens directly receives vital sign data and physiological signals from the Vitaliti™ device via Bluetooth. Significant features of Bluetooth technology that make it an ideal choice for wireless data communication in our system include: (i) adaptive frequency hopping (AFH), which reduces radio impedance and enables seamless transmission of Bluetooth packets; (ii) low energy consumption; (iii) direct

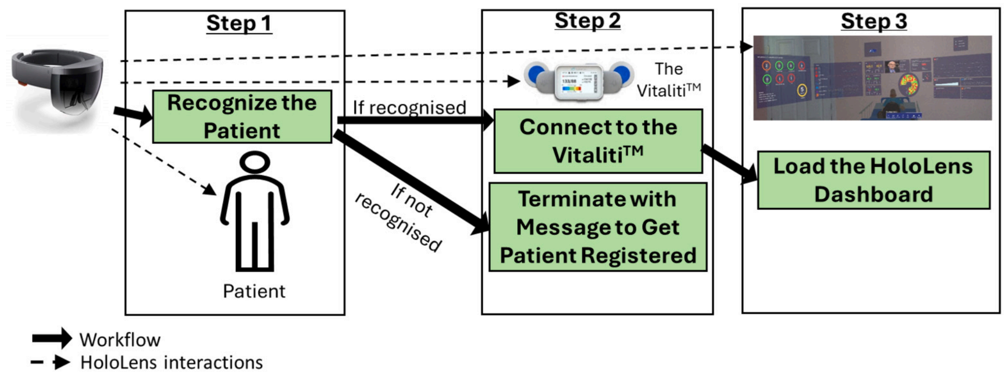

Fig. 3. Overarching workflow process in the *MiVitals* system with Microsoft HoloLens.

transmission to selected and trusted devices; (iv) being a preferred data communication protocol in hospital environments due to its non-interference with sensitive medical devices or equipment [45,10,32].

Each vital data stream and signal received by the HoloLens is then presented as holographic panels to the user wearing the device. Various graphical tools, such as charts, real-time continuously updating graphs, and video clips, are used to represent the data as the clinician views them all at once on the HoloLens dashboard. The mixed reality component of the HoloLens device enables users to interact with each hologram, allowing for actions such as zooming in or out, focusing, and repositioning, thereby enhancing the user-friendliness and effectiveness of vital sign observations.

In addition to presenting the vitals and signals through the HoloLens, all patient vital data are also stored locally on the Vitaliti™ device connected to the HoloLens for a given period of time (e.g., the last 24 hours) [14]. One of the goals of data storage is to allow the application to facilitate monitoring patient vitals and trends over a period of time.

3.1. Workflow of MiVitals

Our holographic system initiates by employing computer vision to recognize the patient. This initial phase of the vital visualization process identifies the patient and subsequently retrieves their vital signs. This section outlines the overarching workflow process in the *MiVitals* system for real-time vital monitoring and visualization. Fig. 3 illustrates the comprehensive workflow process, showcasing the primary steps of patient monitoring and the visualization components of *MiVitals*.

Step 1: As the clinician, wearing the HoloLens, approaches within Bluetooth range of the patient's Vitaliti™ device and faces towards the patient, the system initiates a patient recognition subsystem responsible for checking if the patient is an existing or a new patient. An overview of the patient recognition subsystem is presented in Fig. 4. The system automatically displays a photo-capturing panel on the HoloLens screen. Using the HoloLens onboard cameras, it first detects the patient within the panel and allows the user to capture an image of the patient's face (the Face Detection step in Fig. 4) and then recognizes the patient's face based on already existing patient images stored in a patient profile repository available in the underlying data repository (the Face Recognition).

Step 2: Once the patient's face is recognized, *MiVitals* performs two tasks: i) connects to the Vitaliti™ device the patient is wearing (Fig. 3), and ii) reads and loads the patient's profile information from the underlying database into the HoloLens (the last step in Fig. 4). If the face cannot be recognized, the system considers the patient as new and terminates with a request for the user to capture the patient's profile in the database (Step 2 in Fig. 3). Since *MiVitals* can only monitor vitals for existing patients, it is important that the profile of any new patient be stored in the underlying database before attempting to monitor their vitals using the proposed system (which is beyond the scope of this paper).

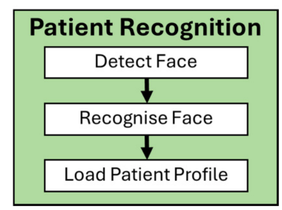

Fig. 4. Patient recognition subsystem.

Step 3: In Step 3 (Fig. 3), the current vitals of the recognized patient are captured in the HoloLens from the Vitaliti™ and presented on the HoloLens dashboard with appropriate user interfaces.

3.2. Vitals visualization

The HoloLens dashboard for viewing patient vitals is depicted in Fig. 5. The dashboard consists of multiple views: (i) the Central Part, displaying all the vitals; (ii) the Trends Part, showing the recent trends of vitals over a time period; (iii) the HEWS Part, displaying the Hamilton Early Warning System scores; and (iv) the Physiological Data Part, exhibiting ECG, PPG, accelerometer, and gyroscope signals. The lab reports, which present reports of the patient's lab work and radiology imaging, are also displayed in the final part.

A detailed view of the central part is presented in Fig. 6. The lower panel on the right side of the central part screen provides a list of available devices (displayed with circle sensors) that are currently within range of the HoloLens' Bluetooth connectivity. Among the list of devices that the patient is using is the Vitaliti™ device. Once the user selects 'Connect' for the chosen device, communication between that device and the HoloLens is established. The HoloLens dashboard is displayed once this connection is established. It is important to note that the device information is stored along with the patient profile and is used every time the patient has a consultation. This feature ensures that the current view of the vitals is collected from the patient being observed. Visual feedback on the Vitaliti™'s connectivity is displayed to guide the user regarding the current status of the device (e.g., green for connected and active devices, red for no connection).

After recognizing the patient's face in Step 3 (Fig. 3) and connecting to the patient's Vitaliti™, the system reads and loads pertinent personal and medical information of the patient (e.g., image, name, date of birth, sex, language, current medication, reported symptoms, and allergies) from their profile, which is displayed in a couple of panels located at the top right corner of the central screen (Fig. 6).

All vital metrics are displayed on the left-hand side of this screen, separated into individual focus panels for each vital: RR, BP, HR, SpO_2, and TEMP. To identify the vital metric, each of these panels shows the name of the vital positioned at the top-left corner and a symbol of the

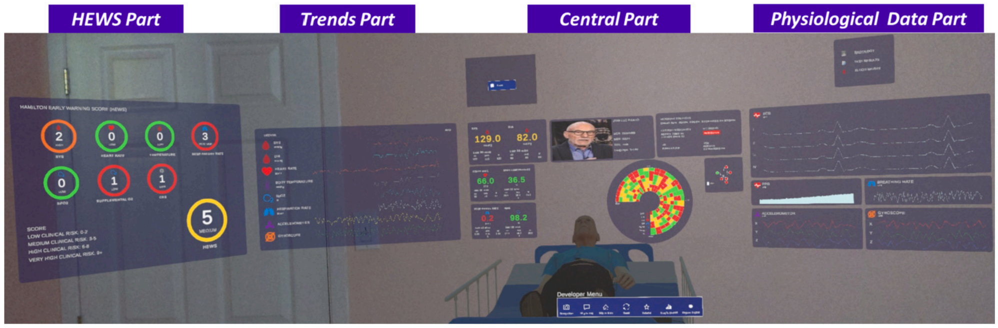

Fig. 5. Overall dashboard of *MiVitals* with Microsoft HoloLens.

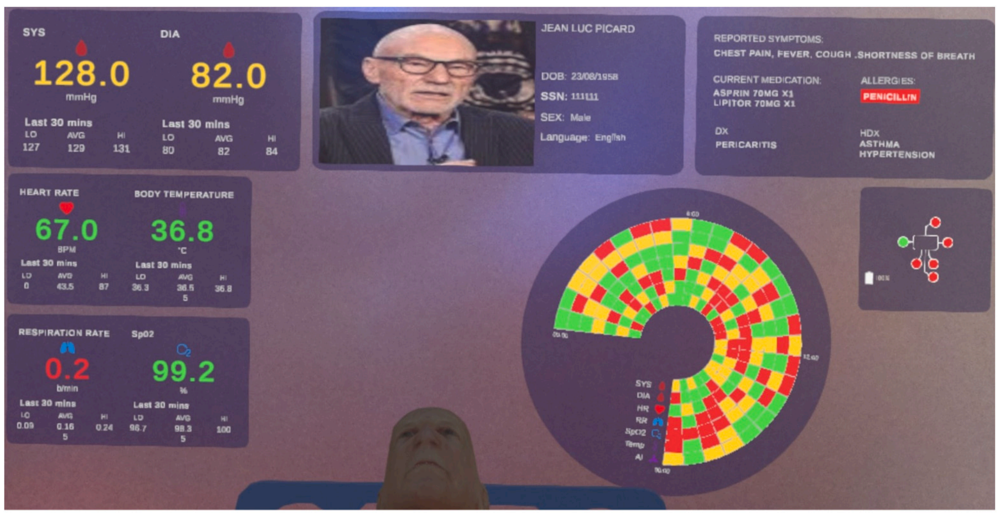

Fig. 6. Central part of HoloLens dashboard.

vital as an icon right after it. The titles of most metrics are displayed in full format, instead of an abbreviation, to make them easy for the user to understand the metric even for non-clinical users. The high, low, and average readings over a time period (e.g., the past 30 minutes) are also displayed at the bottom part of each metric's panel. For example, the values HI = 131 mmHg, AVG = 129 mmHg, and LO = 127 mmHg in the row at the bottom part of the SYS panel in Fig. 6 respectively indicate the high, average, and low systolic blood pressure readings of the patient measured over the past 30 minutes.

The color-coded number in the middle of each vital metric panel displays the current corresponding vital reading (along with its unit). For example, with reference to Fig. 6, the current systolic and diastolic blood pressure readings of the patient being observed are measured as 128.0 mmHg and 82.0 mmHg, respectively, which are presented in the SYS and DIA panels located at the top left corner of the screen. Red, green, and yellow color coding is used on the vital measurement to indicate the vital's range. For example, metrics colored in red indicate an abnormal (i.e., low or high) value, such as the respiration rate metric shown in red as it measures 0.2 b/min, which is considered a low value for respiration rate [2,13]. Additionally, 67.0 BPM and 36.8 $°C$ are considered normal readings for heart rate and body temperature, respectively, and are therefore shown in green. Furthermore, since 128.0 mmHg and 82.0 mmHg for SYS and DIA blood pressure are considered above normal, they are shown in yellow [13].

A novel 24-hour vital metric heat map in a radial timeline is displayed at the bottom right side of the central dashboard. Fig. 7 shows a closer view of this radial graph presentation for 24-hour data from the database.

Each vital is displayed in chronological order with a unified layout in the graph. For example, the innermost circle in the radial graph shows the status of the systolic blood pressure data over the time period. Similarly, data about other vitals such as diastolic blood pressure, heart rate, respiratory rate, blood oxygen saturation, and body temperature are displayed in subsequent circles, respectively.

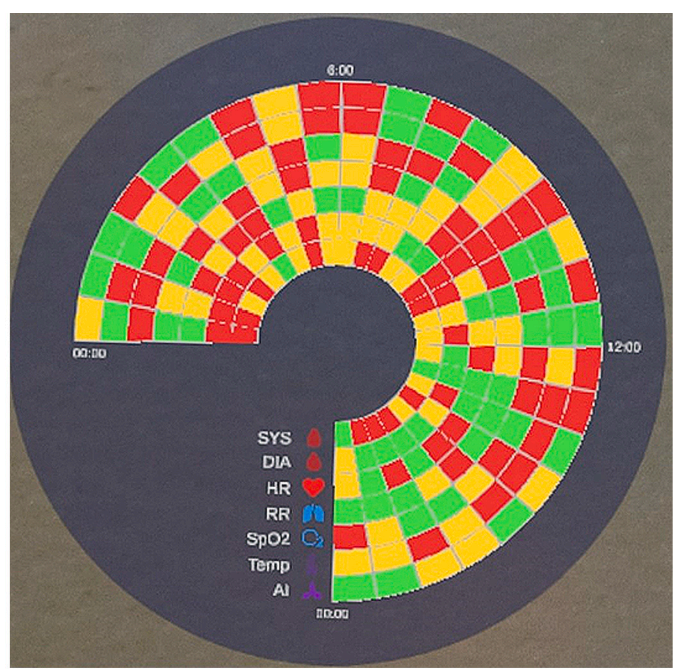

Fig. 7. The radial graph.

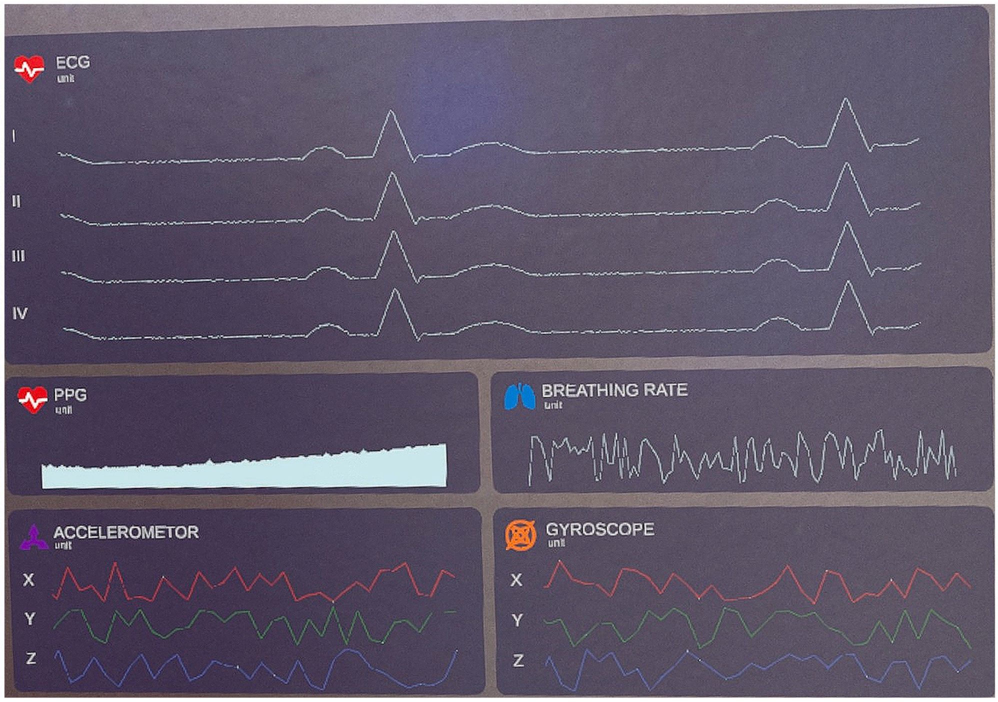

Fig. 8. Physiological signal panel.

The same color-coding scheme used to represent high, low, and normal readings in each vital metric is also applied in the radial graph. With this design and color scheme, the graph demonstrates effective use of space compared to linear layout displays, while still providing useful and easily interpreted information about the patient's vitals. Though this graph may not provide exact quantification of vital measurements, it offers a clear view of the interactions between vital channels over a time period and helps the clinician make reasonable predictions about out-of-range metrics, as it can effectively display the cycling nature of data (e.g., daily trends/activities).

3.3. Physiological reports and imaging visualization

The set of panels just to the right of the central panel displays various physiological signals for the patient, which are also received by the HoloLens device from the Vitaliti™. These signals include the patient's ECG, PPG, accelerometer, and gyroscope signals. Each signal is displayed in a graph indicating current changes in measurements, as shown in Fig. 8.

This part of the HoloLens dashboard also contains a menu list that allows the user to visualize the patient's physiological and radiography test results, images, and video clips extracted from the underlying database. Through the menus 'Radiology,' 'Blood Works,' and 'Test Results' in this list, the user can visualize and interact with various types of pathological test results.

As shown in Figs. 9 and 10, the Radiology menu also assists the clinician in analyzing radiology reports and imaging (e.g., X-ray and MRI). For example, Figs. 10 and 11 demonstrate how to access MRI scan and echo scan reports and imaging of the patient's heart. In a later section, we discuss how the user can access and interact with the chest X-ray report and imaging through the 'Radiology' menu on the menu list and then the 'Lung' sub-menu to view the lung X-ray.

The 'Test Results' menu displays the results of physiological tests and examinations performed on the patient. A dedicated menu, 'Blood Works,' provides a report of all blood work tests conducted. As an example, Fig. 12 shows available sub-menus for the 'Test Results' menu and demonstrates how to access a particular result — in this case, the results of a urine test.

3.4. Vital trends visualization

The panel to the left of the central panel on the HoloLens dashboard displays the continuous trends of various vital metrics over a given time period. This panel relies on historical data already stored in the database. One of the goals of this visual interaction, as detailed in Fig. 13, is to offer enhanced data visualization for evaluating the interactions among different vital metrics and physiological signals or data, which could provide crucial information in various care-providing and patient-condition assessment scenarios. In order to better distinguish between trends of the vitals, different colors are used to identify each vital/signal metric trend graph. One key feature of this view is that it can be extended to accommodate heterogeneous data to be represented in the same rendered graphic (e.g., structured and unstructured types). This layout is very intuitive for the clinical team to interpret and is likely associated with the shortest learning curve.

3.5. HEWS score visualization

The Early Warning System (EWS) [36] scores are used as a tool by medical emergency and general hospital ward teams to recognize early signs of clinical deterioration in order to initiate timely and appropriate intervention and management. The Early warning system score is calculated as an aggregated weighted value derived from weighted numeric measures of several vital sign parameters such as RR, BP, HR, SpO_2, and TEMP. The National Early Warning Score 2 (NEWS2), used within the British National Health Service, has been a popular EWS [36]. The Hamilton Early Warning Score (HEWS) [37], developed by a team of clinicians at Hamilton General Hospital, Hamilton, Canada, is a modification of previous early warning scoring tools, e.g., NEWS2, with the addition of a trigger for delirium and gradation in score depending on the amount of supplemental oxygen required. A recent study in [38] suggests that the HEWS has comparable clinical accuracy to NEWS2 for prediction of in-hospital mortality, and the specificity of HEWS is richer than that of NEWS2.

Inspired by the above findings, the *MiVitals* calculates the HEWS score based on the captured vital measures. The leftmost panel of the

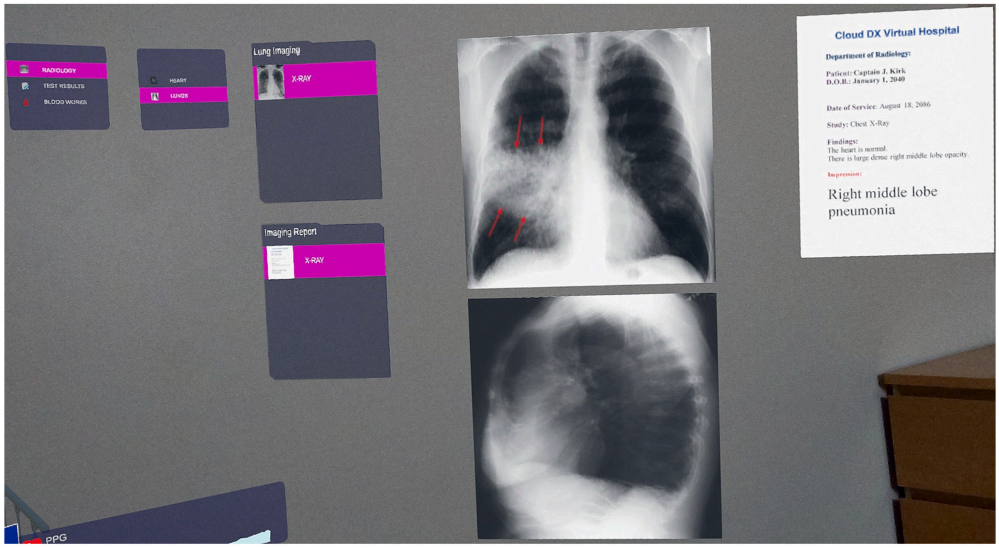

Fig. 9. X-ray report and imaging.

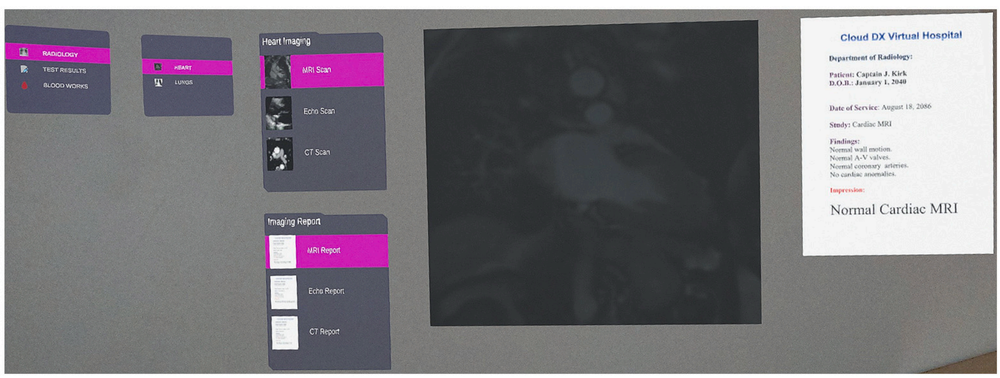

Fig. 10. Heart MRI scan report and imaging.

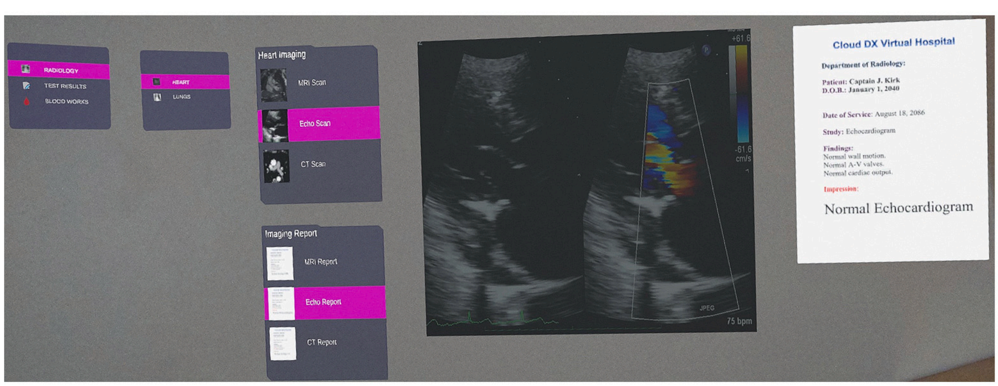

Fig. 11. Heart echo scan report and imaging.

HoloLens dashboard (Fig. 5) displays HEWS data about the patient's current physiological condition, as shown in Fig. 14.

Each circle in the panel indicates a HEWS parameter for a physiological parameter as labeled below. According to the cut-off values for each vital available in the HEWS score calculation method [37], the weight of each physiological parameter is calculated and displayed at the center of each circle. For prominent visualization, a color-coding scheme (i.e., green, yellow, orange, and red) is used for the circles of each parameter, indicating the (low, medium, high, and very high) risk level of individual vital signs. The overall HEWS score, located at the bottom right corner of the panel, is displayed within the same color-coded circle.

In addition to RR, BP, HR, SpO_2, and TEMP, the HEWS score considers supplemental O_2 and central nervous system (CNS) status. Since the supplemental O_2 and CNS data are not automatically captured and do not contribute to the overall HEWS score calculation [37], we display these two metrics in grayscale in the HEWS panel, indicating that they rely on manual inputs.

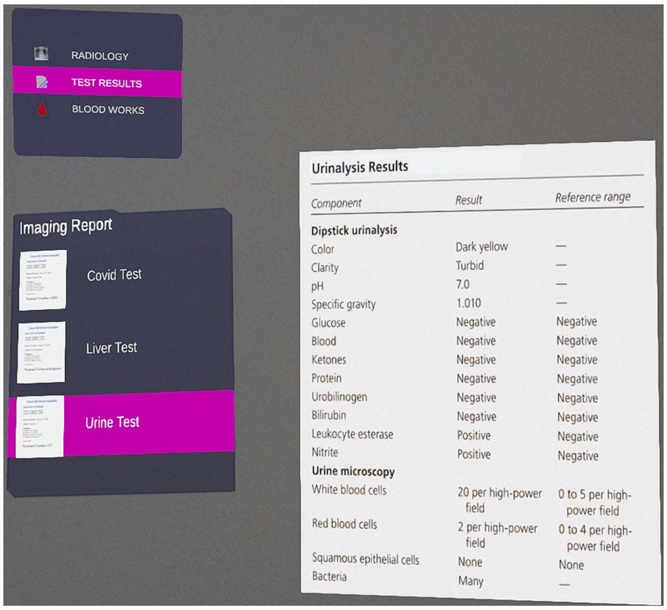

Fig. 12. Urine test report.

With the information displayed in the HEWS panel interface, the *MiVitals* system demonstrates increased attention to patient safety.

3.6. Interacting with HoloLens dashboard components

An inherent benefit of MR platform-based visualization is that the user can interact with the holographic objects through various instinctual actions such as zooming in or out, rearranging positions, resizing, panning, and rotating [29]. The *MiVitals* system exploits this feature to make the vital sign panels intuitively interactable. It provides an option for the user to rearrange, expand, collapse, and pan any panel visualized on the HoloLens dashboard. For example, Fig. 15 displays the status of the HoloLens dashboard after the user rearranged and zoomed in on the BP panels (moving the radial chart upward to make room for BP panels), the physiological signal panels, and, at the same time, viewed the test result for Liver Test: assuming that currently they would like to closely focus on these vitals and test results of the patient.

The far interaction and near interaction features of MR allow the user to move each panel around the dashboard according to their visualization preference. For example, in Fig. 16, the user is interacting with the radial timeline graph to relocate it upward on the dashboard through their ray-guided hand gestures using the far interaction feature of the HoloLens for an improved visual experience.

To enhance the user experience and flexibility in interacting with the holographic images of the HoloLens panels, the *MiVitals* system allows voice command-based interactions with the panels. For example, instead of using ray-guided hand gestures, the user can say the command “Expand Blood Pressure” to zoom in on the BP panel for a better view. The voice command “Collapse” will return the BP panel to its original state. Similarly, to select a button in the test result menu list, the user would say “Select + the button name” (e.g., the command to select the radiology button is “Select Radiology”). The command “Reset” resets all the panels in the HoloLens dashboard to their original arrangement when the user relocated them for a better view. Additional examples of voice commands include “Open lung details” (which shows X-ray lung imaging), “Close lung details” (to close the X-ray image), and “Play heart sounds” (to produce real-time heart beating sounds from the patient for clinical assessments). To assist the user in issuing voice commands, the *MiVitals* system includes a tutorial on voice commands, easily accessible through a user menu. A screenshot of the voice command tutorial is presented in Fig. 17.

Fig. 18 displays the user menu bar, available to the user at all times when interacting with the *MiVitals* system. This menu bar primarily contains icons for basic and major navigation tasks throughout the *MiVitals* system. The rightmost button in this menu bar, a camera icon labeled “Recognition,” lets the user take a picture of the patient to initiate the face recognition task. The “Skip to Reg” icon, located next to the recognition button, is used for registering a new patient (as an alternative to the web-based patient registration system that works independently to support the registration process). The next button in the bar, “Skip to Main,” loads the HoloLens dashboard view. As expected, the “Reset” button can be used to reset all the panels to their original positions (the same action as performed by the “Reset” voice command). The voice command tutorial can be accessed via the “Tutorial” button. The “Graph On/Off” button, located right after the “Tutorial” button, allows the user to show/hide all the graph panels in the main dashboard. The last button, “Organ On/Off,” is used to show/hide holographic images of various organs (e.g., lung, heart), in case the user wants to examine them while visualizing the vital data.

3.7. Evaluation of MiVitals

Our holographic application was evaluated in two distinct ways:

1. A qualitative survey design; and
2. The System Usability Scale (SUS) [39] (Please see Appendix 1).

The qualitative survey comprised two sections: *User Experience* and *Adaption and Use*. The first section facilitated the collection of general user background with mobile and wearable devices (e.g., AR/VR, etc.), while the second part captured the participants’ perspectives and impressions after using our *MiVitals* holographic system.

The second survey utilized the System Usability Scale (SUS), a reliable tool for measuring system usability. The SUS has been employed in over 5,000 research studies [40,39]. It consists of a 10-item questionnaire with five response options ranging from “Strongly disagree” to “Strongly agree.” SUS measurements assess usability in terms of effectiveness (the ability of users to achieve their objectives), efficiency (the effort and resources expended in achieving those objectives), and satisfaction (the overall user experience).

3.7.1. Participants

Participants were enlisted from our educational institution and via our network of healthcare organizations across various mediums, encompassing internal bulletin boards, digital platforms such as Learning Management Systems, and announcements in computer science clubs. Deliberate measures were taken to involve students from medical fields, with a specific focus on those enrolled in our skilled nursing baccalaureate program. This approach proved effective, resulting in 37 participants joining the study. The cohort included 12 active nursing students, 1 practicing medical doctor, 1 medical software developer, 4 computer science professors, and other students enrolled in various programs at the institution. Age-wise, the participants were distributed as follows: 10 in the 17-25 age group, 12 in the 26-40 age group, 14 in the 41-55 age group, and 1 in the 56-70 age group.[3]

In the next section, we discuss the techniques and tools used to implement our *MiVitals* prototype system.

4. Implementation of MiVitals

The overall application of *MiVitals* is built and implemented in partnership with our industry partner, Cloud DX[4] [15]. As mentioned in

[3] This research was endorsed and received clearance from the institution’s Research Ethics Board (REB No: 2018-12-001-035).

[4] Cloud DX, a leading provider of healthcare solutions such as Connect Health™, has emerged as one of the prominent medical technology compa-

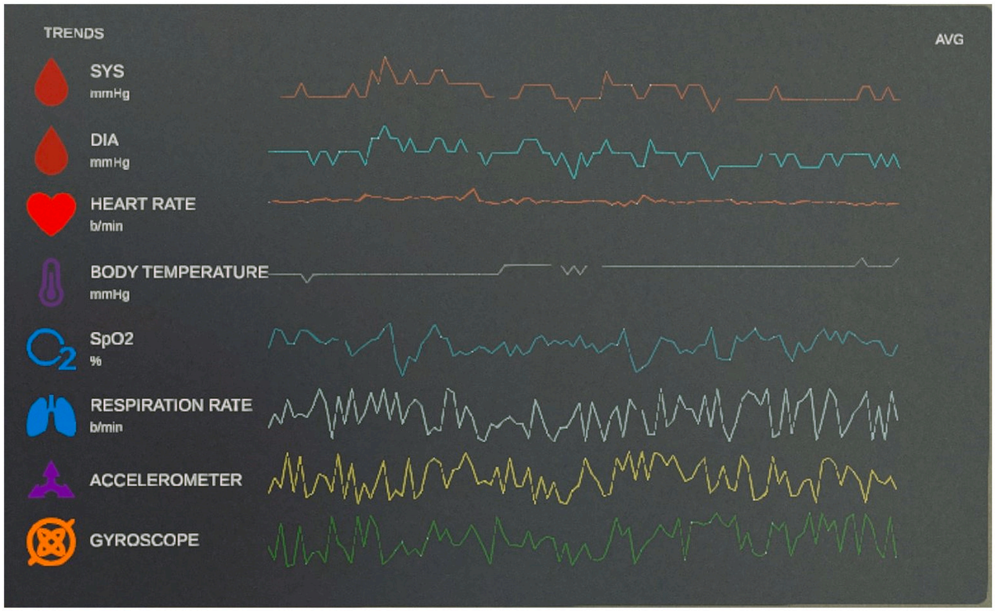

Fig. 13. Vital trends.

Fig. 14. HEWS panel.

the previous section, we utilize Cloud DX's Vitaliti™[5] [14] wearable device to capture vital signs and transfer the data to paired devices for visualization. Vitaliti™, a Continuous Vital Signs Monitor (CVSM), stands as the first of its kind: a portable, wearable, scientifically validated, medical-grade continuous vital sign monitor for patient care. The device complies with the ISO 81060-2:2018 standard [31] and has undergone successful clinical trials [42].

4.1. Patient recognition

The patient recognition process relies on face detection and recognition. *MiVitals* utilizes the facial detection module of the mixed reality device to detect the patient's face. For face recognition, it leverages the Face Recognition Service provided by Microsoft Azure Cognitive Services [43]. This service compares the patient's face image with existing images in the underlying database. If no match is found, the patient is considered as a new, unregistered patient within the mixed reality system.

Since recognition requires the patient's profile and face image to be stored in the database, users must complete the registration process through a web application.[6] This registration process adds patients to the database. Upon finding a match, a Bluetooth connection is established between the patient's Vitaliti™ device and the mixed reality device, enabling seamless transfer of vital sign data.

4.2. Vital data flow

The Vitaliti™ device captures the vital signs and physiological signals of the identified patient in a raw data format (i.e., continuous measurements). This data is processed through multiple stages before it is visualized as holographic images for the user. Fig. 19 demonstrates the progression of vital sign and physiological signal data from the patient's measurements, taken by the Vitaliti™, to the visualization on the mixed reality device's display dashboard (i.e., HoloLens).

A middle layer, utilizing a custom SDK (Software Development Kit) developed to receive raw vital data from the Vitaliti™ and convert it into a platform-independent format (see Fig. 19), facilitates access to data in a format compatible with the device. Applications utilizing this SDK can easily parse vital sign readings. Written in the C++ programming language for efficiency and speed, the SDK also includes functionality for data transfer. Additionally, this middle layer incorporates a secondary layer known as a *Window wrapper*, based on UWP (Universal Windows Platform), which provides essential data conversion toolkits and aids in ensuring that the connected mixed reality device can interpret all received data.

4.3. Visualization and user interactions

As detailed in Section 3, the mixed reality experience is realized using Microsoft HoloLens. The data visualization and interfaces on

nies in Canada. Their focus and contributions in healthcare include reducing workflow bottlenecks, improving clinical operations, supporting virtual care infrastructure, and offering modern technology.

[5] The Vitaliti™ device received the XPRIZE Bold Epic Innovator Award in 2017 [35] and the silver Edison Award in the IoT section of the Science, Medical, and Dental category in 2021 [41].

[6] A web application has been developed as part of the patient care and registration support; however, discussing its details is beyond the scope of this paper.

Fig. 15. HoloLens panels rearranged.

Fig. 16. Hand interaction with vital panels.

the HoloLens dashboard are constructed with Unity, a real-time 3D cross-platform game engine [44]. This module comprises two main components: the rendering unit and the command interpreter and interface.

The rendering unit receives data from the Windows wrapper, generating graphic overlays and displaying vital/physiological signal data on the HoloLens dashboard. Meanwhile, the command interpreter enables user interaction with the dashboard, allowing actions such as loading or unloading displays, moving, repositioning, and zooming images on the dashboard, and establishing or terminating connections with the Vitaliti^{TM} device.

Interactable scripts from the Mixed Reality Toolkit (MRTK) for Unity are utilized to facilitate interaction with holographic objects through a variety of input states and voice commands. These scripts allow holographic elements to recognize and respond to different interaction states, including far and near interactions. Additionally, visual cues and interaction properties specific to the distance of the user from the object are configured to elicit appropriate responses from the vital panels based on the detected interaction state.

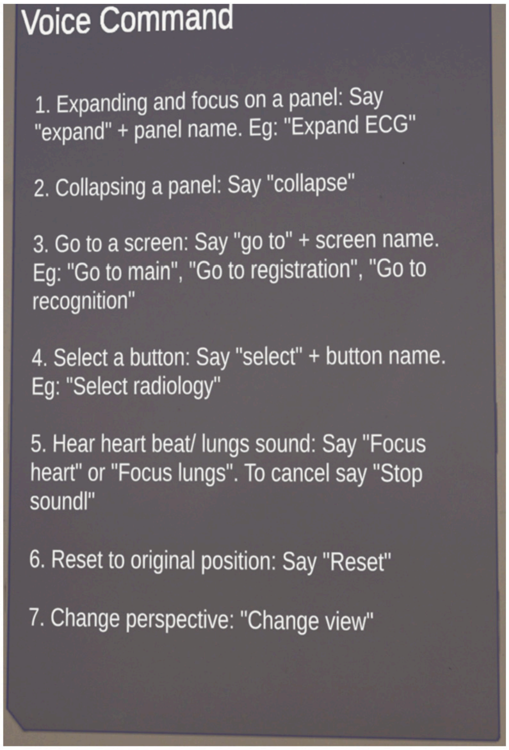

Fig. 17. Voice command tutorial panel.

4.4. Privacy and data protection

Ensuring the security of patient data and maintaining personal confidentiality are paramount in the healthcare domain. The *MiVitals* system employs wireless data communications between the Vitaliti™ and the HoloLens device, necessitating stringent multi-level and multi-faceted security measures at both the device and data communication levels.

Given its portability, ubiquitous internet connectivity, and open communication channels, the HoloLens device is inherently equipped with comprehensive privacy and data protection features [29]. These features encompass network security, operating system (OS) security, physical security, and data protection. The Windows Defender Firewall, integral to network security, remains perpetually enabled on the HoloLens and cannot be disabled [29]. Automatic updates for the HoloLens OS ensure that the device consistently benefits from the latest Microsoft security enhancements. Additionally, enhanced authentication methods, such as PIN-based access, restrict device usage to authorized personnel only. The BitLocker encryption protocol [29], implemented in the device's flash memory, safeguards onboard data.

The Vitaliti™ device adds an additional layer of data security. It is designed to be discoverable and communicable exclusively with trusted devices [14]. It achieves this by maintaining a signature table of trusted devices and authenticating each connection attempt. Moreover, it employs advanced encryption techniques for data transmission over these secure, trusted channels.

In the following section, we present the usability and effectiveness test results of the *MiVitals* system.

5. Usability analysis and findings

5.1. Qualitative survey analysis

Analysis of Part A of the Qualitative Survey revealed significant insights into participant demographics and preferences. The majority (89%) of participants were right-handed. In terms of gender distribution, 68% were female, and 32% were male. Notably, 43% of the respondents had prior experience with AR/VR smart glasses, such as the Microsoft HoloLens, Magic Leap, Quest, or similar devices. A high level of interest in the *MiVitals* HoloLens application was evident, with 97% of participants indicating they were either 'very interested' or 'interested.'

Part B of the Qualitative Survey focused on user experience, and the main findings are detailed in Table 1. Key highlights include the following responses: 95% of participants found the HoloLens device comfortable to use; 95% reported ease in locating and monitoring vital sign information of interest; 97% found it easy to access and monitor ECG, PPG, and other non-vital data; and 97% felt the voice commands were effective.

The following are selected anecdotal comments from the survey, providing insights into participants' experiences and perceptions:

1. *Question 7*: "Excited to see the future of healthcare via technology" *(Participant 2)*, "Very excited to see the future!" *(Participant 13)*, "It is really nice to learn about these new devices like the HoloLens. It is also fun!" *(Participant 29)*.
2. *Question 10*: *Participant 16* found it exceptionally easy to interact with various holographic content panels through voice commands. They noted that the system intuitively, accurately, and swiftly understood and responded to commands such as 'open heart details,' 'expand CT-Scan,' 'collapse lung details.', among other similar voice commands.
3. *Question 11*: "It was my first time trying the HoloLens application. I feel that it would be helpful for future healthcare professionals to easily and intuitively access patient's vital signs." *(Participant 3)*
4. *Question 23*: "Very very exciting technology!" *(Participant 9)* "I think healthcare professionals would enjoy this HoloLens application, for example, for nurses in the future." *(Participant 11)* "Your system will just get better and better as technology improves. I can't wait to see this system in the ward or clinic where it will really have an impact" *(Participant 32)*.

5.2. System Usability Scale (UI/UX) analysis

Quantitative analysis was performed to evaluate our system with the System Usability Scale (SUS) [39]. The SUS odd-numbered items (I1, I3, I5, I7 and I9) express positive statements on the system.[7] In total, 92% of the respondents gave scores of 4 or 5 ("strongly agree" or "agree" with the statement) to items I1, and I5, 78% to I3, 83% to I7 and 94% to I9. Fig. 20 presents positively rated items showing user satisfaction.

The mean SUS score for this group was 84.17 (min = 50, max = 100, $\sigma = 10.80$). The average SUS score from 5,000 studies is 67.5 [40,39]. A one-way ANOVA was performed to determine if there was a difference in the user satisfaction in our *MiVitals* compared to the SUS average. There was a statistically significant difference between the groups at the 0.05 level, $F(1, 70) = 83.333$, $p = 0.001$, showing that the usability of our *MiVitals* system is well above average.

The even-numbered items in the SUS questionnaire (I2, I4, I6, I8 and I10) express negative statements in using the system.[8] Fig. 21 presents the results of the SUS Negatively Rated Items. 67% of the respondents gave scores of 1 or 2 ("strongly disagree" or "disagree") for item I4; 86% or more of the respondents gave scores of 1 or 2 for I2, 83% for I6,

[7] SUS positive rated items: Item I1: "I think that I would like to use this system frequently" Item I3: "I thought the system was easy to use", Item I5: "I found the various functions in this system were well integrated" Item I7 "I would imagine that most people would learn to use this system very quickly" Item I9: "I felt very confident using the system.".

[8] SUS negative rated items: Item I2: "I found the system unnecessarily complex" Item I4: "I think that I would need the support of a technical person to be able to use this system", Item I6: "I thought there was too much inconsistency in this system" Item I8 "I found the system very cumbersome to use" Item I10: "I needed to learn a lot of things before I could get going with this system.".

Fig. 18. User menu of HoloLens dashboard.

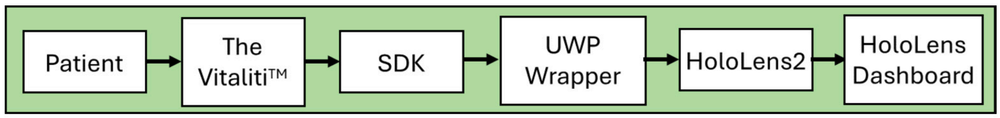

Fig. 19. Vital data flow.

Table 1
User experience survey findings.

Survey Question	"Strongly Agree" or "Agree" with the statement (Likert values of 4 or 5)
How comfortable was it to use the HoloLens device?	95% (35/37 participants)
How easy was it to interact with different contents of the HoloLens display?	70% (26/37 participants)
As a beginner, how easy was it to learn navigating a HoloLens application?	78% (29/37 participants)
Once all the navigation skills have been successfully adapted, how easy would it be to use this HoloLens application?	92% (34/37 participants)
How easy was it to find and monitor the vital sign information that you may be interested in?	95% (35/37 participants)
How easy was it to find and monitor the overall health index score (e.g., HEWS score)?	84% (31/37 participants)
How easy was it to find and monitor the trends of vital sign data?	95% (35/37 participants)
How easy was it to find and monitor the pathological/lab reports?	92% (34/37 participants)
How easy was it to find and monitor the ECG, PPG and other non-vital data?	97% (36/37 participants)
How effective was it to use the voice commands?	97% (36/37 participants)
Did you find everything you wanted on a vital sign monitoring system in this holographic interface?	87% (32/37 participants)
Effort: How hard did you have to work to accomplish what you sought out to find in this system?	84% (31/37 participants) (Likert values 1 or 2)
Frustration: How discouraged, irritated, stressed, or annoyed were you in using this HoloLens Application?	92% (34/37 participants) (Likert values 1 or 2)
Do you think other users would enjoy this HoloLens application?	89% (33/37 participants)

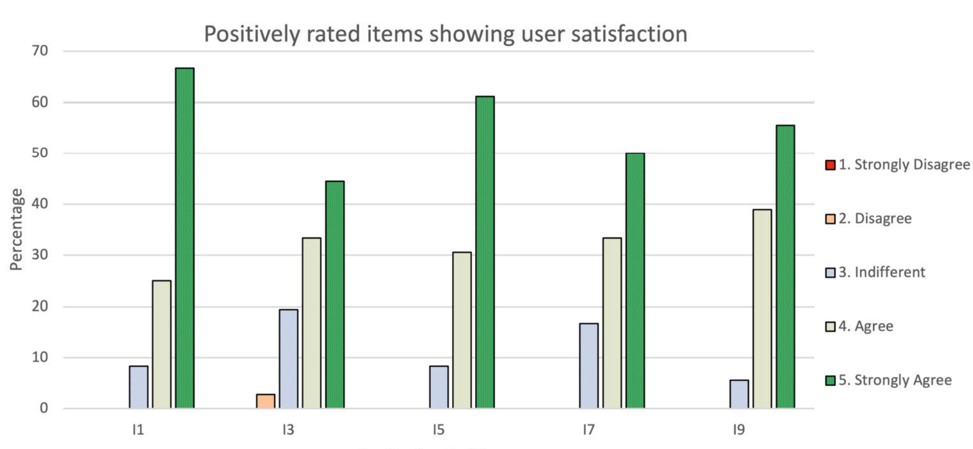

Fig. 20. Positively rated items showing user satisfaction.

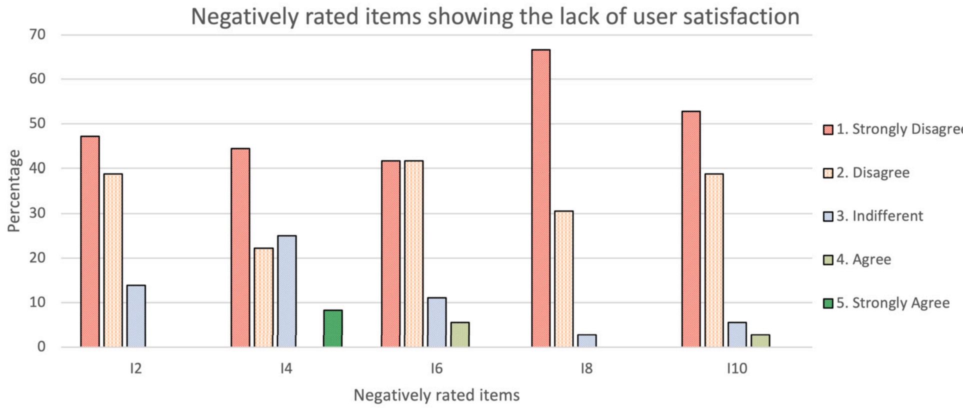

Fig. 21. Negatively rated items showing the lack of user satisfaction.

97% for I8, and 92% for I10. Collectively, these results indicate a high user satisfaction.

5.3. Overall observations and findings

Throughout the usability testing phase, a variety of comments, constructive feedback, and research observation notes were meticulously recorded. Based on the research team's observations of participants' responses to the surveys, the following key findings were identified regarding the ease of use and comfort with the *MiVitals* system:

1. *Comprehensive Use of MiVitals*: Participants successfully utilized all aspects of the *MiVitals* holographic system, aligning well with our design objectives of creating a comprehensive real-time vitals visualization platform. The system effectively supported a diverse range of information panels, alongside novel graphs and visualizations, catering to the needs of healthcare professionals.
2. *Enthusiasm and Eagerness*: A unanimous sense of enthusiasm and eagerness was observed among participants while interacting with *MiVitals*.
3. *Comfort and Ease of Interaction*: All participants reported comfort in using the system, efficiently interacting with the information panels and visualizations to locate necessary information swiftly and effortlessly. This indicates that *MiVitals* is not only effective but also user-friendly, catering to users from a broad spectrum of backgrounds and experiences.
4. *Exceeding User Expectations*: In terms of usability and performance, the proposed system notably exceeded user expectations.

6. Conclusions

In this work, we introduced *MiVitals*, a Mixed Reality system that leverages the Microsoft HoloLens and the biosensor wearable device, *Vitaliti™*. *MiVitals* receives real-time vital signs from the Vitaliti™ device via the SDK and presents these vital signs alongside patient profile information and other physiological data in holographic panels. The system transforms the traditional bedside medical chart into an interactive and visually engaging experience through stunning holographic displays.

Developed in collaboration with medical professionals, *MiVitals* is intended for healthcare professionals monitoring patients in clinical settings. This paper outlined the design, development, and evaluation of *MiVitals*, showcasing several innovative holographic UI/UX features designed to provide clinicians with intuitive and easily interpretable summaries of patient vital signs, enabling rapid decision-making in time-sensitive situations. Additionally, the system offers voice-command interactions with holographic images for hands-free manipulation and includes an early warning score (e.g., HEWS) calculated from the vital signs to aid in identifying clinical deterioration and guiding patient care escalation.

This study conducted a literature analysis of related systems, revealing that *MiVitals* stands out as the only system offering comprehensive mixed reality visualizations for all vital signs, physiological signals, and an early warning score for patient monitoring. Furthermore, the research included the results of a usability study involving medical professionals, which yielded a SUS usability score of 84, indicating high usability for the *MiVitals* system.

6.1. Limitations

Since *MiVitals* is designed for real-time monitoring of vital signs and other health-related information, one may suspect that the communication channel between the wearable device and the HoloLens could be overwhelmed with the volume of data and could compromise the visualization quality. However, it is worth noting that the Vitaliti™ device continuously transmits only vital signs and other physiological data (not including images, video clips, graphs) in a simple text/numeric data format which does not require resource-intensive communication channels. Most high-volume data (e.g., radiology imaging, lab reports, and patient details), which are occasionally updated and accessed, are loaded from the persistent database on-demand. It is important to note that the *MiVitals* system is designed for monitoring patient conditions from close proximity (e.g., on a ward or clinical environment where the distance between patient and clinician is typically much less than 100 m (the maximum range of Bluetooth [45])). With the data transfer capacity (e.g., 2 Mbps or more), and the range of modern Bluetooth technology, the proposed *MiVitals* system is capable of transmitting vitals and other physiological data between the wearable device and the HoloLens in real-time without any data loss [45].

An additional limitation of this work stems from the MS HoloLens wearable itself. While it is truly a novel Mixed Reality device, there are some limitations that were encountered during the design and development phases of the *MiVitals* system. For example, the viewing angle is only 130° [29]. This HoloLens limitation forces the user to move their head side-to-side more than normal to see all holographic visualizations. An additional limitation is the battery lifespan for the HoloLens. Currently, the HoloLens lasts for approximately 2 hours under typical usage of the *MiVitals* application [29]. In real-world environments, this may be a challenge, especially if a clinician was expecting to use it and the HoloLens battery is depleted. However, like all mobile and wearable devices that rely on batteries, this limitation can be mitigated through a charging protocol and backup devices, perhaps positioned at the central nursing station on a ward, so that there is always one available in a 'standby' fully-charged mode.

Lastly, there is a small learning curve for healthcare practitioners to overcome in order to become comfortable using the HoloLens. There are specific HoloLens gestures and interactions that must be learned to interact in the Mixed Reality environment. For example, some time learning how to select and move objects, zoom in and interact with holograms, evoke and discard menus is required to reach a comfortable level of proficiency. Fortunately, most people can acquire these fundamental skills within half an hour of use [29].

6.2. Future work

For future work, we intend to conduct a more robust SUS usability study in a real hospital practice scenario that will involve more participants and fully represent the diverse groups that are the intended audience of *MiVitals*, including medical doctors, registered nurses, and other healthcare professionals.

Other future work activities may include the following:

1. *Cloud-based Data Storage*: One of the significant features of the Vitaliti™ device is that it can automatically stream data to a cloud server as it reads vitals. In the future extensions of our *MiVitals* system, we envision exploiting this feature to better manage the large volume of patient data and offer more functionalities, such as facilitating machine learning-based analyses on vitals.
2. *Privacy and Security*: We also intend to bolster our efforts on security and privacy. Enhancing privacy and security is critical for all healthcare applications [6,22,13]. Our current system uses facial recognition, but future work should explore developing secure methods to ensure that only the correct patient records are accessed by approved clinicians and to ensure data transmitted from the Vitaliti™ to the HoloLens is encrypted.

Declaration of competing interest

The authors claim we do not have any conflicts of interest.

Acknowledgement

We extend our sincere gratitude to Cloud DX and specifically to the R&D Lead, Sara Ross-Howe, for their substantial support and commitment to student mentorship throughout the duration of this project. Furthermore, we are deeply thankful to the Natural Science and Engineering Research Council (NSERC: nserc-crsng.gc.ca) for the funding for this research (Grant Number: CCI-06227), which has been instrumental in our endeavors.

Appendix A

MiVitals HoloLens System – Usability Study

This questionnaire is used to collect each participant's comments regarding the *MiVitals* system.

Name of the Participant: (please print): ______________________

User Experience Questionnaire

Part A. General Participant Information and Background

1. What is your age group?

(a) 17 – 25
(b) 26 – 40
(c) 41 – 55
(d) 56 – 70
(e) 71+
(f) Prefer not to answer

2. Are you left or right handed?

(a) Right
(b) Left
(c) Prefer not to answer

3. How do you describe your gender?

(a) Female
(b) Male
(c) Other
(d) Prefer not to answer

4. What is your profession sector? (please select multiple, if appropriate)

(a) Student
(b) IT professionals (e.g., faculty, researchers, software developer, project manager etc.)
(c) Healthcare/patient care professionals (e.g., physician, nurse, physiotherapist, psw, etc.)
(d) Administration/office management (e.g., office staff, etc.)
(e) Healthcare application development (e.g., software designer/developer, specialized healthcare device designer/developer/user/regulator/project member, etc.)
(f) Other, please specify: ______________________

5. How often to do use electronic devices (e.g., smartphones, laptops, etc.)?

(a) Often – several times a day
(b) A couple times a day
(c) A couple times a week
(d) Occasionally
(e) Never

6. Have you ever used any augmented/virtual reality glasses i.e., Smart Glasses (e.g., Microsoft HoloLens, Magic Leap One, Oculus Quest 2, Google glass, Lenovo Star Wars, etc.)?

(a) Yes
(b) No

If Yes, how often did you use the smart glasses?

(a) Often – several times a day
(b) A couple times a day
(c) A couple times a week
(d) Occasionally
(e) Only a few times

If Yes, what was the primary reason for using the smart glasses (please select multiple, if appropriate)?

(a) Research and development (e.g., developing AR/VR applications)
(b) Testing AR/VR applications/demonstration
(c) Trying out AR/VR application for usability study/feedback/experiencing the application
(d) Using AR/VR applications for study (e.g., course work)
(e) Using AR/VR applications for profession (e.g., engineering, teaching, healthcare, etc.)
(f) Other (please specify)

7. How interested were you in using the *MiVitals* HoloLens application? (please circle)

Not interested Very interested
1 2 3 4 5

Please share any additional comments (if any): __________

Part B. Adaptation and Use

8. Do you use (prescription) glasses?

(a) Yes
(b) No

9. How comfortable was it to use the HoloLens2 device?

(a) Comfortable without any issue
(b) Somewhat comfortable
(c) Difficult to use
(d) Difficult to fit on top of my glasses

10. How easy was it to interact with different contents of the HoloLens2 display?
Very hard Very easy
1 2 3 4 5
Please share any additional comments (if any):______________

11. As a beginner, how easy was it to learn navigating a HoloLens2 application?
Very hard Very easy
1 2 3 4 5
Please share any additional comments (if any):______________

12. Once all the navigation skills have been successfully adapted, how easy would it be to use this HoloLens2 application?
Very hard Very easy
1 2 3 4 5
Please share any additional comments (if any): ______________

13. Which feature(s) of this HoloLens2 application you like the most (please select multiple, if appropriate)?

(a) Navigation
(b) Hand tracking
(c) Voice command
(d) Interface design and layout
(e) Interactions with components (e.g., zooming, relocating, collapsing, expanding, etc.)
(f) Other, please specify ______________

14. How easy was it to find and monitor the vital sign information that you may be interested in?
Very hard Very easy
1 2 3 4 5

15. How easy was it to find and monitor the overall health index score (e.g., HEWS score)?
Very hard Very easy
1 2 3 4 5

16. How easy was it to find and monitor the trends of vital sign data?
Very hard Very easy
1 2 3 4 5

17. How easy was it to find and monitor the pathological/lab reports?
Very hard Very easy
1 2 3 4 5

18. How easy was it to find and monitor the ECG, PPG and other non-vital data?
Very hard Very easy
1 2 3 4 5

19. How effective was it to use the voice commands?
Very hard Very easy
1 2 3 4 5

20. Did you find everything you wanted on a vital sign monitoring in this holographic interface?
Not at all Yes, everything
1 2 3 4 5
If not, what was missing? ______________

21. Effort—How hard did you have to work to accomplish what you sought out to find in this HoloLens2 application?
Worked very hard Very little work involved
1 2 3 4 5
Please share any additional comments (if any):______________

22. Frustration —How discouraged, irritated, stressed, or annoyed were you in using this HoloLens2 application?
Very high Very low
1 2 3 4 5
Please share any additional comments (if any): ______________

23. Do you think other users would enjoy this HoloLens2 application?
No, not at all Yes, very much
1 2 3 4 5
Please share any additional comments (if any): ______________

24. Please share any additional comments regarding this study (if any):______________

Thank you for completing this survey.

Part C. System Usability Scale Survey

Q1. I think that I would like to use this system frequently
Strongly disagree Strongly agree
1 2 3 4 5

Q2. I found the system unnecessarily complex

Strongly disagree Strongly agree
1 2 3 4 5

Q3. I thought the system was easy to use
Strongly disagree Strongly agree
1 2 3 4 5

Q4. I think that I would need the support of a technical person to be able to use this system
Strongly disagree Strongly agree
1 2 3 4 5

Q5. I found the various functions in this system were well integrated
Strongly disagree Strongly agree
1 2 3 4 5

Q6. I thought there was too much inconsistency in this system
Strongly disagree Strongly agree
1 2 3 4 5

Q7. I would imagine that most people would learn to use this system very quickly

Strongly disagree				Strongly agree
1	2	3	4	5

Q8. I found the system very cumbersome to use

Strongly disagree				Strongly agree
1	2	3	4	5

Q9. I felt very confident using the system

Strongly disagree				Strongly agree
1	2	3	4	5

Q10. I needed to learn a lot of things before I could get going with this system

Strongly disagree				Strongly agree
1	2	3	4	5

References

[1] Khanam F-T-Z, Al-Naji A, Chahl J. Remote monitoring of vital signs in diverse non-clinical and clinical scenarios using computer vision systems: a review. Appl Sci 2019;9.
[2] Weenk M, Bredie SJ, Koeneman M, Hesselink G, Goor Hv, Belt THvd. Continuous monitoring of vital signs in the general ward using wearable devices: randomized controlled trial. J Med Internet Res 2020;22.
[3] Calzavacca P, Licari E, Tee A, Downey A, Egi M, Quach J, et al. The impact of rapid response system on delayed emergency team activation patient characteristics and outcomes—a follow-up study. Resuscitation 2010 2010;81:31–5.
[4] Beckett DJ, Gordon C, Paterson R, Chalkley S, Macleod D, Bell D. Assessment of clinical risk in the out of hours hospital prior to the introduction of hospital at night. Acute Med 2009;8:33–8.
[5] Zhao F, Li M, Qian Y, Tsien JZ. Remote measurements of heart and respiration rates for telemedicine. PLoS ONE 2013;8.
[6] Choi A, Chung K, Chung SP, Lee K, Hyun H, Kim JH. Advantage of vital sign monitoring using a wireless wearable device for predicting septic shock in febrile patients in the emergency department: a machine learning-based analysis. Sensors 2022;22.
[7] Rouast PV, Adam MTP, Chiong R, Cornforth D, Lux E. Remote heart rate measurement using low-cost RGB face video: a technical literature review. Front Comput Sci 2018;12:858–72.
[8] Soon S, Svavarsdottir H, Downey C, Jayne DG. Wearable devices for remote vital signs monitoring in the outpatient setting: an overview of the field. BMJ Innov 2020;6:55–71.
[9] Vitalconnect. Available from: https://vitalconnect.com/remote-patient-monitoring/. [Accessed 10 February 2023]; 2023.
[10] Spry health. Available from: https://sprypt.com/. [Accessed 10 February 2023]; 2023.
[11] Vandrico inc. Available from: https://vandrico.com/wearables/device/eq02-lifemonitor.html. [Accessed 10 February 2023]; 2023.
[12] Sotera digital health. Available from: https://soteradigitalhealth.com/, 2023.
[13] Haveman ME, v. Melzen R, Schuurmann RCL, Moumni ME, Hermens HJ, Tabak M, et al. Continuous monitoring of vital signs with the everion biosensor on the surgical ward: a clinical validation study. Expert Review of Medical Devices 2022;18:145–52.
[14] Vitaliti – a revolutionary continuous patient monitoring device for ambulatory care. [Accessed: 2023-02-10]; 2023.
[15] Cloud DX. Available from: https://www.clouddx.com/. [Accessed 10 February 2023]; 2023.
[16] Besher KM, Subah Z, Ali MZ. Iot sensor initiated healthcare data security. IEEE Sens J 2021;21(10):11977–82.
[17] Besher KM, Beitelspacher S, Nieto-Hipolito JI, Ali MZ. Sensor initiated healthcare packet priority in congested IoT networks. IEEE Sens J 2021;21(10):11704–11.
[18] Mourtzis D, Siatras V, Zogopoulos V. Augmented reality visualization of production scheduling and monitoring. Proc CIRP 2020;88:151–6.
[19] Teng C-C, Redfearn B, Nuttall C, Jarvis S, Carr J, Jensen J. Mixed reality patients monitoring application for critical care nurses. In: ICMHI 2019; 2019. p. 49–53.
[20] Klinker K, Wiesche M, Krcmar H. Digital transformation in health care: augmented reality for hands-free service innovation. Inf Syst Front 2020;22:1419–31.
[21] Wu M-L, Chien J-C, Wu C-T, Lee J-D. An augmented reality system using improved-iterative closest point algorithm for on-patient medical image visualization. Sensors 2018;18:2505–11.
[22] Park S, Bokijonov S, Choi Y. Review of Microsoft HoloLens applications over the past five years. Appl Sci 2021;11:7259–67.
[23] Jiang T, Yu D, Wang Y, Zan T, Wang S, Li Q. HoloLens-based vascular localization system: precision evaluation study with a three-dimensional printed model. J Med Internet Res 2020;22:16852–60.
[24] Hanna MG, Ahmed I, Nine J, Prajapati S, Pantanowitz L. Augmented reality technology using Microsoft HoloLens in anatomic pathology. Arch Pathol Lab Med 2018;142.
[25] Kuhlemann I, Kleemann M, Jauer P, Schweikard A, Ernst F. Towards X-ray free endovascular interventions–using HoloLens for on-line holographic visualisation. Healthc Technol Lett 2017;4:184–7.
[26] Kumar RP, Pelanis E, Bugge R, Palomar R, Brun H, Aghayan DL, et al. Use of mixed reality for surgery planning: assessment and development workflow. J Biomed Inform 2020;112.
[27] Mojica CMM, Navkar NV, Tsekos NV, Tsagkaris D, Webb A, Birbilis T, et al. Holographic interface for three-dimensional visualization of MRI on HoloLens: a prototype platform for MRI guided neurosurgeries. In: IEEE 17th international conference on bioinformatics and bioengineering (BIBE); 2017. p. 21–7.
[28] Traub J, Sielhorst T, Heining S, Navab N. Advanced display and visualization concepts for image guided surgery. J Disp Technol 2008;4:483–90.
[29] Microsoft. Microsoft HoloLens 2. Available from: https://www.microsoft.com/en-us/hololens. [Accessed 10 February 2023]; 2023.
[30] Xu B, Liu D, Xue M, Miao M, Hu C, Song A. Continuous shared control of a mobile robot with brain–computer interface and autonomous navigation for daily assistance. Comput Struct Biotechnol J 2023:3–16.
[31] McGillion MH, Dvirnik N, Yang S, Belley-Côté E, Lamy A, Whitlock R, et al. Continuous noninvasive remote automated blood pressure monitoring with novel wearable technology: a preliminary validation study. JMIR mHealth uHealth 2022;10.
[32] Hodzhev Y, Tsafarova B, Tolchkov V, Youroukova V, Ivanova S, Kostadinov D, et al. Visualization of the individual blood microbiome to study the etiology of sarcoidosis. Comput Struct Biotechnol J 2023:50–7.
[33] Thalor A, Joon HK, Singh G, Roy S, Gupta D. Machine learning assisted analysis of breast cancer gene expression profiles reveals novel potential prognostic biomarkers for triple-negative breast cancer. Comput Struct Biotechnol J 2022:1618–31.
[34] Chien J-C, Tsai Y-R, Wu C-T, Lee J-D. HoloLens-based ar system with a robust point set registration algorithm. Sensors 2019;19:3555–65.
[35] XPRIZE Bold Epic Innovator Award. Available from: https://www.xprize.org/prizes/tricorder/teams/clouddx. [Accessed 10 February 2023]; 2023.
[36] Smith MEB, Chiovaro J, O'Neil M, Kansagara D, Quinones A, Freeman M, et al. Early warning system scores: a systematic review. Berlin: Springer; 2014.
[37] Skitch S, Tam B, Xu M, McInnis L, Vu A, Fox-Robichaud A. Examining the utility of the Hamilton early warning scores (HEWS) at triage: retrospective pilot study in a Canadian emergency department. CJEM 2018;20(2):266–74.
[38] Fernando SM, Fox-Robichaud AE, Rochwerg B, Cardinal P, Seely AJE, Perry JJ, et al. Prognostic accuracy of the Hamilton Early Warning Score (HEWS) and the National Early Warning Score 2 (NEWS2) among hospitalized patients assessed by a rapid response team. Crit Care 2019;23:60.
[39] Brooke J. SUS: a retrospective. J Usability Stud. 2013;8(2):29–40. System Usability Scale.
[40] Brooke J. SUS: a "quick and dirty" usability scale. Usability evaluation in industry. London: Taylor and Francis; 1996. System Usability Scale.
[41] Edison awards. https://edisonawards.com/winners2021.php. [Accessed 10 February 2023]; 2021.
[42] Clinicaltrials.gov. https://clinicaltrials.gov/ct2/show/NCT03493867. [Accessed 10 February 2023]; 2023.
[43] Microsoft azure. Available from: https://azure.microsoft.com/en-ca/free/cognitive-services/search/. [Accessed 10 February 2023]; 2023.
[44] Unity technologies. Available from: https://unity.com/. [Accessed 10 February 2023]; 2023.
[45] Bluetooth. Bluetooth specifications and documents. Available from: https://www.bluetooth.com/specifications/specs/. [Accessed 4 February 2024]; 2024.