Solar Energy Systems Design in 2D and 3D: A Comparison of User Vital Signs

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***Abstract*—Current solar energy systems design methods mainly rely on experts developing designs on 2D flat screens using outdated CAD models. Immersive 3D design methods may democratise the design process, such that systems can be designed quickly and accurately. Therefore, in this manuscript we measure user engagement or stress levels in both a 2D and 3D immersive virtual reality environment during a solar energy systems design task. User engagement was measured by estimating a user's vital signs using a non-invasive FMCW radar. In our pilot study, four participants tried a 2D and 3D interface while their vital signs were being monitored. According to participant feedback from self-reported questionnaires, our results clearly indicate that the 3D virtual reality offers higher user engagement. These findings could have a tremendous impact on the way we develop renewable energy systems of the future.**

***Index Terms*—Immersive virtual reality, vital signs, FMCW radar, Engagement level.**

I. Introduction

Virtual and augmented reality technology is a rapidly developing technology used in various industries, including gaming, education, entertainment, medicine, the military, sports, and more [1]. The first report on virtual reality as a tool for simulation dates back to the 1960s [2]. Since then, creating various 3D immersive forms rather than 2D computer screens has been widespread. These technologies intend to facilitate new user experience and go beyond what is possible with 2D displays. Since physiological monitoring technologies have advanced so quickly, it is now possible to apply several biofeedback modalities and investigate how they may impact user experience. Numerous empirical studies have presented evidence that creating an immersive virtual environment for users by collecting biofeedback can help provide a better emotional state and behaviour for users [3]–[5].

The sense of presence in the virtual environment, engagement and immersive level is highly correlated with the change in heart rate and skin reaction. For instance, Felnhofer *et al* in [6], established a study where electrodermal activity was recorded that the feeling of presence is related to emotional reactions. McNeal *et al* in [7], also monitored the engagement level of students using a skin biosensor called galvanic skin response (GSR).

Our experiment was conducted to compare the level of user engagement during the design of a solar energy system using a 2D simulations application with an immersive virtual reality (VR) environment via two biosensors: Frequency Modulated Continous Wave (FMCW) radar [8] and a medical grade belt [9]. Moreover, self-reported perceptions were collected to confirm the relations between the collected data.

We chose the solar energy systems design field since we believe that tackling some of the world's toughest climate change problems requires a paradigm shift in the way these systems are designed. Current design methods rely on experts developing solutions on 2D flat screens using traditional CAD models [10], [11]. Moreover, these designs are often developed hundreds or even thousands of miles away from the actual site or community, leading to low levels of user engagement with the project. Therefore, we hypothesize that a 3D virtual world environment will lead to higher engagement than a 2D computer screen application.

This paper is organized as follows: Section II provides an overview and explanation of the experimental setup with the process of data collection. In Section III, we discuss the data processing of the radar. Results are discussed in section IV and finally, we highlight the future research directions and conclusion in Section V.

II. Experimental Design

A. VR application

This project aims to mimic 2D software in designing a solar energy system in an immersive environment where users can interact with the system components and feel more engaged with the virtual environment. To visualize the application, we used Oculus Quest 2 headset. The application uses Quest 2 hand tracking to interact with the 3D objects, which are solar energy components. This system can recognise hands well even if they are partially hidden or moving swiftly and detects the most important gestures. This feature was used to make the application interactions more realistic. The application also uses the Oculus XR Plugin package for all of Oculus's features. The VR application was developed using the Unity3D game engine and blender software for modelling some components like the solar panel stands. Scripts using the C# programming language were used to control the behaviour of the game objects in Visual Studio within the game engine. Unity store was also utilised for getting some assets for the application.

The application consists of four scenes: the earth, house, power room and roof. In the earth scene, the opening scene of the app, users choose the location on the map then the location's details will appear, such as latitude, longitude, elevation and standard outdoor temperature. The scene will then be changed to a house where users have to design and

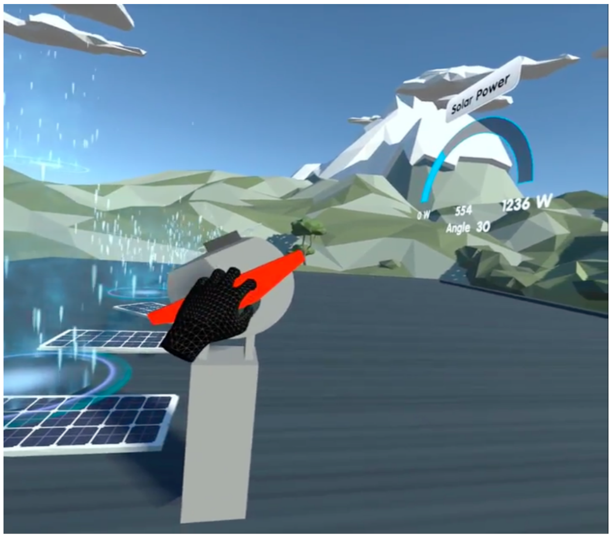

Fig. 1: Image showing a user installing solar panels in a 3D environment.

install the components of the solar energy system. The system presents in the application is an off-grid system that contains a battery, inverter, charge controller and solar panels. In the application, users can enter a power room to pick up the objects and place them in the necessary positions.

Once the user picks up the component, the app shows where the component has to be placed. Next, users can click on the up arrow to go to the house roof, then grab and place the solar panels to generate electricity. Each panel placed will give a voltage depending on the stand's angle. However, the voltage will be visible in the voltage bar once all the components are placed in the power room. A gauge chart appears after installing all the system components and shows the electricity generated with this system. Users can add and remove the solar panels and change the tilt of the panels by changing the stand angle using the stand's handle - Fig. 1.

In this process, users can notice how the solar panels' number and tilt affect the generated electricity in a fully immersive environment.

B. Radar Sensor Overview

To carry out the experiment and implement the vital signs, the FMCW radar IWR6843AOPEVM from Texas Instruments [12] was used, with the Icboost carrier. This is a so-called mm-wave radar, whose wavelengths are in the order of millimetres (microwave frequency region). The IWR6843AOPEVM is a (PCB, Antenna on Package) MIMO radar chip with a FMCW transceiver consisting of 4 integrated receivers and 3 transmitters, all being patch antennas with 120° Field of View (FoV).

It operates by transmitting a sawtooth FM waveform, using Time Division Multiplexing (TDM) or Binary Phase Modulation to obtain orthogonality between transmitted signals. For the Local Oscillator (LO) signal and coherence, the chip uses a 40 MHz crystal oscillator, with a phase noise of -92 dBc/Hz at 1 MHz offset. This signal is synthesized to produce an FM chirp ranging from 60 to 64 GHz. The communication with the radar was carried out between the Universal Asynchronous Receiver Transmitter (UART) and USB interfaces through serial communication.

C. Radar Configuration for Experiment

The Table. I, shows the final configuration for radar using to measure the vital sign during engagment level.

TABLE I: Parameter setting for vital sign estimation

S. No	Parameter	Value	Unit
1	No. of Tx	2	-
2	No. of Rx	4	-
3	Center Frequency	60	GHz
4	Bandwidth	2	GHz
5	Sampling Rate	10	Msps
6	ADC Samples/chirp	256	-

D. Data Collection

A total of 4 postgraduate students from the University of Glasgow volunteered to participate in our pilot study. Brief instructions were given to participants on how to complete the application, which took around 5 minutes. Our experiment was conducted in a quiet lab where we ensured enough area to move freely in the VR application. In the beginning, participants had to wear the medical grade belt, and then the radar was directed toward them at a distance of 50cm. Afterwards, participants designed and built a solar energy system using a 2D application. Participants were provided with a document explaining the steps and instructions they should follow. Building the solar energy system depended on dragging and dropping the system components. After collecting the vital signs from participants, they were directed to try the 3D virtual reality application to build the solar energy system. Participants were still wearing the medical grade belt and facing the radar from a one-meter distance to monitor their vital signs while interacting with the virtual environment. Fig. 2, demonstrates the experiment setup for 2D application and 3D immersive virtual reality. To evaluate the engagement level and students' experience with the two different interfaces, participants were invited to complete an online self-reported questionnaire containing eight questions. Before gathering data, participants received consent forms. Students who participated in the study were told that their participation would not influence their grades and that any information they gave would be kept anonymous and private.

Regarding to vital signs, raw-ADC data was collected from radar using another device, the Texas Instruments DCA1000. This configuration enables real-time data capture for up to ten seconds, which is then sent to the PC over LVDS (low-voltage differential signalling) lines at a high data rate of 600Mbps. ADC samples were obtained from participants in various scenarios of virtual reality environments and saved in a separate file. As a result of the preceding process, a .bin file containing the raw ADC data is generated. This raw data is then post-processed on a host PC using the MATLAB signal processing method.

Fig. 2: Overall system architecture in (a) 2D application and (b) 3D virtual reality environment with vital sign estimation.

E. Radar Signal Processing

As shown in Fig. 3, the signal processing chain for FMCW radar. The beat signal is the combination of the transmitter and receiver mixed signal. A DSP and an ARM processor are integrated inside the radar for post-processing. The Radar data is stored in a .bin file and converted to a.csv file using MATLAB programming. We can extract the breathing signal and heartbeat signal from the raw data using a Bandpass filter with a cutoff frequency of 0.16 to 0.4 Hz for breathing and 0.8 to 4 Hz for estimating heart rate. As shown in Fig. 4 and 5, the filtered data for breathing and heart rate with significant variations due to engagement level.

After filtering the raw data, the Fast Fourier Transform (FFT) technique is used to generate the peaks spectrum. The FFT method provides a frequency domain vital sign estimation. The peak detection technique was employed to estimate both the breathing rate (breaths/min) and the heart rate (beats/min) in time domain as well.

Fig. 3: Signal processing chain of radar signal.

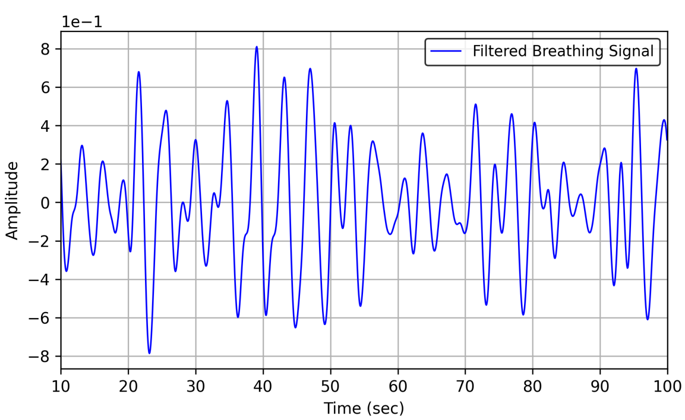

Fig. 4: Breathing signal measurement during engagement level.

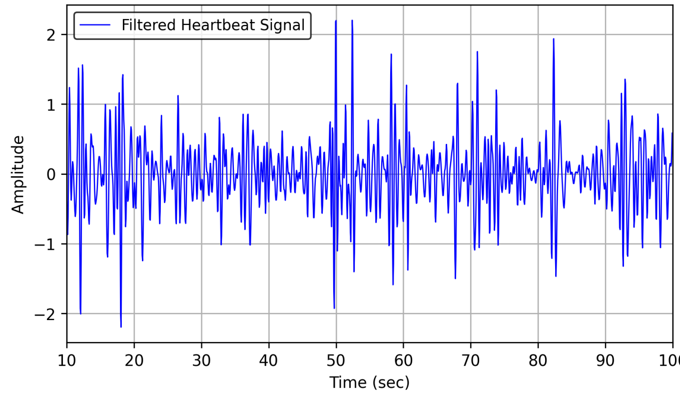

Fig. 5: Heartbeat signal measurement during engagement level.

III. Results and Discussion

The study investigated the amount of engagement of users with two different interfaces. The first interface was a 2D application that operated on a laptop, while the second was a 3D VR-based application. The user was instructed to sit firmly when using the 2D interface, and radar was utilised to estimate vital signs at a distance of 50cm away from the radar user.

A. Questionnaire

Participants completed a self-reported questionnaire that measured their engagement level and application preference. The majority of the participants, 75%, already had experience with virtual reality. Interestingly, on a scale from 1 to 5, with five being the highest, all the participants rated their VR experience as having the highest rate of excitement. Moreover, when asking the participants whether they felt engaged, 50% mentioned that they strongly agreed while 50% agreed.

The participants rated 4.5 out of 5 when asked how much engagement they found in the VR application and the feeling of real interaction during the virtual environment. All participants selected the 3D virtual reality application as it is more engaging than the 2D application. In addition, all the participants recommended VR applications for designing solar energy systems rather than 2D applications. None of the participants experiences any symptoms like nausea, dizziness, double vision, etc., while using the VR application.

B. Vital Sign Estimation

The breathing rate from the radar FFT approach was shown in Fig. 6, and the results are validated with a medical-grade respiration belt. As can be observed, the breathing signals vary as the user becomes more immersed in the 3D VR experience.

The same is evident for the user's heartbeat signal, as shown in Fig. 7, which shows the difference in the signature between highly engaged and moderate engaged participants during the 3D virtual reality application..

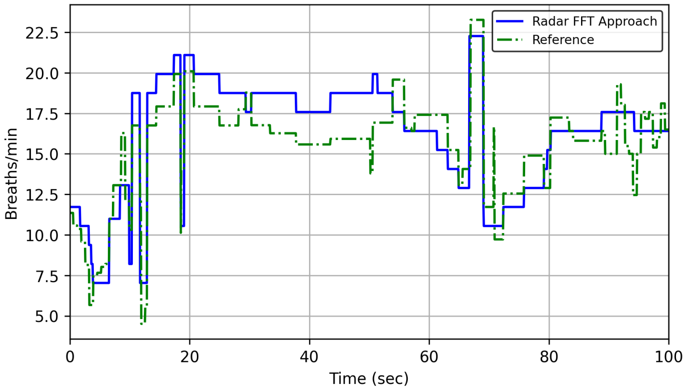

Fig. 6: Comparison of Radar with Reference Sensor for Breathing Rate

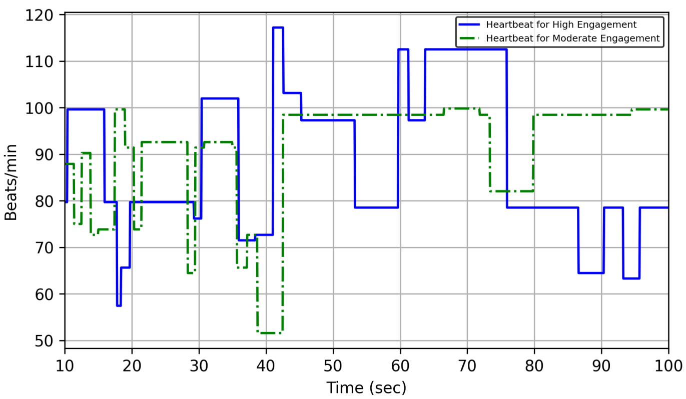

Fig. 7: Heartbeat From Two Participant Engagement Level During 3D Virtual Reality

C. Validation

The user was then invited to wear the VR for the 3D interface, and the same radar was employed to assess the vital sign to determine the user's interest level. In all scenarios, we use a medical-grade breathing belt to validate the radar data. The findings from various participants are shown in the Table II. These data are from the 3D VR environment, which reveals different breathing and heart rate variations as users become more involved. Based on our results, both participants were engaged in 2D and 3D interfaces, however, 3D was shown to be more engaged than the other.

TABLE II: Vital signs and the engagement level, from the self-report questionnaire, for each participant while using 3D virtual reality application

Participant	**HR**	**BR**	**Ref**	**Engagement level (out of 5)**
1	82.90	16.5	17.2	4
2	117.1	22.4	23	5
3	99.8	19	19.8	4
4	102.6	21.7	20.6	5

IV. Conclusions

This study investigated participant engagement and behaviour in two visual modules, a 2D application and a 3D immersive virtual reality application for a solar energy system design task. To do this, we developed a virtual reality application that mimics a 2D application. Next, we monitored the participant's vital signs while using both applications. The data was collected from participants using a non-invasive FMCW radar for estimating the vital signs and from a self-reported questionnaire. We found that participants enjoyed the immersive experience. Moreover, our results indicated that the virtual reality application offers greater engagement and immersion than a 2D application. The future aim of this work is to include eye-tracking technology to compare 2D and 3D interfaces. The eye-tracking technology may help us better understand how people navigate around an application, what they look at and how their attention is drawn to different design interfaces we make.

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