# UNOBTRUSIVE RADAR SYSTEM FOR MONITORING HEART ACTIVITY IN ASSISTIVE LIVING ENVIRONMETNS

## PhD Industrial Project

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## Abstract

In this report we present the scope, current progress and future actions of the industrial project taken in collaboration with Kosnic ltd. and the department of computer Science at The University of Reading. We focus on the development of an unobtrusive ultra-wideband radar system for the task of measuring heart and respiratory activity using various signal processing and machine learning tools.

## Initial project objectives

The primary aims for year one of this PhD industrial project was to investigate the hardware capabilities for the purpose of measuring heart activity using the radar device provided by the industrial Partner. There was also an emphasis on identifying a databank for ECG signals to be used for the development of the final device. The extension on the objectives includes collecting a novel dataset of ECG recordings using Ultra-Wideband radar (UWB) technologies and pairing these with readings recorded using a clinical device, such that the dataset can be applied to machine learning algorithms to classify heart activity. In addition, there remains the task of optimising the current hardware using available tools or digital enhancement.

To summarise the initial tasks set out, the following list encapsulates the objectives:

- Investigate hardware capabilities for heart activity detection.
- Identify a databank to test machine learning algorithms prior to practical application.
- Collect a novel dataset of ECG signals recorded using the radar module.
- Infer breathing activity from either ECG data specific measurements.
- Find ways of optimising the current hardware to improve measurement performance.

## Extended objectives

Furthermore, the task of separating the heart activity measurements of two or more people from a radar measurement is to be an extension of the work carried out in this project. This is a task of blind source separation in which signals from different sources are to be extracted from a single waveform carrying information. Another extension initial objective is to classify heart activity that may be indicators of a health hazard occurring. Expectantly leading to a developed model capable of recognising heart and respiratory activity using unobtrusive radar module and machine learning algorithms on embedded hardware

## CNN Based Filter Selection

We focus our initial attempts at optimising the hardware for improved classification of measured signals using machine learning algorithms. Measurements made using sub-optimal radar devices often carry with them large amounts of noise disturbances which may affect any following analysis of the underlying signals. This is particularly detrimental to the overall ability of a classification algorithm to generalise data. Signal measurements from UWB radar system contain noise from various sources when conducted within an indoor environment. Adaptive signal filtering methods exist; however, these techniques are still often unable to remove sufficient disturbances from the objective signals and thus are labelled an under-filtering the signal, or in certain situations, may remove important features from the raw data and are over-filtering the data at hand.

Both over and under filtering of raw signals may be detrimental to any future analysis we may carry out on the signals. There is a need of identifying a method of finding the optimum noise removal method. We develop a digital signal processing (DSP) method for effectively analysing windowed waveforms of ECG signals using convolutional neural networks (CNN). In this work we utilize CNN architectures to classify the optimum filtering method, between the wavelet filtering method and elliptical filtering method, for a given noisy waveform.

The proposed model functionality is as seen in Figure 1. The deep learning model is used to 1) window a continuous noisy signal, 2) identify the optimum signal denoising filter and 3) apply the filter to the noisy windowed signal, resulting in a denoised waveform.

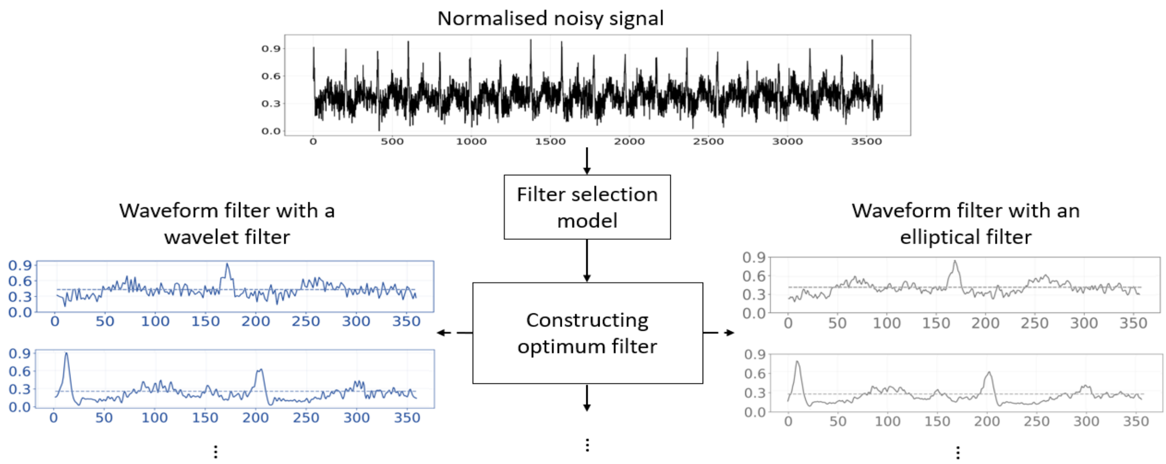


Figure 1. Showing the proposed model functionality for a noisy full-length signal being used as an input for a filter selection model followed by an optimum filter. Shown on the left side in blue is the waveform filtered using an optimum wavelet filter and show on the right side is the waveform filtered using an elliptical filter.

The dataset used within the experimentations was the MIT – Beth Israel Hospital (MIT-BIH) normal sinus rhythm (NSR) ECG dataset. The full dataset contained 360 full-length signals of length 3600 datapoints, which were subsequently formatted into 3600 signals with length 360. The windowed signals were then used to both test and train the developed CNN model. An illustration of the developed model can be found in Figure 4. The CNN model achieved a test set accuracy of 92.8%.

The full architecture of the proposed system can be seen from Figure 2 and further explained by Figure 3 and Figure 4.

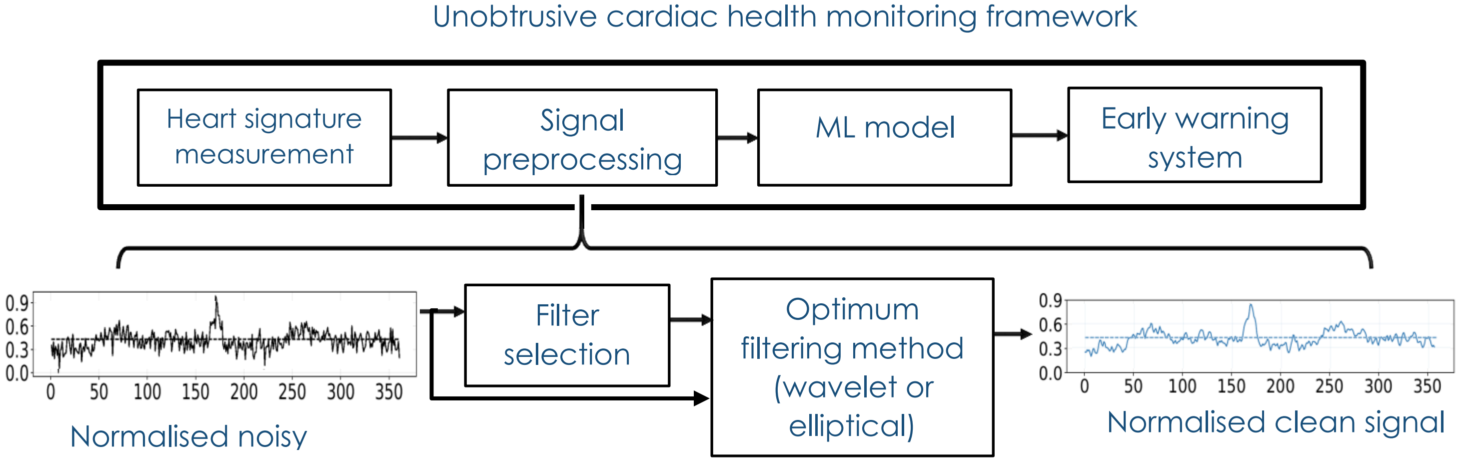


Figure 2. The Unobtrusive cardiac health monitoring framework is shown with higher level process blocks. We focus our attention on the signal preprocessing stage particularly and aim to utilise the power of deep architectures to automate the task of preprocessing noisy signals.

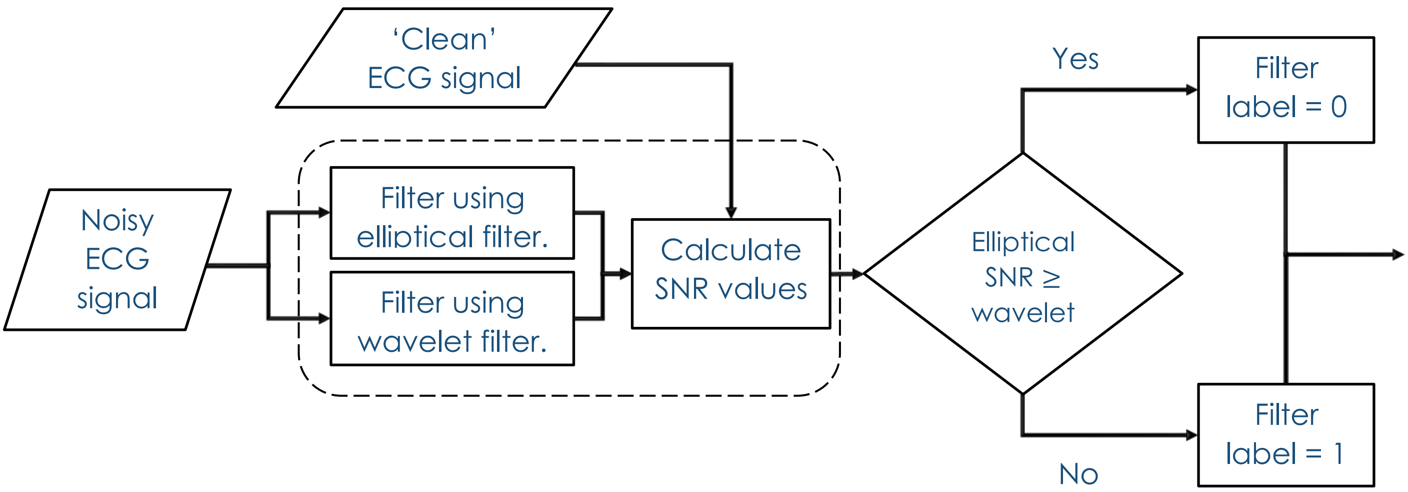


Figure 3. The filter selection block from Figure 2 is expanded to show its internal processes. The figure shown here is the labelling algorithm that identifies the optimum filter label for a given noisy waveform. The labels are then used to train the CNN model used for predicting the optimal denoising signal processing filter.

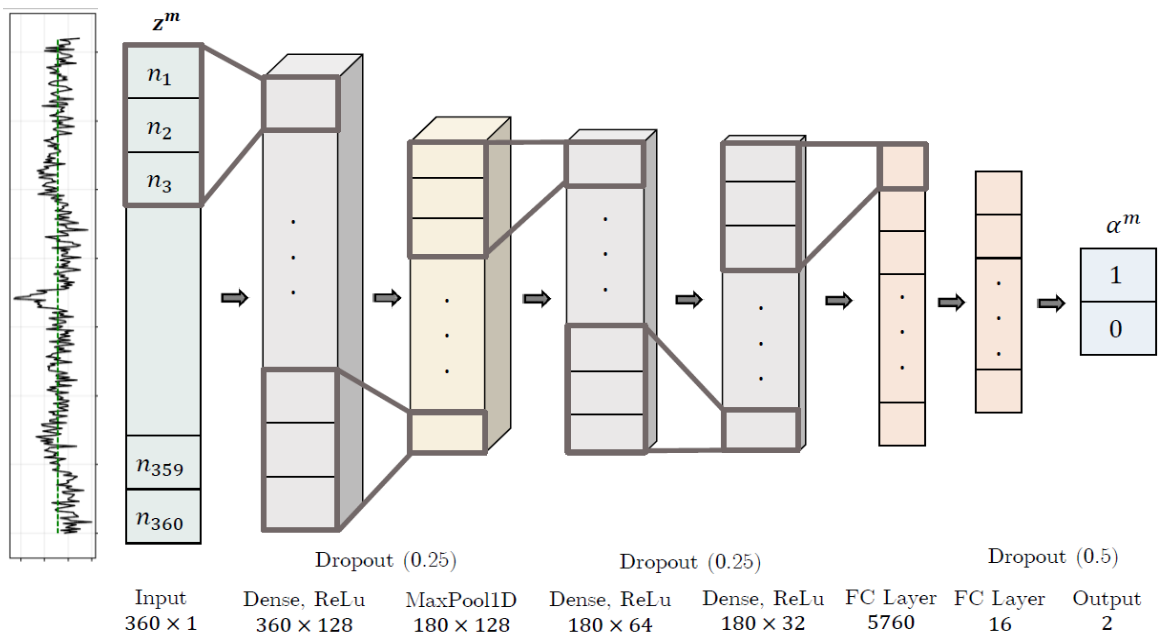


Figure 4. The CNN was configured with the following parameters in sequential order: a 128 dense layer, a maximum pooling layer with pooling size of 2, a 64 dense layer, a 32 dense layer and a 16 dense layer, all using ReLu activation functions. Represented by $z^m$ is the noisy waveform to be classified and given by $a^m$ is the identified optimum filtering label. A unit dropout rate of 25% was used after the 128 dense layer and 64 dense layer, followed by a 50% rate after the flattened 16 dense layer, this was applied in order to avoid overfitting. A stochastic gradient decent (SGD) optimizer using back propagation was used for the learning method and the model was trained for 20 epochs

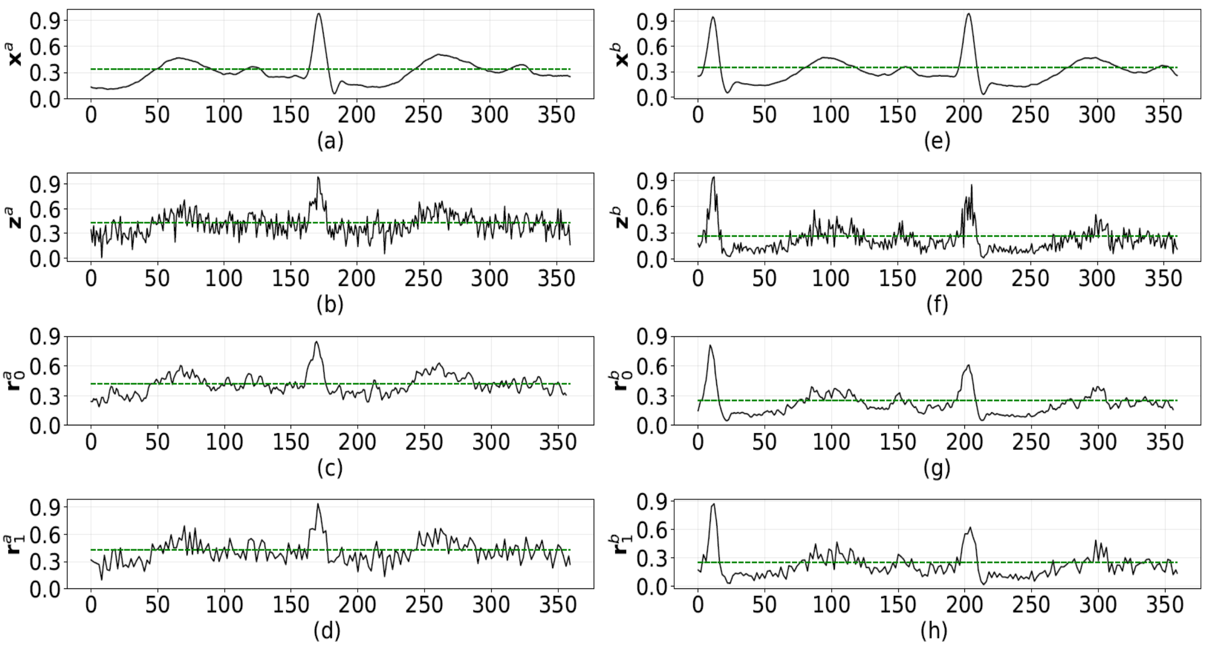


Figure 5. Showing two different clean signals a) and e) with the respective signals applied with additive white gaussian noise shown by b) and f) respectively. The filtered signals c), g) and d), h) are the wavelet and elliptical filtered signals for clean a) and e) respectively.

The processes explained in Figures 2, 3 and 4 show how deep neural networks (DNN) can be used to automate the task of preprocessing noisy signals and shown in Figure 5 shows how two different source signals can be filtered differently.

The data preprocessing stage is an essential aspect of any measurement device employed in the real world. Applying DNN model to automate the task aims to make the process more robust against variations in data. The experimentations carried out, and accompanying results acquired thus far have only considered the MIT-BIH NSR ECG dataset. The proposed experimental procedure is given below.

## Applications of the current work

The CNN based filter selection algorithm has the potential to be applied to various tasks where noisy signal measurements are required for analysis and classification. This includes application in assisted living environments. This can be either by having the algorithm implemented within the system on chip (SoC) module for application in assisted living environments or by implementing the algorithm within a stand-alone digital signal processing (DSP) module for use in various different systems.

Including the algorithm within a fully developed SoC could be done by implementing the model within the central processing unit. This would add additional computations for the central processing unit, as it would now need to pre-process the recorded signals using the proposed algorithm and analyse the resulting filtered signals and further application. The process would need to be carried out live and the pre-processing and classification processes would need to be implemented consecutively.

With developing a stand-alone DSP chip with a preprogramed CNN enabled denoising filter gives the advantage of having a module that can be applied for various tasks. The possibility of making the AI enabled DSP chip would require additional research into the adaptability for various applications. This method of implementing this algorithm would also enable the DSP module to be applied to existing system where noisy data measurements are present.

The algorithm detailed within the previous section has been trained and tested on a pre-recorded dataset which had been recorded under clinical conditions and with various steps taken to reduce the amount of noisy found within the signals. The premise of the proposed model is to automate the pre-processing of noisy data measured in the real world. This would require the model to be trained and tested on real data acquired from a suitable experimental set-up. The following section details the experimental set-up suggested to measure the required data and evaluate the proposed model.

## Experimental Set-Up Proposal

This experiment will investigate the detectability of biometric signals, such as respiration and heart rate (ECG), using an unobtrusive frequency modulated radar system. Furthermore, the research will advance onto detecting and adaptively separating, the ECG waveforms of multiple persons in motion within a closed environment. An unobtrusive radar system is proposed for carrying out the measurements from a distance, and a skin contact ECG recording device is proposed to measure the base signal to which the radar measurements can be compared for developing the learning algorithm. The scientific aim of the project is the proposed notion of using novel machine learning techniques for the adaptive denoising and automatic detection of vital signs from both single and multiple sources. The proposed task carries with it various technical problems; the showing effect, background noise and changing movement patterns by individual(s) within a closed environment being but some of the issues we aim to overcome using novel machine learning algorithms.

Participants will be iteratively introduced into the experimentation laboratory and the unobtrusive radar system will take measurements of signals within the laboratory. Along with the radar measurement, a direct measurement of the participants heart rate will also be carried out using a skin contact ECG measurement device. The signals acquired using the skin contact ECG measurement device will be used as reference signals against the waveforms measured by the radar system. Each participant will have their own skin contact ECG measurement device attached to them throughout the experiment. At the end of the experiment the participant will also be asked to fill out a short questionnaire regarding their age, gender, height, and a confirmation of their ability to walk and sit without any physical distress.

The primary research question to answer with this experiment being can we improve the measurement capabilities of unobtrusive radar systems in closed environments for detecting vital signs, using novel machine learning techniques? The secondary research question to be answered by the proposed study being Can we use machine learning to efficiently separate the vital signs of two people from the measurements made using an unobtrusive radar system?

## Experimental Design and Procedure

The 2 experiments consisting of 3 procedures each, with 5 trials for each procedure for both experiments. Each experimental procedure is expected to last 30 seconds whilst recordings are made. Both experiments are the same in structure, the only difference being that the second experiment will involve two participants, whereas the first experiment will only include one participant. There will be time between each trial for 10 seconds of rest for the participant(s) whilst the new data recording is prepared and a further 60 second break between the different procedures whilst the laboratory assistant(s) set-up the next procedure. An extended break of 3 minutes is planned between the two experiments whilst the second participant is introduced to the experimental set-up. At any point, the participant(s) can request for a break, should they require it.

For experiment 1, procedure 1, the participant will be asked to sit on a chair with a skin contact ECG measurement device connected to them, taking recordings whilst the unobtrusive radar system takes measurements from a distance of 1 meter away. This will be followed by procedure 2, which involves the participant sitting 1 meter away with their back to the radar system and skin contact device recording ECG signals. The chair will be rotated by the laboratory assistant(s) who will be present throughout the experiment guiding the participant and facilitating the various procedures. The third and final procedure will involve the chair being removed from the experimental set-up and the participant will be asked to walk, firstly away from the radar system, for a distance of 4 meters away from the original starting point at a steady and natural pace, and then turn around and walk towards the radar system whilst facing it directly, all the whilst the skin contact ECG recording device and radar system will be taking measurements.

Experiment 2 will follow the same procedures as experiment 1, with two participant simultaneously. For experiment 2, procedure 1, the two participants will be sitting on individual chairs 1 meter away from the radar system, both participants being separated by a distance of 2 meters. Both participants will have individual skin contact ECG recording devices attached to them whilst the radar system records data. For procedure 2 in experiment 2, both participants will be asked to face away from the radar system with the skin contact ECG measurement device connected throughout. The final procedure involves the two participants walking away to a distance 5 meters away from the starting point, with their backs facing the radar system and whilst both being separated by 2 meters. The participants will then be asked to turn around and walking back towards the radar system. Both when walking towards and away from the experimental set-up, the participants will be asked to walk at a steady, natural pace whilst keeping in line with each other. The walking line and 2-meter separation between the participants will be clearly marked on the floor for the participants to follow.

Shown in Figure 6 are the 2 proposed experiments, along with the 3 different procedures for each experiment. Prior to the experiment commencing, participants will be asked to fill out a short questionnaire regarding their age, gender, height, confirmation of the participant not having any physical ailments that may prevent them from walking or sitting on a chair and finally, consent for their vital signs to be measured and analysed anonymously. The answers to these questions will be used in conjunction with the data collected for any work that may be published as a result of the experimental findings.

Heart rate recordings will be done using a fingertip heart rate sensor. This sensor attaches to the index finger of the participant and records the heart rate non-invasively. This is a painless measuring device and the connection to the figure can be adjusted to fit comfortably on any figure size. The radar measurements are unobtrusive and non-invasive, such that the participant will be unaffected by the measurement device. Furthermore, the system being a low power source of electromagnetic radiation, does not interfere with other devices in the environment and is completely safe for the human body, even at short distances. Participants will be asked to sit whilst both the fingertip heart rate and radar measurements are conducted over 30 second trials for 3 different test procedures. Each procedure run being repeated 5 times each.

Clear instruction of the procedures will be given to the participants before and during the experiment. If the participant has any questions regarding the study and/or experiment being conducted, a researcher will always be present inside the lab to answer and queries. Participants are asked to remain as relaxed and still as possible for the duration of the recording stage.

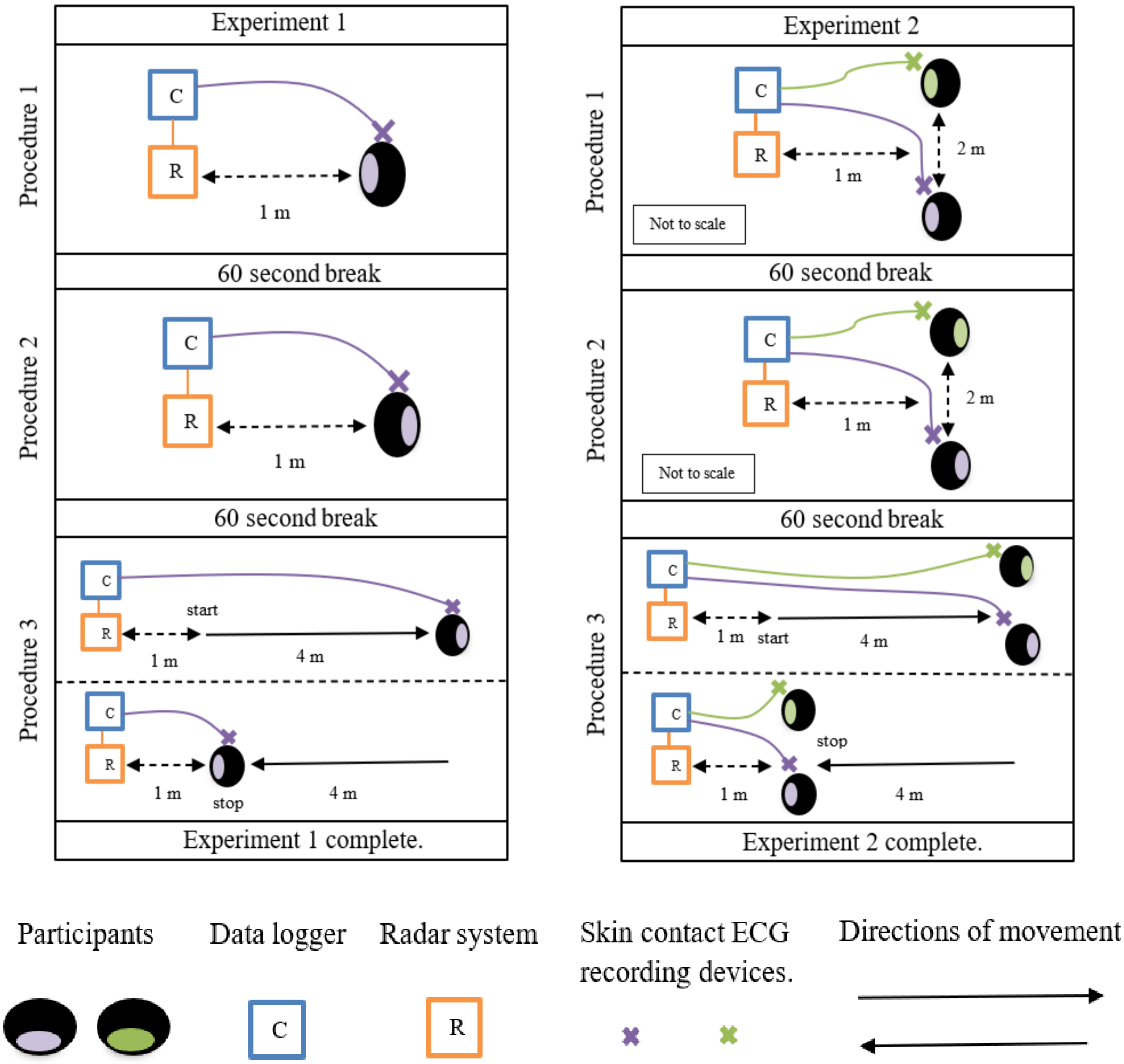


Figure 6. Showing the proposed experimentations and procedures. The study involves two different experiments, each consisting of three different procedures. The symbol legends are shown above for clarity.

## Experimental Design and Procedure

Data collected in this experiment is of two categories- 1) Digital: Radar system and skin contact device measurements. 2) Hard copy: questionnaire.

*1) Digital data storage and confidentiality*

*Heart rate:* The radar system will aim to collect signals from the laboratory during the experimentation. These waveforms will contain within them information about the participants heart rates, alternatively known as ECG signals. A more direct measurement of heart rate will also be taken using the fingertip heart rate sensors. Each participant from the study will be assigned an anonymous user ID with all data acquired from the study also being anonymized with the corresponding ID labels. The electronic data acquired from this experiment will be stored on a secure shared drive located on the university's internal server. Access to this drive will allowed to the research team carrying out the study and will be regulated by the central IT department of the university. There is no confidential information in heart rate and to the best of the researcher's knowledge, heart rate cannot be used to identify or distinguish between people.

2) Hard copy of questionnaire:

*Questionnaire:* This short questionnaire will ask the participant for the following details: age, gender, height, confirmation of participants not having any physical ailments which may prevent them from walking to and sitting on a chair and confirmation of the participant's consent to their data being used for further analysis. The questionnaire will not be shared with anybody outside of the direct research team and will also be anonymised with a unique ID, which will henceforth be the label for each corresponding participant's response. The questionnaire will be stored securely in a locked cabinet within the department, reserved for just such documents. These will not be shared to anyone outside of the research team.

A written information sheet outlining the proposed experimental procedure and relevant data measured will all be presented to the participant upon agreeing to the study. A document detailing all the procedures involved in the study, as well as all data storage, usage and security precautions taken to ensure safety will be presented to the participant in the beginning of the experiment and asked for a written consent of acknowledgment. Each participant has the right to withdraw from the experimental procedures at any time without the need of any reason.

This consent document will be the only form that will contain the participant's name and so these documents will be handled with equal, thorough care and not be shared with anyone outside of the research team. They will be locked in the secure storage facility within the department dedicated for such sensitive documents. The consent forms will be stored for 5 years after completion of the PhD and then destroyed securely by the department.

## Ethics Approval Response

The response received form the ethics form review, from the proposed supervisor of the proposed experimentation, was that the unobtrusive radar device in question does not fully meet the criteria required for university-run experimentations. According to the ethics reviewer, any medical device, or any device that measures human health conditions must firstly be CE certified before it can be considered as the measurement device within an experiment. For this reason, the supervisor's recommendation was to 1) run experimentations with a similar, CE certified device instead of the module currently being considered or 2) source an established dataset of radar system measurements for use within the developed deep learning algorithm.

The final decision for the experimentations detailed above was that the University of Reading's ethics approval department would not consider the proposed experimentations as appropriate for a PhD level project. The primary issue flagged for the decision being the radar measurement device evaluated. The suggestion was given to adapt the experimentations for a similar, already CE certified module and attempt a second ethics review. An alternative suggestion given by the ethics document reviewer was to source an independent, relevant dataset of radar system measurements and use the data from the published dataset for the training and testing of the developed CNN model. Furthermore, the reviewer detailed that any experimentations done regarding the health of participants would require the measurement devices and experimental set-up, including data storage and analysis, to be far more rigorous than experimentations evaluating non-health related data.

## Alternative Research Strategies

Given the decision and information given by the ethics form reviewer, detailed above, there are different areas this research project may progress into; the first being to utilise a similar alternative radar system as part of the data recording, and the second being to revaluate the research goals of this project. There are several manufacturers of radar modules with CE certifications similar to the type of device being considered within this project, the one found to be most appropriate being the KM-series and KL-series of transducers from RFbeam Microwave GmbH. The subject of this study, irrespective of radar module considered, must also be revaluated to avoid any health-related data acquisition and analysis. To circumvent this issue, the alternatives are to redesign the scope and specifications of the PhD project.