Development and Evaluation of a Non-Obtrusive Patient Monitoring System with Smart Patient Beds

Ruben van Dijk
University of Technology Eindhoven
Eindhoven, The Netherlands
r.j.j.v.dijk@student.tue.nl

Jun Hu
University of Technology Eindhoven
Eindhoven, The Netherlands
j.hu@tue.nl

ABSTRACT

UPDATED—15 June 2017. In this paper the development and evaluation of a non-obtrusive patient monitoring system with smart patient beds for hospitals is described. The goal is to improve the relation between patients and the medical staff, to reduce workload and improve the experience of the patient. Piezoelectric sensors are used to sense heart beat and respiration using the method ballistocardiography. The work is part of a final master project at the faculty of Industrial Design, University of Technology Eindhoven.

Author Keywords

Ballistocardiography; presence sensors; monitoring; patient-doctor relationship; hospital beds.

INTRODUCTION

In Chinese hospitals there is a tension between patient and doctors [1,2]. Patients experience long waiting lists, increasing out-of-pocket healthcare expenditure and the making of an appointment with a qualified doctor is difficult. That is the reason why patients want to make sure they receive good treatment once they are finally being treated. Due to this situation the patients raised awareness about their protective rights. However, the patients are lacking knowledge about the medical specialism of the doctors. On the other side the doctors are not satisfied with their jobs due to low income, long working days and the feeling that they are not appreciated by the patients and society. But the management in Chinese hospitals is not always professional. Rules and regulations cannot be executed strictly. The levels of professionalism of the Chinese doctors vary. This results in the making of mistakes by lower skilled or experienced doctors causing the loss of trust of the patients in the Chinese doctors [3]. The tension between patient and doctor sometimes even results in violent conflicts [4]. Also it occurs that patients sue the hospital because they think they are not treated well. The Chinese hospitals want to avoid this. This is why there is a regulation in Chinese hospitals in which every patient has to be checked by a nurse every hour during the night. In this routine the medical staff makes sure there are no emergency situations. However, these actions can be annoying for the patients who are trying to sleep.

Tech startup BOBO turned this problem into a design opportunity. We wondered if non-obtrusive monitoring technology could be used to keep track of the patients' heart rate and respiration, to make sure everything is OK without waking them in their night-time. In this way the hospital can provide better care for their patients and reduce the workload. This is what the Chinese hospitals are aiming for [5]. One important design challenge is the social part in this project: how to communicate to the patient that they are being monitored? The patient needs to have the feeling that he or she is taken care of and should trust the system. The method used in this design project is iterative design.

Related work includes the investigating of low-cost wireless occupancy sensors for beds [6] in which two solutions to sense presence of people in beds are compared: capacitive proximity sensors and accelerometers. Also the sleep trackers of the company Emfit are related to this project [7]. The company uses ballistocardiography (BCG) as a method to sense heart beats [8] and calculate the beats per minute (BPM) and heart rate variability (HRV) to tell the user something about their sleep quality. The sensor is placed under the mattress so there is no contact with the patient.

In this project a sensor system for hospital beds is developed which is able to display the heart rate and respiration of patients in the connected beds in real time.

SYSTEM DESIGN

The designed system consists of smart patient beds which are wirelessly connected to the computers at the nurse station running the so called Nurseweb application. The smart patient beds contain:

1. Piezoelectric sensor to monitor the heart of the patient.
2. Presence sensor sensing force to detect the presence of a patient in the bed.
3. Interactive LED light below the bed which changes color and intensity based on the presence of the patient.
4. Wi-Fi module which sends the data to the nurse station.

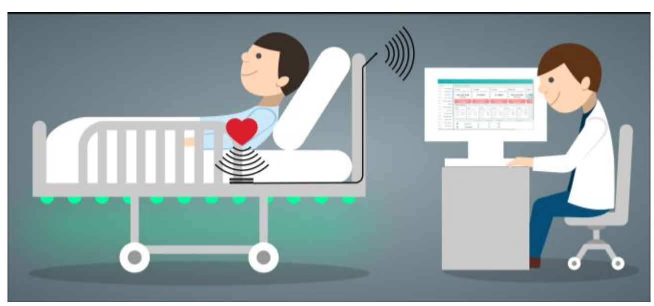

Figure 1. An illustration of the designed system consisting of smart patient beds and connected Nurseweb application.

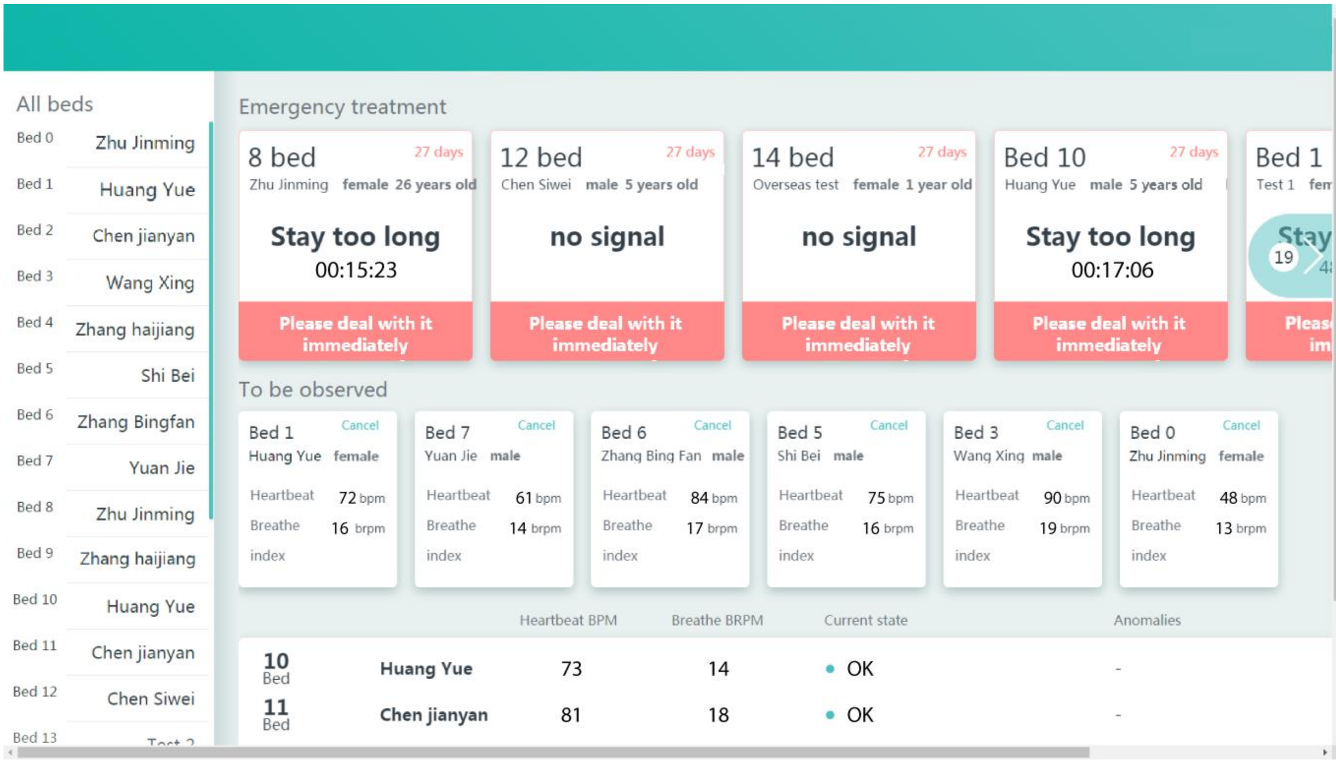

Figure 2. Nurseweb application which gives an overview of all connected patient beds providing BPM and respiration. The beds that need to be checked immediately appear on top of the page with a red box beneath it indicating they have a high priority.

Nurseweb application

The Nurseweb is a web-application running on the computers in the central nurse station. It was designed to give the nurses an overview of the health data (like the BPM) of patients in the connected beds. In addition, the function of the Nurseweb application is to warn nurses in case of emergency situations detected in individual beds. Situations in which nurses may be warned are:

- Presence sensor detects presence but piezoelectric sensor does not detect heart beat and/or breathing.
- Presence sensor detects absence of the patient in the bed for abnormal time.
- Piezoelectric sensor senses abnormal signal e.g. irregular heart beat and/or breathing intervals.

Piezoelectric sensor

To measure the heartbeat of the patient lying in the bed the method ballistocardiography (BCG) is used. In this method the ballistic forces of the heart are measured with a thin sensitive sensor below the mattress which is able to capture the smallest vibrations. This design decision is made because we were looking for a non-obtrusive way to monitor the patients. No sensors need to be attached to the body and it brings less privacy issues with it than monitoring with cameras. A patient does not feel the difference between no sensor under the mattress and a sensor beneath the mattress. In this project an 80 cm long piezoelectric sensor is used.

Figure 3. Top view of two piezoelectric sensors (first two strips from above) which have the length of the full width of the bed.

When the patient lies on the bed, the vibrations generated by his or her beating heart pass through the mattress to the piezoelectric sensor. At every heart beat the sensor is pressed very gently which results in a small voltage generated by the sensor. A prototype with filtering circuit was designed to filter the signal [9]. This signal can be analyzed with an algorithm with peak detection. The interval between two beats (RR) can be measured which can be used to calculate the BPM.

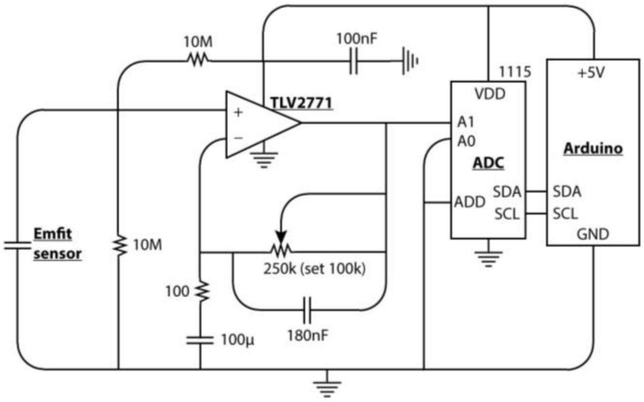

Figure 4. Circuit diagram of designed signal filtering prototype in which a piezoelectric sensor from Emfit was used.

Because the patient also makes other movements like breathing (small movements) and turning around (big movements) the signal needs to be filtered.

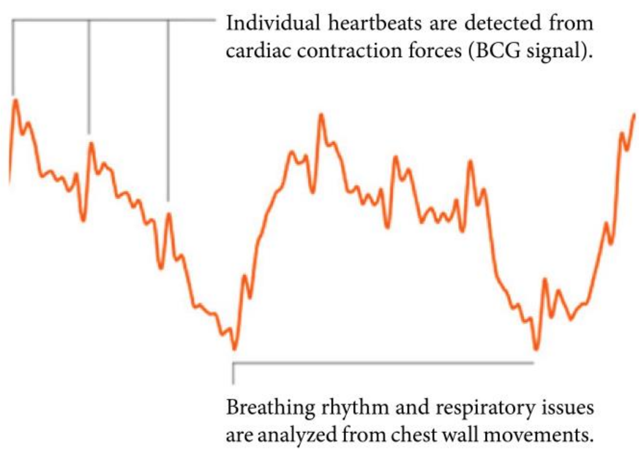

Figure 5. Example of BCG signal containing information about heart rate and respiration.

We want to make explicit that we do not aim to replace electrocardiography (ECG) which is the standard for monitoring the heart. However, ECG is used when it is very important to monitor the heart and it requires the placement of electrodes on the body of the patient. We believe that in all other situations the BCG signal contains enough information to monitor the patients and avoid emergency situations. The BCG signal coming from the piezoelectric sensor was also analyzed by dr. Lin Xu from the faculty of electrical engineering which also developed the algorithm to count beats.

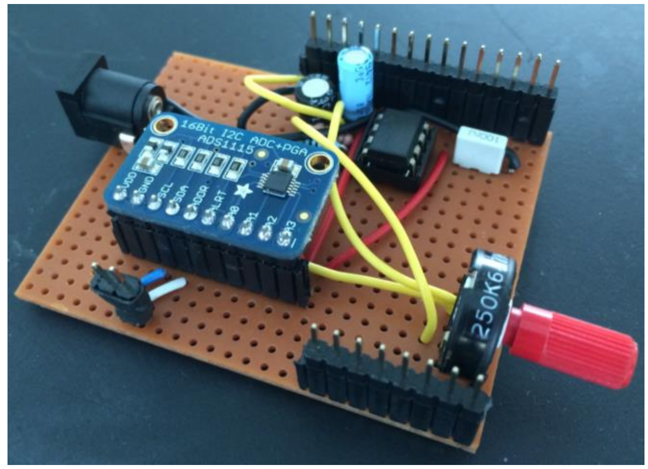

Figure 6. BCG filtering circuit prototype board which was designed to fit on an Arduino Uno.

Presence sensor

In order to immediately detect the presence of a patient in the bed a force sensing resistor (FSR) was selected. In the evaluation section in this paper the design decision to use this sensor rather than other sensor types is clarified. The piezoelectric sensor cannot be used for this because no signal coming in could mean that the patient has left the bed but also that the body of the patient has stopped working. The FSR sensor is as thin as the piezo electric sensor (approximately 1mm) and can therefore be combined with the piezoelectric sensor. The sensors need to be placed under the mattress beneath the chest of the patient.

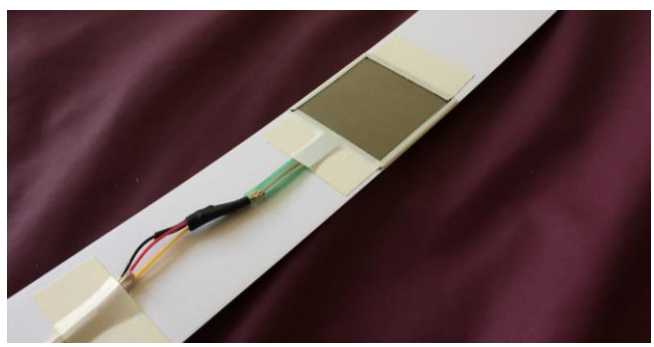

Figure 7. Force sensing resistor (square) combined with piezoelectric sensor (white strip).

When the sensor is placed under the mattress of the hospital bed, it needs to be calibrated. When nobody is lying on the bed the threshold can be set. In the future also the weight of the patient can be used as input for the calibration.

Interactive LED light

In order to improve the experience of the patient, a relation between the presence of the patient in the bed and the color and intensity of the light in the patient room was designed. For demonstrative and experimental purposes now was chosen to place the LED light under the hospital bed out of sight. The light itself however is visible through the reflection on the bed and floor. In the designed demonstration the light was colored bright light blue when the patient is out of the bed to assist the patient with walking in the patient room. It turned red when the pressure sensor sensed a patient in the bed to create an atmosphere for sleeping. Besides the function of the light to assist the patient, the idea is that the interaction also lets the patient realize that he/she is being monitored because the bed (and in the future the patient room) reacts to entering and leaving the bed. This experience however still needs to be tested.

Figure 8. Hospital bed with interactive LED light below. In this case nobody is on the bed so the light is blue.

EVALUATION

All sensor parts of the system were tested and evaluated in the International SmartHealth Lab in Hangzhou from technology startup BOBO and labs at University of Technology Eindhoven. Also a piezoelectric sensor prototype with real time output was demonstrated and evaluated in The First Affiliated Hospital, Zhejiang University, Shengzhou Branch, China.

Piezoelectric sensor

In the development process of the piezoelectric sensor both the visualized BCG signal coming from the designed prototype as well as a plot of BPM with 10 second delay were demonstrated in the Zhejiang University hospital. A device measuring the blood flow through the finger tip of the patient was used to compare the generated BPM. The difference between the two BPMs sometimes differed up to 5. The doctors concluded that the concept was promising but the signal filtering and analysis technology should be further developed for more accurate output.

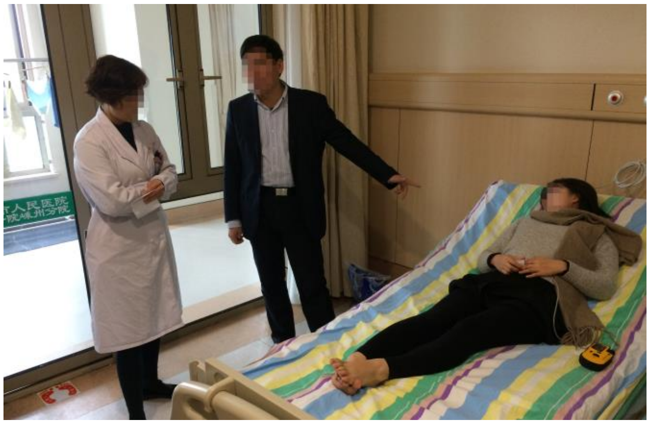

Figure 9. The prototype is tested and demonstrated to the doctors in The First Affiliated Hospital, Zhejiang University, Shengzhou Branch, China.

At the University of Technology Eindhoven, a hospital bed from Maxima Medisch Centrum was arranged for experiments to improve the sensor system. Data was recorded using a PCB filtering board connected to the piezoelectric sensor which was connected to a laptop over the serial port. The data was saved with Processing and loaded into a Matlab code developed by Dr. Lin Xu from the Electrical Engineering department. Again, the data was compared with a finger BPM measuring device in order to work towards a more accurate algorithm.

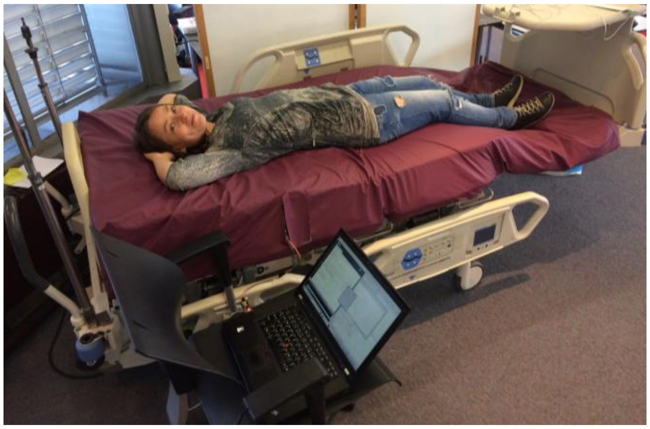

Figure 10. With a test subject on the bed data was recorded with the piezoelectric sensor.

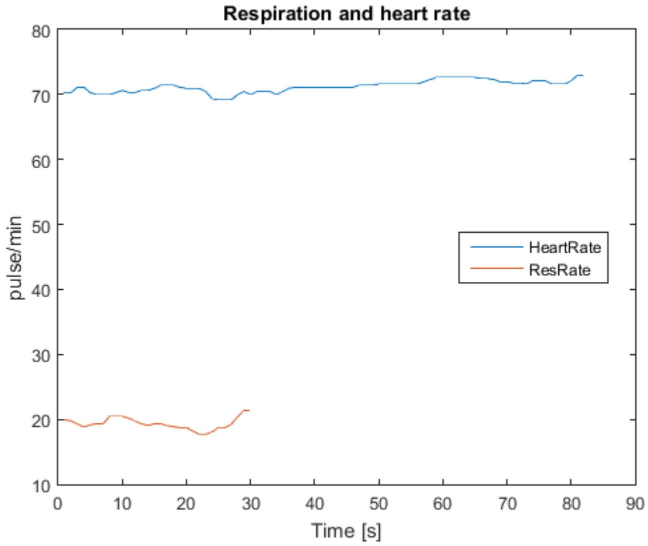

Figure 11. Matlab plot of calculated BPM and respiration with data from piezoelectric sensor as input.

Presence sensor

For immediate presence detection we needed to explore different sensors and evaluate their usability in our context. The prototyping and experimenting process and results will be described per sensor below and the advantages and disadvantages will be presented in a table for an overview.

Load cell

The first sensor that was explored was the load cell. This sensor is also used in scales. To get enough pressure on the load cell in order to see a difference in the signal, we needed to add some material on top to focus the force to the points where the load cells were placed below the mattress. This made the design too thick, even in further developed prototypes. The thickness resulted in a noticeable bump in the mattress. We concluded that this design was not comfortable for the patient.

Figure 12. Load cell proof of concept prototype with POM bar on top to focus the force on the load cells.

Capacitive sensor

Several capacitive sensor prototypes were developed. First aluminum foil was used as the conductive material for a quick proof of concept. The presence of a human body could be detected even without contact. Because of the successful test a capacitive cover with conductive fabric in which the piezoelectric sensor could be placed was designed. Again the sensor was very useful. However, when the piezoelectric sensor was turned on, the two sensors interfered with each other which made the capacitive signal unreliable.

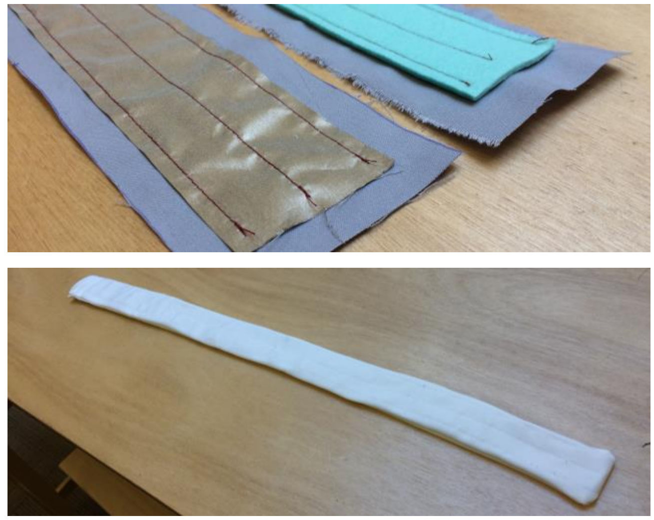

Figure 13. Two capacitive sensor sleeve covers for the piezoelectric sensor were designed. On top the conductive (left) and soft felt (right) inside layers can be seen.

Velostat

This material also seemed promising because it is very thin and flexible. However, when experimenting with it a big force was needed in order to see a difference in the signal. The reason for this may be the relative big surface of the material compared to the other resistor and voltage chosen in the circuit.

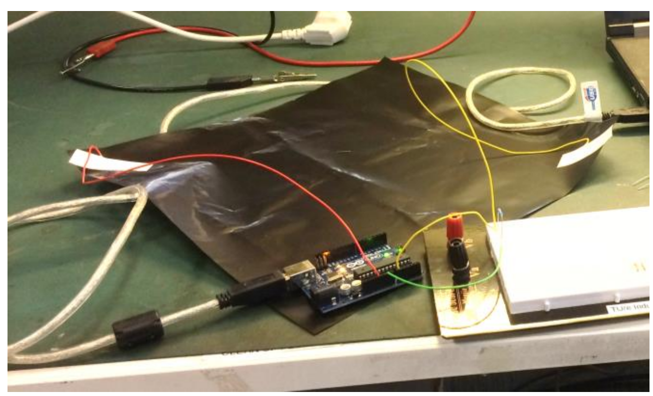

Figure 14. Experiment with Velostat (black sheet material) by pressing on it and analyzing the difference in resistance.

Force sensing resistor

Finally, the FSR was tested. Like the capacitive sensor, the sensor is very thin and only requires a small pressure to notice a difference in weight. In contrast to the capacitive sensor this sensor does not interfere with the piezoelectric sensor. In our experiment we used a square shaped sensor of 4cm x 4cm which we taped to the piezoelectric sensor. However, it is recommended to design a flexible cover which wraps around the piezoelectric sensor and FSR placed next to each other, not on top of each other. In this way the piezoelectric sensor keeps the freedom to vibrate and absorb the movements from the body of the patient through the mattress. FSRs are also available in long shapes of 60cm in web shops like Sparkfun: https://www.sparkfun.com/products/9674

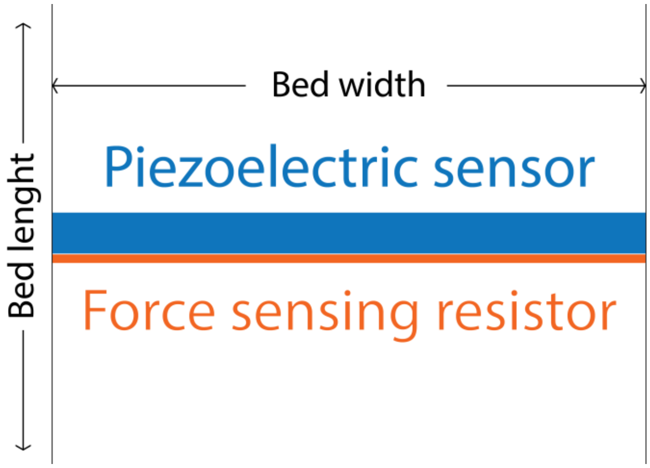

Figure 15. Schematic top view of recommended placement of sensors beneath the mattress of the hospital bed.

Concluding, the FSR can be use best as the presence sensor in this context as can be seen in the following table:

Sensor	Advantages	Disadvantages
Load cell	Can withstand big forces	Thickness of sensor
Capacitive sensor	Can even sense without direct contact	Interferes with piezoelectric sensor
Velostat	Thin material	High pressure needed
Force sensing resistor (FSR)	Thin material, very sensitive	-

Table 1. Advantages and disadvantages of sensors that were compared to sense presence in the hospital bed.

DISCUSSION

Like discussed in the chapter evaluation, the hospital is interested in the system. However, the demonstrated BPM calculating algorithm needs to be more accurate before they would use such systems in their hospitals. Qualified algorithms of BPM calculation already exist and are in practice. Future work includes the analysis and improvement of Heart Rate Variability (HRV) derived from BCG. Many diseases can be observed by analyzing HRV. Also sleep stage classification derived from the signal coming from the piezoelectric sensor is considered. This is also very complex and should be further researched. One of the biggest challenges in this projects remains the filtering of noise in the signal due to movements of the patients. Also privacy should be considered because the hospital would be able to constantly follow the presence and absence of patients in their bed. Finally, we have to consider that the medical staff may rely on the system too much whereas it is highly imaginable that the system makes mistakes and does not warn the nurses in time. These scenarios will have to be tested in the real hospital settings carefully in controlled situations.

CONCLUSION

We presented and evaluated a non-obtrusive patient monitor system which could be used in Chinese hospitals. The system consists of a piezoelectric sensor to measure heart rate and respiration, a force sensing resistor to measure presence of the patient in the bed and the Nurseweb application which provides the nurses with real time health information about the patients. We conclude that ballistocardiography and force sensing are usable technologies to use in this context. The interactive light system still needs to be evaluated in future work. Especially the effect on the patient-doctor relationship needs to be taken into account. BOBO will continue to further develop the system into a product that can be sold to hospitals.

ACKNOWLEDGMENTS

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