Sensor integration for perinatology research

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Abstract: The number of high-risk pregnancies and premature births is increasing due to the steadily higher age at which women get pregnant. The long-term quality of life of the neonates and their families depends increasingly critically on the ability to monitor the health status of mother and child accurately, continuously and unobtrusively throughout the perinatal period. Advances in sensor integration have enabled the creation of non-invasive solutions to improve the healthcare of the pregnant woman, and her child before, during and after delivery. In this paper, we present the design work of a smart jacket integrated with textile sensors for neonatal monitoring and software architecture of advanced sensor integration for delivery simulator. A balanced integration of technology, user focuses and design aspects is achieved. Prototypes are built for demonstrating the design concept and the experimental results are obtained in clinical settings.

Keywords: sensor integration; neonatal monitoring; smart textiles; software architecture; P2P technology; design process; perinatology; perinatal monitoring; delivery simulator; ECG; electrocardiogram.

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1 Introduction

It is a societal trend that pregnancies occur at a steadily higher age. Statistics confirm that first-time births to women in their thirties are rapidly becoming the norm. As a result, mother and child face increasing risks for miscarriage, premature delivery, birth defects and health problems later in life. This makes it increasingly important to continuously monitor the health status of mother and child throughout the pregnancy, so as to permit timely medical action when acute health risks are detected. Premature neonates are normally admitted to neonatal incubators. Neonatal medicine has progressed strongly in the past decades (Costeloe et al., 2000). As a result, incubators are populated by steadily younger neonates. The long-term health prospects of the neonates and the mothers depend increasingly critically on reliable and comfortable health-status monitoring systems.

Recent advances in sensor technologies and wireless communication technologies (Goldsmith, 2005; Tao, 2005; Yang and Yacoub, 2006; Yuan et al., 2006; Wang et al., 2009) enable the creation of a new generation of healthcare monitoring systems with wearable electronics and photonics. Ambient intelligence (Aarts and Encarnação, 2008) has become quite influential in the development of new concepts for sensor integration and information processing by combining multidisciplinary fields. The design and implementation of non-invasive health monitoring systems will drive the applications of smart health monitoring environments, in a way that the sensors and equipments will be moved to an invisible background. The area of non-invasive health monitoring involves multi-disciplinary research and collaboration, including sensor technology, medical science, industrial design, electrical engineering, etc.

The Eindhoven University of Technology (TU/e) in the Netherlands has started a 10-year project on perinatology in cooperation with the Máxima Medical Centre (MMC) in Veldhoven, the Netherlands. The goal of this research collaboration is to improve the healthcare of the pregnant woman, and her child before, during and after delivery. The design skills needed range from medical science, human factors, material knowledge, smart textiles and form-giving to circuit design, user research, power management, signal processing and software engineering (Chen et al., 2009a).

Some intelligent designs have been developed covering different aspects of non-invasive perinatal monitoring with advanced sensor integration, such as pregnancy monitoring (Vullings et al., 2006; Rabotti et al., 2008), vital signs monitoring for neonates (Bouwstra et al., 2009; Chen et al., 2010a; Chen et al., 2010b), data transmission (Chen et al., 2009b), device to support cardiopulmonary resuscitation of neonates (Chen et al., 2010c), power supply for neonatal monitoring (Chen et al., 2008; Chen et al., 2009c), neonatal behavioural state detection based on facial expression analysis (Hazelhoff et al., 2009) and delivery simulators (Peters et al., 2008).

In this paper, we first present the design work of a smart jacket integrated with textile sensors for neonatal monitoring and then the software architecture of sensor integration for delivery simulator. The smart jacket is the vision of a wearable unobtrusive continuous neonatal monitoring system realised by advanced sensor integration. The smart jacket aims at providing reliable health monitoring as well as a comfortable clinical environment for neonatal care and parent–child interaction. We demonstrate the prototype smart jacket with textile sensors integrated for ECG (Electrocardiogram) measurement and show the experimental results obtained in clinical setting.

In the design of the delivery simulation system, distributed sensors and actuators are integrated into the mother manikin, the baby manikin, as well as the environment for the purpose of medical team training. We introduce the software architecture that supports open and flexible integration, in which XML (Extensible Markup Language) based messaging mechanisms and the P2P network technology play important roles.

The paper is organised as follows. Section 2 explains the design and implementation of the smart jacket for neonatal monitoring, including the design concept, the prototype implementation and clinical testing. Section 3 describes the delivery simulation system and its software architecture for distributed sensor and actuator integration. Section 4 provides discussions and vision on further development. Section 5 concludes the paper.

2 Design of smart jacket for neonatal monitoring

A Neonatal Intensive-Care Unit (NICU) is equipped with incubators to host and treat sick full-term and pre-term babies. Current neonatal monitoring techniques provide continuous monitoring of the vital signs of the critically ill patients and contribute to the increase in survival rate of critically ill neonates. However, placement of the adhesive sensors and presence of all the wires lead to discomfort and even painful stimuli when the electrodes have to be removed. These negative stimuli can interfere with the normal growth and development of the neonates and hamper the parent–child interaction. Additionally, in an attempt to reduce discomfort due to the excessive light, blankets are applied to cover the incubator, but unfortunately this also impairs the observation of important clinical signs.

The future incubators at NICU are envisioned to provide non-invasive reliable neonatal monitoring by the integration of inductive, capacitive, acoustic and optical sensing technology into the incubator for multimodal monitoring. Smart incubator network architecture is foreseen to carry sensor signals from sources such as smart garment sensors and camera data with plug and play connectivity. Different users (e.g. the neonate, clinical staff and parents) will interact with the smart incubator. The architecture encompasses hardware, software, user interaction and system integration. To achieve the smart incubator network architecture, an iterative design process is followed from user and technology research, design concept, system integration, prototype implementation to clinical validation. In this section, we present the smart jacket design for neonatal monitoring which is a key component of the future smart incubator.

2.1 Design concept

The vision of the neonatal smart jacket is a wearable unobtrusive continuous monitoring system realised by sensor networks and wireless communication, suitable for monitoring neonates inside the incubator and outside the incubator during Kangaroo Mother Care (World Health Organization, 2003). The neonatal smart jacket aims at providing reliable health monitoring as well as a comfortable clinical environment for neonatal care and parent–child interaction.

Methodologies from the field of Industrial Design are applied in the design process, which involves a unique integration of knowledge from medical science, design and sensor technology. The iterative process begins with an information search that includes user research involving doctors and nurses at the Máxima Medical Centre (MMC) and gathering of information on neonatal monitoring, smart textiles, power supply, etc. Requirements were derived from the information search, forming a base for brainstorm sessions which resulted in ideas about technological challenges, functionality issues within NICU as well as form and senses. The ideas are then placed in a morphological diagram and combined with several initial concepts. Design choices are made through an iterative process in which proof of technology and user feedbacks provide knowledge for further development. The three aspects 'technology, user focus and design' are strongly interwoven along the process.

The first step towards the smart jacket is the design of a jacket that:

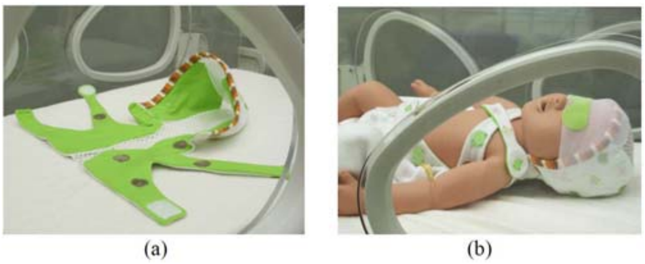
1. contains the integration of conductive textile sensors for ECG monitoring
2. forms a platform for future research in which wireless communication, power supply and sensors are developed
3. obtains a sense of trust by parents.

The concept of Diversity Textile Electrode Measurement (DTEM) is applied for the smart jacket design. The neonate wears a baby jacket that contains six conductive patches that sense biopotential signals at different positions to perform diversity measurements. Depending on the way the baby lies or is held, there are always patches that are in close contact with the skin because of pressure. When one sensor becomes loose from the skin, another sensor can provide a better signal. The system continuously measures which leads of the suit have superior contact and chooses the strongest signal for further processing. The concept offers a solution for skin contact, without jeopardising comfort by tightness. It might also solve the problem of searching optimal electrode positions in the jacket, which varies per baby.

2.2 Prototype and sensor integration

A prototype smart jacket as shown in Figure 1 was built based on the results of user research in MMC, study, testing and comparison of different textile sensors. Six textrodes are integrated in the jacket for ECG monitoring. We chose the silver-coated textrodes from Shieldex® and gold-printed textrodes from TNO Science and Industry. The wiring was implemented with conductive yarn, which is silver-coated nylon from Shieldex®. The six textrodes are located at different positions in the jacket to perform diversity measurements. When one sensor becomes loose from the skin, another sensor can provide a better signal. By this way, unstable signals caused by movement artefacts can be reduced by always choosing the stronger signal for further processing. The frogs in the jacket indicate the locations of different textrodes and at the same time bring friendly and familiar images to the users. The jacket is open at the front and has an open structure fabric on the back and hat, with the purpose of skin-on-skin contact, phototherapy and medical observation. The hat contains eye protection and leaves room for future sensors. The aesthetics are designed to appear as regular baby clothing. The colour combination of white and green with colourful happy animal heads is chosen because it is unisex while looking cheerful and clean.

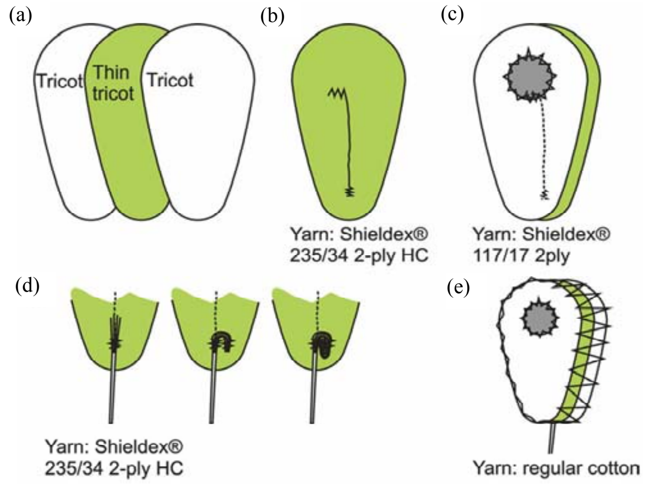
Figure 1 (a) Prototype smart neonatal jacket and (b) a baby mannequin wearing the smart jacket inside the incubator (see online version for colours)



Different textile sensors were tested for the integration into the jacket. Figure 2 demonstrates the test patches with different versions of silver and gold textile electrodes and a blanket with large silver electrodes. The silver textile electrodes consist of silver-plated nylons produced by Shieldex®. Construction details are shown in Figure 3. Three layers (Figure 3a) of cotton are used and on the middle layer (Figure 3b) the circuit is sewn with Shieldex® silver-plated yarn. On the first layer the electrode is sewn, stitching through the circuit on the middle layer (Figure 3c). The electrodes connection to the monitor is realised by carbon wires obtained from regular disposable gel electrodes: the end of the carbon wires are stripped and sewn onto the circuit on the middle layer (Figure 3d). (Carbon wire is a good alternative to metal buttons which are often applied, because it avoids the less stable soft-hard connection.) Finally, the third cotton layer for isolation is sewn to the others (Figure 3e).

Figure 2 Test patches and blanket (see online version for colours)

Figure 3 Construction of textile electrodes (see online version for colours)



The gold-printed electrodes consist of a thin smooth fibre with a metal print developed by TNO at Eindhoven, the Netherlands. The gold test patches are created in a similar way to the silver test patches; however, in future application the circuit and electrode can be printed in one piece. Considering the user aspects, the prototype is designed to have a stress-less dressing process as shown in Figure 4:

1 the baby is laid down on the open jacket

2 the lower belt is closed

3 the hat is put on

4 finally the chest straps are closed.

Figure 4 Stress-less dressing process (see online version for colours)

2.3 *Clinical testing*

Several experiments were carried out, ranging from experiments on adults as alternative subjects to neonates in the NICU at the MMC Veldhoven, the Netherlands. The goals are comparisons between the various textile electrodes, verification of their functioning on a neonate and verification of the DTEM concept. Finally, a wearability test of the jacket was performed.

An analysis of risks was performed before applying the prototypes to the NICU. Together with clinical physicists, a hospital hygiene and infection expert, and a neonatologist, the safety of the monitoring system and hygiene and allergy risks were analysed. Precautions such as disinfection and allergy tests were taken. The ethical commission of the MMC approved the experiments.

First, we tested the quality of the ECG signals obtained by textile electrodes varying in material and size and gel electrodes (3M™ 2282E) are qualitatively compared. Figure 5 shows the test set-up. With the consent of parents, the textile electrodes were tested with two subjects: one neonate of 30 weeks and 5 days and one of 31 weeks and 6 days, both admitted in the NICU at MMC. The ECG is sensed by three textile electrodes in regular configuration and the data are acquired with a GE Heathcare Solar® 8000M. The unprocessed digital data of derivation II were obtained from a network and imported and filtered in MATLAB. A notch, high-pass and low-pass filter, is applied to remove the 50 Hz and higher harmonics, DC (direct current) component and high frequency noise.

Figure 5 Test set-up (see online version for colours)

From Figure 6, we can see that the quality of ECG obtained by the gold-printed textile electrodes is good and the QRS complex can be seen clearly. The ECG curve in Figure 6 is representative of the ECG quality by gold electrodes when the baby lies still.

Secondly, we carried out tests to find out whether the concept of DTEM (Section 2.1) can improve the signal quality. The ECG obtained by large silver textile electrodes in a blanket where the neonate lies on is compared with the ECG obtained by large silver patches held on the back. By this way, the effect of pressure by body weight can be investigated. From Figure 7 we can see that the quality of ECG obtained by the silver textile electrodes is good and the QRS complex can be seen clearly as well. The shape of the ECG complex looks different from Figure 6, because the heart is monitored from another angle.

Apart from reliable technology, the success of the smart jacket largely depends on the wearable comfort of the jacket. Tightness is desirable for sensor contact, although it might be in conflict with wearable comfort. Therefore, extra caution is taken by performing a wearability test in an early design stage. Figure 8 shows a stable neonate of 34 weeks being dressed in the first prototype of the smart jacket while being filmed. Compared to the stress that was caused when undressing the regular premature baby clothing, the dressing process of the smart jacket was very calm. The dressing time is about one minute. The model needs to be more adjustable in size due to large variations in proportions and range of dimensions: in the NICU neonates can grow from 500g to 2000g and body proportions vary especially when caused by medical conditions. The straps need to be improved for comfort in the next design iteration.

Figure 6 Gold-printed electrodes D = 15 mm (see online version for colours)

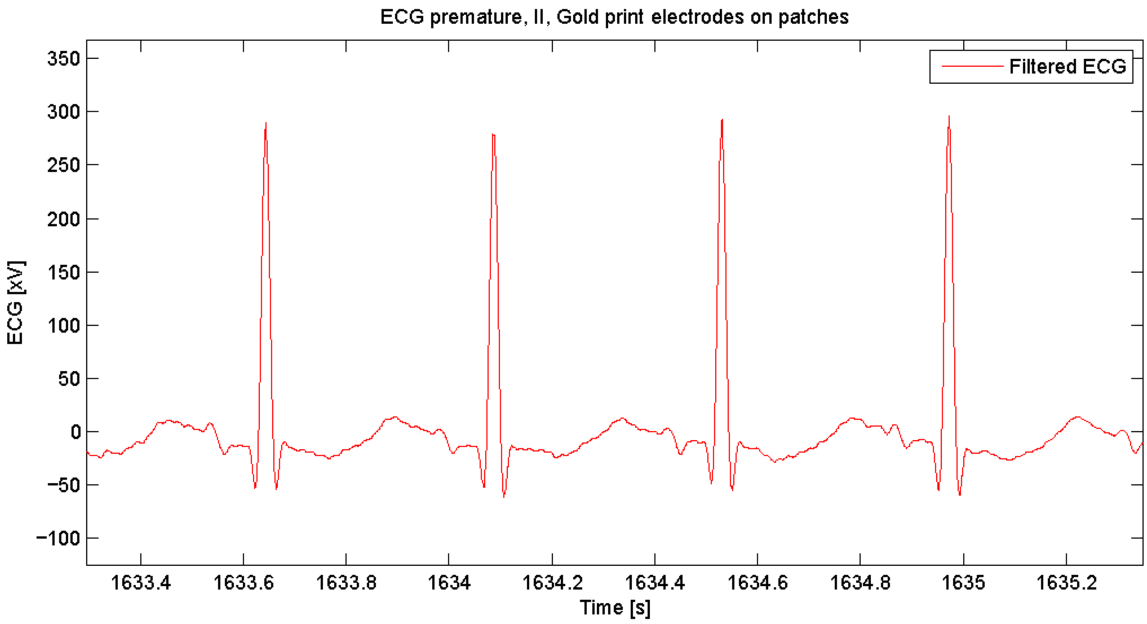


Figure 7 Silver Shieldex®, 50 mm × 60 mm, blanket (see online version for colours)

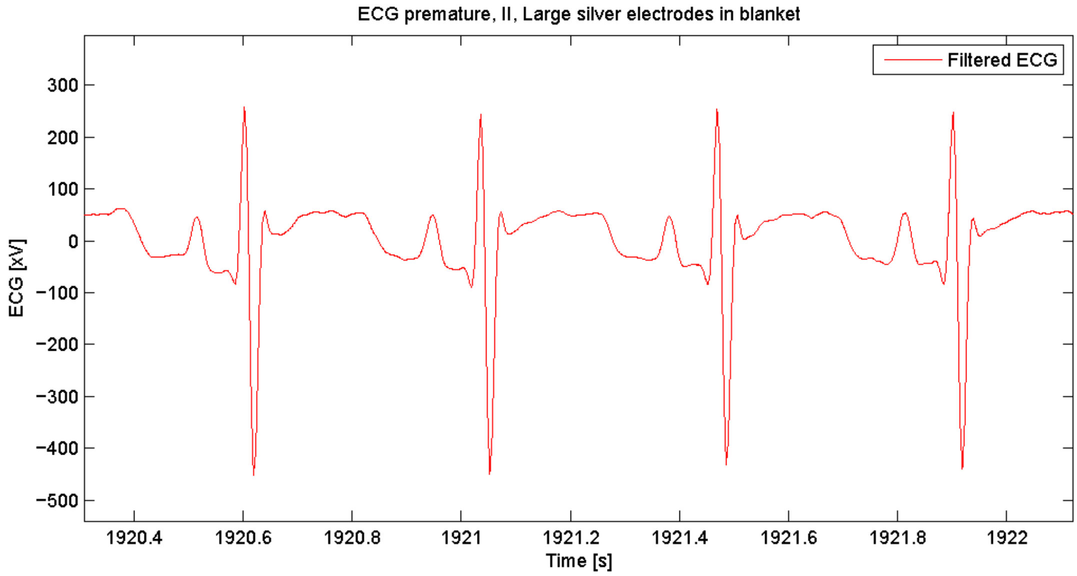


Figure 8 Wearability test with the first prototype (see online version for colours)

2.4 *Results analysis and improvements*

Because of the nature of conductive textiles, the quality of the ECG signal obtained with textile electrodes cannot exceed the gel electrodes: they are 'dry' electrodes with relatively loose skin contact and have a flexible structure that causes artefacts. However, the specific application of ECG monitoring on neonates offers new design opportunities:

- A premature has smoother skin, which results in better skin contact
- The premature moves relatively little, which results in less movement artefacts
- The premature always lies or is being held, which offers continuous pressure, which leads to better skin contact.

Two textile electrode designs turn out very promising:

1 large (± D = 40 mm) silver-plated textile electrodes

2 small (± D = 15 mm) gold-printed electrodes.

Both have different strengths and weaknesses. Large silver electrodes offer a stable ECG signal with low noise under the condition that pressure is applied. The silver seems hypoallergenic and does not change properties considerably after a few washing cycles. The small gold-printed electrodes obtain a stable ECG signal with low noise under the condition that pressure is applied in the beginning; once skin contact is established, little pressure is required. The gold print however is not hypoallergenic and looses conductivity after washing, due to corrosion of the metal layer beneath the gold. Although the silver electrodes could be applied without much adjustment, the gold prints are worth further development. They require less space due to higher conductivity, have a smoother surface that leads to better skin contact, are less flexible which leads to less artefacts and are seamless which leads to more comfort.

The monitoring of a neonate's ECG by diversity measurements realised by textile electrodes in the jacket definitely is a useful idea. Through experimental verification it is found that the quality of the ECG signal improves significantly due to a neonate's own body weight and is comparable to the quality of ECG signal obtained by gel electrodes. Based on interviews with parents and medical staff, the conclusion can be drawn that the user groups are positive about the first results. They especially appreciate the freedom of movement, the aesthetic design, stress-less dressing process and integrated eye protection. Improvements have been made on the design and a new version of the smart jacket has been developed as shown in Figure 9.

Figure 9 New version of the smart jacket (see online version for colours)

The new version contains an extremely stretchable fabric that likely ensures adjustability to different sizes and proportions. The hat is kept separate for the same reasons. Furthermore, the straps are designed to prevent tightness around the neck. Large silver textile electrodes are applied in the new version. They are connected only on one of the four sides, in order to allow stretch of the jacket without stretch of the electrode itself. The medical staff and parents embrace the latest version of the smart jacket. At present this prototype is ready for further clinical testing within the MMC Veldhoven. The development of the smart jacket will be continued, initially by further development of the ECG sensors, wireless transmission and an adjustable size for different patients which enable clinical reliability tests. More monitoring functions will be integrated into the jacket. Developments and clinical tests have been carried out on body temperature monitoring (Chen et al., 2010b), reflective pulse oximeter sensors for neonatal blood-oxygen saturation monitoring (Chen et al., 2010a) and wireless transmission (Chen et al., 2009b).

3 Software architecture for delivery simulator integrated with distributed sensors

In medical education, how to act in emergency situations is often trained on an individual basis. In practice, patients are however handled by a team from multiple disciplines, hence the training must target on the entire team. A British study shows that regular team training leads to 50% less brain damage caused by lack of oxygen during birth (James, 2006). In the last 3 years, MMC Veldhoven has been providing such multidisciplinary team training with the help of medical simulation. The team training is given by a gynaecologist and an experienced midwife, taking place in a fully equipped delivery room that tries to reproduce the real-life situation (see Figure 10). The training uses a patient simulator that is the most advanced up-to-date. The aim is to increase the skills of a multidisciplinary group of employees in the delivery room and especially to prevent inadequate communication in critical obstetric situations.

Figure 10 Team training with delivery simulators at MMC (see online version for colours)

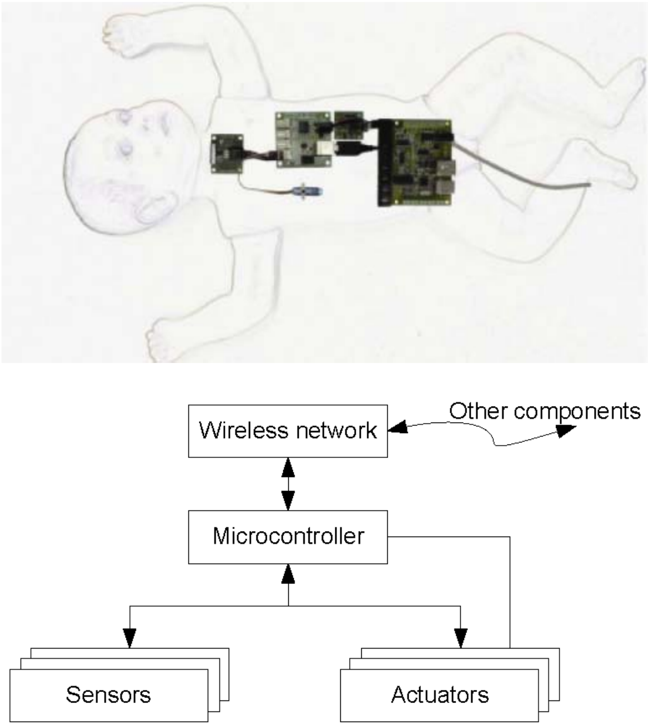
Patient simulators are already commercially available from several suppliers (Hu and Feijs, 2009b). Although technically advanced, the level of realism is not particularly high. Next to the toy-like external appearance, it is also not the really flexible material applied which has the effect that the training experience is still quite remote from the reality. Especially, most of the commercial products today are designed as a standalone system that does not really take the aspects of the training environment and team training into account. These team training aspects are, for example, the communication among team members, the position of every member, the monitoring and analysis of the team performance and so forth. In the training environment, not only the mother and baby manikins should be used, but also the medial monitoring equipments, the space layout and arrangement, lighting and noise conditions should be taken into account. It results in a distributed training environment and the distribution would enhance the training experience and effect (Hu et al., 2005). Hence, the cooperation between TU/e and MMC aims at the next generation simulation-based training facilities. The result of the effort is the MedSim system.

In MedSim, sensors and actuators are integrated into the mother and baby manikins to simulate the delivery process and to react on the actions taken by the team. Figure 11 shows the structure of the baby manikin. Sensors are integrated to detect the position of the baby when the baby is manoeuvered inside the birth channel, the pulling and holding force being applied when the baby is pulled through the birth channel with an instrument, and positions of the body parts (head, arm and legs). Actuators are integrated into the baby manikin to simulate the muscle tone, skin colour and breathing behaviour. These sensors and actuators are connected to a microcontroller. The microcontroller has a wireless network component that communicates with other system components, for example, the mother manikin that has sensors and actuators integrated in a similar manner.

For a more realistic experience and an optimal training result it is necessary to involve as many different senses as possible: vision, sound, smell and also importantly a realistic touch experience (moistness, warmth, friction). To realise the technology should allow mixing things that are real and things that appear to be real, and augmented reality seems to be promising. Augmented reality is already applied, at present, for several training goals where the real experience is too dangerous or too expensive. Examples are training firemen (judging risks for collapsing of a building or the probability of an explosion with a tanker truck overturn) or military personnel (training with realistic impacts of shells). In our implementation the augmented reality is used, for example, to simulate the massive blood flow when things go wrong during the delivery process.

Next to patient simulators there are also additional possibilities and requirements for visualising a realistic environment (virtual reality). One can think of adding objects in the background (walls, doors, windows, equipment, but also persons walking by). The advantage of virtual reality is that the very same training room can be used for very different training scenarios with little effort, changing from a delivery room to an emergency room or a mobile situation in an ambulance.

Figure 11 Structure of a baby manikin (see online version for colours)



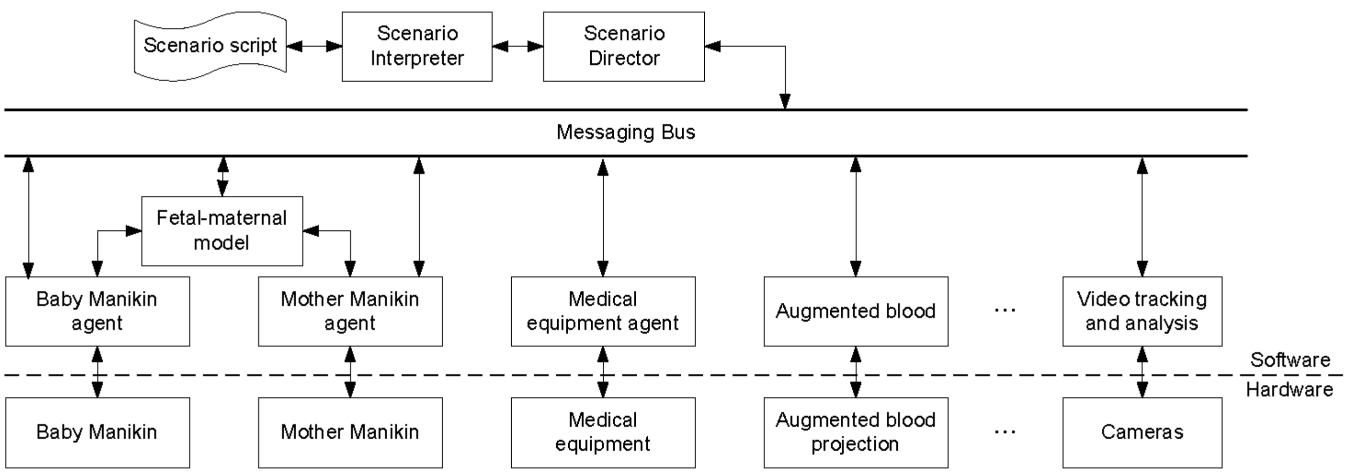
For team performance monitoring and analysis, video-based techniques such as 3D visual signal processing and video content analysis are applied. 3D depth map generation techniques create the depth map from a non-calibrated video sequence using the 'structure-from-motion' algorithm. This technique facilitates the creation of a 3D model of a scene from any view angle, which is an essential component in human body and behaviour simulation. Human behaviour analysis and simulation are started by the analysis of human motion, since motion reflects the behaviour, focusing not only on the global motion estimation, such as human segmentation and tracking, but also on the feature-based motion analysis. Further, human modelling techniques including a 2D or 3D human geometry (skeleton) model and a fitting algorithm link the detected motion to the model, generating a reliable human model that tracks the motion with sufficient accuracy. It enables fast semantic analysis of human behaviours. Based on these technologies, combining with sound and facial expression analysis, it is possible to couple emotional state recognition to the imposed conditions of the delivery simulator.

The aforementioned concepts bring more software and hardware devices and components into the training room than a single patient simulator. We also aim at an open system architecture that is flexible and extensible enough for the industry to introduce further development and future technologies into simulation-based team training.

3.1 *Software architecture*

The MedSim system uses a script-driven, agent-based architecture (Hu and Feijs, 2003; Hu and Feijs, 2006; Hu and Feijs, 2009a; Hu et al., 2010). During a training session many distributed components are employed, including the mother and baby manikins, tracking cameras, augmenting projections, medical monitoring equipments, etc. Every physical component has integrated sensors and actuators to detect the actions of the team and the status of delivery process and to react upon these actions and status according to pre-scripted scenarios and fetal-maternal models. Each physical component has a software counterpart and is modelled as a software agent. Distributed agents communicate over a messaging bus using a dedicated messaging protocol. A director agent interprets the training scenario script and coordinates the actions and reactions of the agents accordingly as shown in Figure 12.

Figure 12 MedSim system overview



3.2 Messaging protocol

In the system the agents operate separately in a decentralised manner. Communication among the agents is designed not to be managed through a central server, but to be carried out by following an XML-based protocol that is independent of network protocols, hardware and software platforms and implementation languages. The aim is that not only in a running system can a component join or leave the system at any moment, but also such a component can be developed and provided separately by a third party as long as it follows the protocol.

XML-based messages are easily extensible, easy to read, process and exchange. There is a variety of XML protocols, including XML-PRC, SOAP, WDDX, XMI, Jabber, ebXML, WSDL, WIDL, SCL, etc. XML-based messaging mechanism has been used in many distributed applications (Hu, 2003; Hu, 2006; Hu and Feijs, 2006; Hu and Feijs, 2009c). The messaging protocol for the MedSim system went through several design iterations and the final version (0.1.3) is based on SOAP (Simple Object Access Protocol) (Gudgin et al., 2003). Although SOAP was originally designed as a basic messaging framework upon which web services can be built, it was later extended for general purposes in exchanging structured information in a decentralised, distributed environment in a way that is independent of any particular programming model and other implementation specific semantics, which satisfy the requirements of the communication between the MedSim agents. Simply saying, the MedSim messaging protocol is an application of SOAP. As an application, implementation of such a protocol can easily make use of a rich set of existing SOAP-based communication libraries for many different hardware and software platforms.

A MedSim message has a header part and a body part. The header part defines the related information such as version control, transportation source and destination, identifications for communication sessions and quality of service requirements. In the body part concrete message entries are defined, each with a list of parameters. A simple example of such a message is shown in Figure 13.

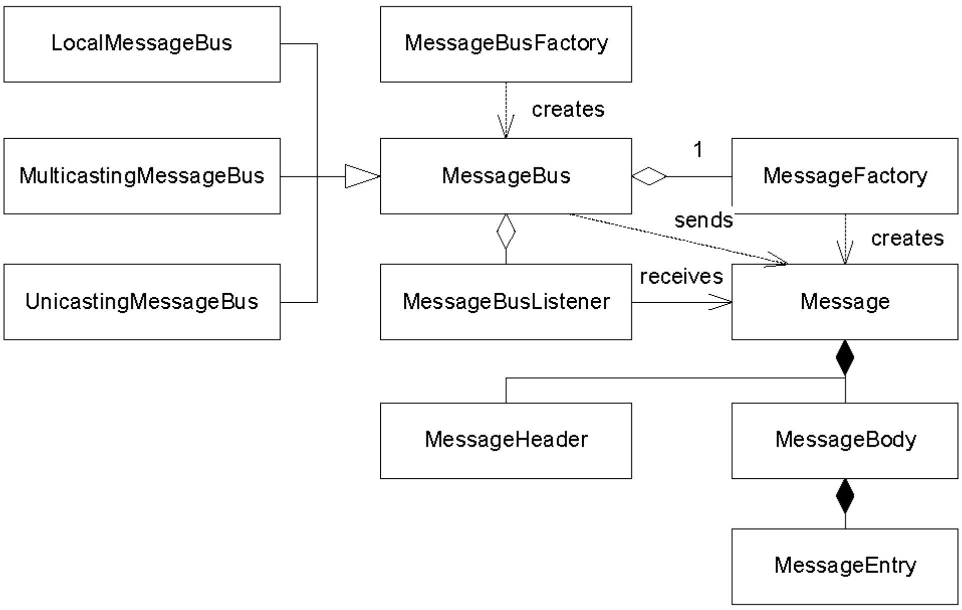
Figure 13 Example of MedSim messages

```
<?xml version="1.0" encoding="UTF-8"?>
<SOAP-ENV:Envelope
xmlns:SOAP-ENV=http://schemas.xmlsoap.org/soap/envelope/
xmlns:medsim="http://www.deliverysimulator.id.tue.nl/medsim/">
  <SOAP-ENV:Header>
    <medsim:Sender>Baby</medsim:Sender>
    <medsim:Receiver>Mother</medsim:Receiver>
  </SOAP-ENV:Header>
  <SOAP-ENV:Body>
    <medsim:HeartBeat>
      <rate>100</rate>
      <isNormal>true</isNormal>
    </medsim:HeartBeat>
  </SOAP-ENV:Body>
</SOAP-ENV:Envelope>
```

3.3 Messaging bus

The communication channels in the system architecture are implemented as a function of the ‘Messaging Bus’, with which the agents can send messages to or receive messages from the other agents. The structure of the messaging bus is shown in Figure 14. The components in this structure are specified as abstract interfaces such that it can be implemented by a third party using different tools on different platforms.

Figure 14 Messaging bus



During the project we created three reference implementations in Java, firstly 'local' then 'unicasting' and 'multicasting'. The local messaging bus was created firstly for testing purposes, which only channel the communication among agents on the same local machine. The unicasting and multicasting messaging buses were implemented using JXTA protocols (Gong, 2001). The JXTA protocols are a set of six protocols that have been specifically designed for ad hoc, pervasive and multi-hop peer-to-peer (P2P) network computing. Using the JXTA protocols, peers can cooperate to form self-organised and self-configured peer groups independently of their positions in the network, and without the need of a centralised management infrastructure. The multicasting messaging bus propagates the message to all the peers connected to the same bus. Although multicasting may cause higher demand on the network traffic, for a small amount of peers, it is convenient. If the system scales up, the multicasting bus can be easily switched to a different type, namely a unicasting bus, by requesting a different bus from the *MessagingBusFactory*.

4 Discussion

Last but not least we ought to explain why we believe it is beneficial to use precisely the same architecture and protocols for both neonatal monitoring and simulation training. The first reason is that this allows for a smooth transition from innovative techniques in monitoring to training with the same techniques. The second reason is a smooth transition the other way around: when testing innovative techniques in monitoring, before applying them to real children or mothers, the manikins and the training environment turn out to be extremely helpful. An example is the work reported by Bambang Oetomo et al. (2009), where the efficacy of an innovative resuscitation device could be proven using an instrumented manikin first.

In the area of body sensor networks, as the number of body signals and sensors increases, it is no longer feasible for each sensor or sensor modality to take another set of wires, amplifier box, power supply, etc. Then it becomes essential to embed multiple sensors in a single carrier (such as a baby jacket), sharing power sources and sharing wireless channels. At the system level, wirings become buses and wireless protocols, algorithms become embedded software and the power supply becomes a power management system. The system has to be reliable and robust enough to be used clinically. The key to success lies in incremental development and standardisation. Even then, realising embedded systems prototypes is very labour intensive.

The central theme of non-invasive perinatal monitoring is improving a pregnant woman's or a pre-term neonate's comfort without compromising signal quality. The challenges come from both integration of sensors and other technologies for system performance enhancement and user-friendly design for comfort improvement. First, during the integration of non-invasive sensors (e.g. textile-based bioelectric sensors and optical sensors), it is important to establish system model and optimise numbers and locations of sensors considering different noise sources, interference and the movement artefacts. Secondly, management of autonomous or adaptive sensor systems is essential for self-calibration of sensors and artefacts suppression. Thirdly, the design for comfort improvement is multifaceted and multidisciplinary, requiring skills ranging from medical science, ergonomics, human factors, material knowledge, smart textiles and form-giving to PCB design, power management, signal processing and software engineering. Thus, multidisciplinary collaboration among clinical specialists, engineering experts and industrial designers plays an important role in creating the non-invasive neonatal monitoring systems and its further developments. Finally, apart from the women and neonates, there are several categories of users and stakeholders: doctors, nurses, partners, parents, technicians and maintenance personnel. Their distinct expectations and requirements must be collected and balanced by a suitably structured design process.

The projected global transition to patient-centric care depends critically on powerful non-invasive monitoring techniques for use in ambulatory and at-home settings. A key benefit of the perinatal field lies in the fact that the end users in this field tend to be young and receptive to new technologies even if these technologies are not yet mature. This attitude is essential to iteratively improve technologies to the maturity level that is required for broader patient-centric markets like those of elderly and chronic patients. Hence advanced sensor integration for perinatology can be viewed as a significant step towards patient-centric care.

5 Conclusion

In this paper, we presented the design work of sensor integration for perinatology, including a smart jacket integrated with textile sensors for neonatal monitoring and the software architecture for a delivery simulator. We demonstrated the prototype neonatal smart jacket with textile sensors integrated for ECG measurement and showed the experimental results obtained in the clinical settings. We described the software architecture with XML-based messaging mechanisms and the P2P network technology that supports open and flexible integration of distributed sensors and actuators into the delivery simulation system. The smart jacket and MedSim system have already been used as platforms for further research. TU/e researchers from different departments and medical staff from MMC are working together towards the future non-invasive perinatal solutions.

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