Wearable Sensor System Prototype for SIDS Prevention

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***Abstract*— Sudden Infant Death Syndrome (SIDS) causes unexpected death of infants; a variety of risk factors for SIDS have been detected through the years. A significant number of deaths occur when the children are being cared by non parental caregivers. We found that, using wearable systems some of those risk factors can be constantly monitored and the gathered information can be sent to the parents through a mobile application. In this paper, we present and evaluate a prototype of an augmented object and a mobile application that could help the prevention of SIDS. A wizard of Oz validation helped us determine the feasibility of developing and implementing the prototype. Testing results of the prototype showed positive parent reception to wide range monitoring and acceptable performance of the application.**

Keywords- Wearable system; health monitoring; HCI; augmented objects

I. INTRODUCTION

Sudden Infant Death Syndrome (SIDS) is an unknown phenomenon that causes the death of infant from birth up to the first year of age [1]. The American Academy of Pediatrics issued in 1992 a series of recommendations to prevent SIDS. Although the mortality rate has decreased, there are still SIDS cases reported worldwide [2][3][4].

According to the Institute for Clinical Systems Improvement, stomach or side sleeping are major risks for SIDS [5]. Therefore, they advise that children should sleep on their backs. Side sleeping was an alternative position, however this position is no longer recommended.

Besides SIDS, there have been reports that show a rise in the number of children deaths by accidentally suffocation or strangulation in bed [6].

Tintinalli et al. [7] stated that SIDS main risks can be categorized into two types of factors extrinsic and intrinsic. On one hand extrinsic factors include: prone or side sleeping, bedclothes overhead, sleeping on sofa or soft furniture, high ambient temperature, soft bedding, bed sharing, postnatal smoke exposure and prenatal smoke, alcohol or drug exposure. On the other hand, intrinsic factors include, but are not limited to: prematurity, family history of SIDS, gender, race and poverty.

In the United States, approximately 20% of SIDS deaths occur while the infants are in the care of a non-parental caregiver [1]. This may be due to a change on the sleeping position.

Nannies or other caregivers could place the baby in the stomach sleeping position and the babies are not accustomed to being placed in that position [7]. To address this issue, we develop an application that allows wide range remote monitoring using Wi-Fi. Common approaches of baby monitoring mainly use short range communication.

The main recommendations of the American Academy of Pediatrics to prevent SIDS are [1][3][4]:

- Supine sleeping position
- Firm sleeping surface
- No loose objects on the crib
- Sleep close but separate of the baby
- Avoid overheating
- Do not use home monitors as a strategy to reduce the risk of SIDS.

Even though authors explicitly say that parents should not focus on a single risk factor [1][3], technology nowadays allows us to verify the position of the baby and the environment's temperature very easily using wearable sensors.

Some wearable systems are based on augmented objects. Augmented Objects are basically everyday objects provided with additional characteristics through hardware and software in order to allow users to interact with computation systems through those objects [8].

Our contribution in this paper is to provide a description of the state of the art in wearable systems for child security on SIDS. We studied academic and industry efforts to create devices to help prevent SIDS. Also, we took into account the reported recommendations of experts in medicine and pediatrics.

We present the description and evaluation of an augmented object that is able to extract the baby´s information. The information is send to a computational device that analyzes it and sends it to the parent's phone through a mobile application. We used Wi-Fi as our wireless technology to enable constant wide range monitoring.

Also, we provide some data on the time frames required to provide assured information to parents when monitoring their babies. Performance testing was conducted to assert the possibility of managing multiple monitoring and notification devices concurrently. We present the benefits of product validation techniques used in the development process of ubiquitous computing applications.

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In the following, Section II of this paper shows related work to this research, some different approaches in SIDS prevention. Then, Section III describes the design and implementation of the augmented object, the mobile application and all the configurations required. Section IV presents the results of the evaluation carried with the object. Finally, Section V presents conclusions and further work.

II. RELATED WORK

Over the past decades there has been an extensive research on bio-monitoring techniques. In 2003, Budinger [9] stated that the first success on remote monitoring systems for babies was the use of wireless breathing monitor using radio signal. Author also presented additional research however results produced up to 50% false positive signals.

In 2006, Linti, Horter, Österreicher and Planck [10] developed a sensory baby vest used to continuously monitor respiration, temperature and humidity. Authors used a personal computer to run the monitoring software which also alerts when parameters exceed the threshold established. The main drawback of this research was the lack of remote communication in order to allow monitoring of gathered data.

In 2007, Cao and Hsu [11][12] presented a non-invasive and remote infant monitoring system using CO2 sensors that uses exhaled air from an infant to reduce the potential risks for SIDS. The proposed system uses sensors placed on the crib´s edge. The main advantage of Cao and Hsu proposal is that it incorporates wireless communication capabilities. Other large advantage is that the system is non invasive. However, several sensors are required to approach the problem and even though authors mention the possibility of risky sleeping positions they do not addresses the recommendations given by the American Academy of Pediatrics (AAP).

Rimet et al. [13] presented a surveillance system for infants using a specially designed infant shoe to carry on a pulse oximetry in order to determine the CO2 saturation. The designed shoe also has an integrated 3-axes accelerometer.

Other examples of systems used to monitor children are Sensory Baby Vest, baby suit, baby glove and the already mentioned BBA bootee all these systems are wearable. There have been of course, efforts in the development of non-wearable systems such as augmented cribs, instrumented toys and others. However, toys or other loose objects in the crib go against the recommendations to help prevent SIDS [14].

Another interesting work was presented by Ziganshin, Numerov and Vygolov [15]. The authors present an ultra-wide band baby monitoring system that unlike the common sound or video baby monitor, constantly monitors the babies. This system is a peer to peer system with a sensing unit and a parent unit.

Most of the mentioned prototypes were developed on academic environments and laboratories and never reached the industry or were massively sold.

Besides academic prototypes, there are some instruments offered in the industry, such as Snuza Breathing Monitor[16], which is a small device that can be clipped to a baby´s diaper and vibrates or sounds when it does not detect breathing. It also has visual indicators.

Babysense V Hisense is a monitor that detects the baby´s movement using pads that are placed under the mattress. It incorporates communication to mobile phones however the information that it sends is a breathing graphic [17].

TiltMon Baby Sleeping Posture Monitor [18] is another peer to peer sensing monitor that alerts parents when the baby´s tilt is dangerous. WeMo [19] by Belkin is a monitor that helps to analize sleeping and crying patterns and notifies parents through a mobile application; however, it notifies only through audio as a common monitoring system.

Also, some non-technological efforts have been made including: Baby Sleeps Safe that is a two piece sleep system that replaces loose bedding and prevents the baby from turning around [20].

The last product that we would like to address is Sensible Baby. This product was first globally seen at the International Consumer Electronics and Consumer Technology tradeshow, CES 2014. Sensible Baby monitors position, temperature and movement or breathing sending alerts when a risk is detected [21].

Some issues with the actual approaches in industry are:

- They use loose objects to monitor the baby´s status.
- Communication is peer to peer: one monitoring device and one notification device.
- Communications are short range: communication protocol normally allows only a few meters between the monitor and the notification devices.

Our prototype addresses all the presented issues. By being an augmented object rather than a loose object it addresses the recommendations of the American Academy of Pediatrics. The used wireless technology (Wi-Fi) and architecture allow multiple notification devices to monitor one sensing device. Moreover, Wi-Fi allows large range communication and monitoring as well as short range. This feature provides more functionality to our proposal and addresses the fact that 20% of SIDS deaths occur while the infants are in the care of a non-parental caregiver.

III. PROTOTYPE DEVELOPMENT

This section presents the design and development of an augmented object that senses motion, position and temperature to prevent SIDS.

The augmented object presented is complemented with a mobile-Web application that displays the information gathered by the augmented object.

The augmented object prototype was developed following an Augmented Object Development Process (AODeP) [22][23]. This method ensures that all the stages in the development are focused on the problem to solve and from an engineering perspective.

AODeP proposes six main stages: (1) problem definition; (2) context of use definition; (3) requirement definition; (4) selection of the object; (5) development; and (6) testing with users. We will explain the development through these six steps.

Through studying the reality that parents live and the commercial systems we observed that, the problem we must address is the continuous monitoring of babies, providing nonstop feedback to the parents when possible or at least locally in order to prevent some of the risk factors of SIDS.

The system usage context actually depends on the user. We addressed the context of a particular baby and at least one person monitoring the baby´s condition.

The requirements of the system -defined by the authors by studying the users- are the following:

- The system must be able to detect the baby´s position and send the gathered data to the mobile application.
- As it is been confirmed by medical pediatric institutions the back sleeping position is the best one to prevent SIDS. So, the system must be able to detect any other position and trigger an alarm on all monitoring artifacts.
- The system must be able to detect ambient temperature and trigger alarms if thresholds are violated.
- The systems must be configurable.

The sensing device (augmented object) needs to be selected. Following the proposed methodology presented by Guerrero, Ochoa and Horta [23] a set of candidate objects were identified and we selected a clothing patch. Table 1 shows all the possible candidates for monitoring and notification. The notification message would be through a mobile application and the local notifications will be addressed through future analysis.

TABLE I. CANDITATE OBJECTS TO BE AUGMENTED

Objects		
Monitoring Object		*Notification Object*
Blanket	Tank top	Baby monitor
Crib	Clothes patch	Phone Application
Pijama	Belt	Alarm clock

A. System´s Architecture

Architectures have been presented by several authors through the years to approach wearable health monitoring systems [24]. Normally raw data is not processed locally at the smart device but at the "cloud" [24]. We decided to follow that approach.

The system is composed by: (1) the sensing device that would be attached to the baby´s clothes, (2) the notification system that displays the main information gathered on the parent's phone and (3) a central Information Management Unit that processes and manages the information and displays the information in a Web site. Figure 1 shows the main modules of the system.

The communication technology between the sensing patch and the information management unit is Wi-Fi using a local area network. We assume that the parent's phone has access to Internet, either using mobile network or wireless network.

The main application flow consists of the monitoring objects sampling the data gathered by the sensors, sending it to the information management unit that process and stores the information gathered, and publishes it on a Web site.

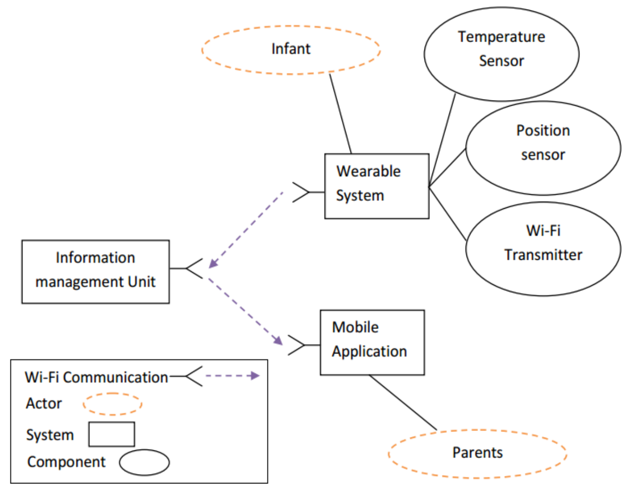

Figure 1. System´s Architecture.

The Web site uses Google's Open Id as the way to login. This information can be accessed through any web browser in case you do not have your phone but the main flow will use a phone so that if an alert is triggered the phone capabilities are used to alert the parent.

B. System´s Configuration

The application configuration is quite simple. It requires the user to configure the web site URL, when the information management unit is configured. This process is carried using a wizard approach on the server side. This wizard guides the process to set up the monitoring device and provides the URL that must be set on the parents or caregivers phone.

When the information management unit is configured an emergency phone number is required. This number is accessible through a panic button on the application interface. Usually this number would be the one of the caregiver or house where the child is located.

The next configuration is temperature. This is required in order to allow the correct functioning of the application in different latitudes and altitudes. The parent is required to set the "normal" range of temperature and the threshold acceptable depending on the variations.

Finally, the tilt acceptable for the application is configurable because some doctors indicate that the crib mattress should be tilted to about a 30° to 45° angle. If there is no tilting this parameter is not required but it is available to counteract the surface tilting.

C. Monitoring Device Design

We built the prototype of the sensing object using Phidgets sensors [25]. The sensors used in the system are the temperature sensor and a gyroscope with accelerometer.

We set all the parts inside a cloth patch (shaped as a bear) adhered to the child's clothes and that can be removed when needed. However, in order to remove it caregiver interaction is required.

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Figure 2. Doll with attached sensors used for lab testing

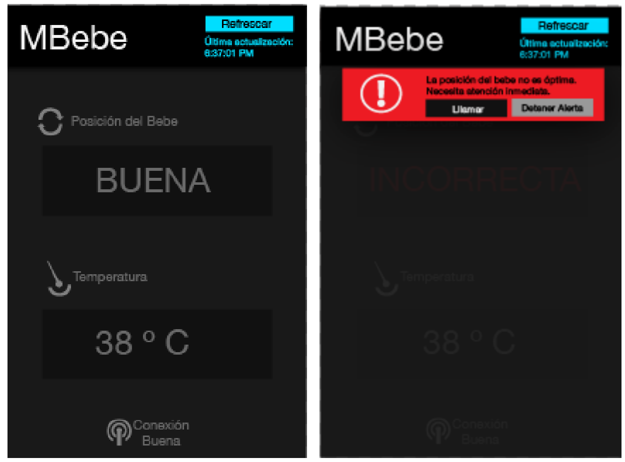

Figure 3. Mobile application screenshot

The sensors used were a temperature sensor and a 3-axis accelerometer. Figure 2 shows both sensors on a doll to demonstrate size. Using Phidgets to create the prototype did not allow us to construct a smaller sensing device but did allow us to test the product. In order to incorporate in the industrial setting more specific and smaller sensors must be used.

The incorporation of complex processing algorithms in wearable systems is very limited because of autonomy and capability of the components. Therefore we decided to use a centralized approach. The components only read and send the data and the Information Management Unit process it.

The Information Management Unit is a computer that process the information gathered by the sensors and publishes it on a web page that can be accessed through the internet.

Temperature sensor included in the prototype allows measurement rated at -30°C to +80°C with and error threshold of ± 2°C with a current consumption of 1 miliAmperes. The error threshold is taken in count when monitoring since ± 2°C are subtracted and added to the reported data and compared with the configured parameters.

The 3-axis accelerometer allows a measurement of acceleration up to ± 8 g. The gyroscope information allows a speed of ± 2000°/s (degrees per second). 0.07°/s is the minimum required speed that can be detected. The compass allows a 5.5 Gauss as the maximum magnetic field measured.

The maximum speed of sampling is 4 s/s (samples per second). However, to avoid server saturation we use one sample per second on our prototype. Wireless communication depends on the routers and server speed.

D. Mobile Web Application Design

The mobile Web application was built using a WebView to embed the web page displaying the information into the phone, instead of using mobile web browser because browsers has already known vulnerabilities that attackers are targeting [24].

Other important aspects that lead us to develop the system using a mobile-web application was the access that these applications get to the main components of the phone as the Ringtone Manager, Internet access, vibration, and the ability to bring to foreground the application when the alarm is triggered.

The mobile-web approach provides the parents with the possibility of accessing the system via Internet browser; of course, this approach limits the capabilities of the system.

Figure 3 shows screenshots of the application. The application was developed in Spanish. However, it allows multiple languages.

The left part of Figure 3 is the application on a normal state, which provides the position and temperature information and the connection status. It also allows a manual refresh of the information for a confidence boost, however the data is updated automatically every few seconds, this parameter can be configured.

When the alarm is triggered the image on the right is displayed. The alarm states: “The position of the baby is not optimal. Attention needed immediately”. This second screen has two buttons the one on the left is used to call the emergency number previously configured, the concept behind this emergency call number is that it will contact the person in charge of the baby at the moment; the one on the right “Detener Alerta” stops the alarm.

We considered using a Trusted Execution Environment for this application to increase the security of the application and the information.

The authentication on the application (actually the Web application) is done by Oauth2with Google credentials.

IV. PROTOTYPE EVALUATION

This section presents the evaluations performed to out prototype, starting with a concept validation through a Wizard of Oz approach [26]. Afterwards, we performed functional testing and performance testing. We measure the response time of the application on a load demand setting and on stressed settings with up to a 1000 connections.

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A. *Concept Validation*

The first part of the evaluation process was a concept validation. We interviewed 5 users in their actual context who were related to care giving for children. During these interviews, some interrogations emerged: What is the safest position for a baby? Which exact tilt degree is dangerous? Is the phone app important for the notification or are notifications only necessary near the baby's location? Are users going to be looking at the monitoring app frequently enough? What is the correct size for the object given that it will be adhered to a baby? Where is the correct place to put the patch in the body? What would happen if the baby moves a lot?

To answer these questions we decided to conduct a Wizard of Oz validation. Wizard of Oz is a technique for validating new ideas and evaluating prototypes. It is a simulation in which participants are given the impression that they are interacting with an actual system. However, participants are actually interacting with humans, which pretend to be the system [26].

The Wizard of Oz validation consisted of 5 different people that were given the task of monitoring a "baby" through a mobile application. We had people in charge of trigger the alarm on the phones to simulate a threshold violation. From this validation we decided to reduce information on the application interface to improve readability and make it easier to use.

This was done to verify the ability to detect movements of the baby, to validate the connection with the notification system. Our Wizards were given the task to tilt the dolls position at random times and our participants were tasked with keeping their babies alive, calling to check if they noticed that something was wrong in the babies' environment.

Each session consisted of a timeframe where the caregiver was away from the baby and had to monitor the environment remotely with the mobile device, which as we previously stated is used as an interface for the information the augmented object is sending. We would validate after each session that the prototype for sensing was working correctly, and the response from the user was appropriate.

In the post-session interviews, we verified if the information appeared to be timely and enough, and validated the information displayed times by performance testing. To allow quick response the application was designed to update the data periodically although the page only requires 1.9 KB of data per update.

These validations helped us to determine the acceptance of wide range monitoring from the parents, and that they are able to react to an alert from our prototype.

B. *Functional Testing*

In parallel to our study about our user's confidence and information needs, we also had to test some physical characteristics about our prototype. We developed a clothpatch. We tested the prototype on a real baby, who was monitored at all times. The purpose of this experiment was to determinate the best position for the augmented object and to evaluate if it was comfortable for the baby, despite is prototype limitations. We conclude that the baby is not able to take the object off or turn it off, and that they are able to sleep comfortably without the object interfering.

We tested the sensing device on few people in order to make sure that the position was comfortable when sleeping in the correct position and that the babies could not take off the device. However, at our university and country there is a real challenge getting official permission to run clinical tests. Therefore, we conducted the tests with people related to the project and volunteers.

C. *Performance Testing*

We conducted a series of test using both online and offline tools to check our application's performance. The first test was carried using a website performance monitoring tool: CA APM Cloud Monitor. Our information management unit was a Quad-Core AMD Opteron™ Processor 2382 at 2.59GHz with 1.00 GB of installed RAM and Windows Server 2008 R2 Enterprise 64-bit.

We designed the mobile-web application so that it would perform as fast as possible. Table 2 and Figure 4 show the results of an evaluation using CA APM Cloud Monitor [27]. The main results show that the average result is 180ms on the download time. An interesting assessment that can be viewed in Figure 4 is that all the countries in Europe have a difference of 36 ms and Asia has the biggest download time. These results were expected due to the communication latency.

All this data shows a normal behavior considering the geolocation. It is obvious that, if the system was to be launched at an industry level many servers would be placed all over the world in order to provide reliability and stability therefore reducing the times to probably a similar rate of the one showed by U.S.A of 92 ms.

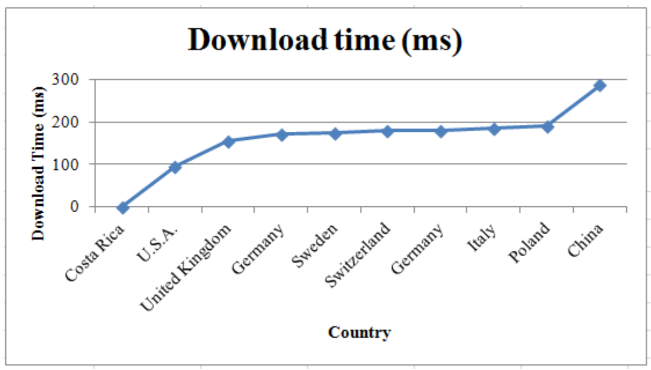

Figure 4. Graphical represention of data gathered with CA APM Cloud Monitor

The main defects found, that if fixed would help speed the process for download is:

- Some issues with JavaScript could be fixed by eliminating render-blocking and CSS.
- It could be also helpful to compact the JavaScript code.
- Sizing need to be improved depending on the displaying device

TABLE II. CA APM CLOUD MONITOR RESULTS

Test Perform from	**Measured Parameters**		
	Connect Time (ms)	***Download time (ms)***	***Download Size (Bytes)***
Costa Rica	0.0032	0.0036	2059
U.S.A.	92	96	2065
United Kingdom	152	155	2066
Germany	169	172	2068
Sweden	170	173	2065
Switzerland	176	180	2069
Germany	181	180	2068
Italy	183	185	2071
Poland	188	191	2076
China	283	287	2075

Figure 4 shows that the farther the parent is from the baby the higher the time to get feedback, however this time could be reduced by improving communications depending on the location of usage.

We propose a content delivery network approach to achieve high performance on our system, although this could increase the costs of operation. However, this approach could not be tested.

We test the systems performance through stress testing using two different configurations. The first configuration was: Users Count (40-600), user increase rate (10), network configurations (LAN and 3G). Table 3 shows the results of this configuration.

TABLE III. RESULTS OF PERFORMANCE TEST USERS 40-600

Counter	***Min***	***Max***	***Average***
User Load	40	600	320
Pages/Sec	14	291	153
Response time	0.019	0.30	0.048

The second configuration was: users count (1-1000), user increase rate (100), network configurations (LAN and 3G). Table 4 shows the results of this configuration.

TABLE IV. RESULTS OF PERFORMANCE TEST USERS 40-600

Counter	***Min***	***Max***	***Average***
User Load	1	1000	634
Pages/Sec	1	424	271
Response time	0.0046	1.1	0.36

The main results of the performance evaluation are that average response time is lower than 0.36 seconds either with 1 or 1000 users accessing the server. The inputs ranged from one to 357 sensing devices.

V. CONCLUSION AND FUTURE WORK

SIDS is a cause for concern amongst parents of infants, however there are risk indicators that given the proper technology could notify parents in time that their baby's environment is not optimal.

In this paper, we have presented the development of an augmented object prototype using a combination of the AODeP and HCI methodologies that can successfully notify caregivers of changes in the baby's environment.

The prototype here presented focuses mainly on sensor-based interfaces due to the requirements of the case study and is successful in monitoring the environment. It is important to note that the development of this augmented object required sensitivity due to the fact that this object will reside in the baby's clothes and that the study conducted to test the viability of this object being present when a baby was sleeping was extremely important.

Future work for this prototype could include incorporating the feedback received during the Wizard of Oz study to improve the accuracy and confidence level of the device in the eyes of the baby's primary caregivers.

We also need to perform more tests in order to evaluate reliability of the data.

One of the main improvements identified would be to select another object to augment in the local environment to address short range communications. This object would be used to notify the care-giver in the house, having a redundant system of notifications with hopes that either the parents outside of the house or the care-giver in the house will take immediate action upon the alert.

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