A Service-Based Perspective on Neonatal Critical Care

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ABSTRACT
This paper describes a service-based approach to the development of monitoring technologies for neonatal intensive care. We illustrate the design of an adaptable monitoring system targeting the specific requirements of a critical setting such as the Neonatal Intensive Care Unit. The system is based on two main components: (a) a browser that supports the creation of loosely-coupled services to allow the neonatal team to adapt the equipment to the requirements of individual newborns, and (b) a set of networked technologies for unobtrusive monitoring of vital parameters. The system is implemented using a middleware architecture that enables the neonatal team to create new correlations among existing and newly introduced monitoring devices. The architecture supports the dynamic assembly of services provided by a distributed computational system. In this way, it is possible to compare the vital parameters detected by different sources in order to obtain a more accurate monitoring of the newborns.

Keywords: neonatal Intensive care, service architecture, SOA, critical care, assemblies, prototypes, evaluation

1. INTRODUCTION
The Neonatal Intensive Care Unit (NICU) represents a highly dynamic and modifiable environment. The setting, including the incubators, external devices, sensors, and the preterm child itself, requires constant monitoring, configuration, and manipulation. To capture and respond to changes in the infant's health status, to handle device breakdown situations, and to comprehend mismatches between different sensor data are only some examples of important activities. From a medical staff's perspective, these activities are rather unsupported in the current practice. Doctors and nurses have to rely on their intuition, experience, and acquired knowledge base related to similar, previous occurrences. They ask for advice from colleagues when available and carry out 'trial and error' strategies to solve the problem at hand. Indeed, the current setting lacks

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support for traceability in error or breakdown situations and the possibility to validate the correctness of sensor data output. This article introduces the NICU as a setting for pervasive computing from a service-based perspective and discusses (a) how a Service Oriented Architecture (SOA)-based framework is constructed to allow end user manipulation of data, and (b) how service aggregation can support the care of preterm children and the medical staff in the health status assessment of preterm children. Furthermore, the service-based approach discussed in this paper, allowing services to be composed and decomposed 'on the fly' in runtime by users into loosely-coupled aggregated service entities, enables the care practice to overcome the current limitations as presented above.

Ambient and ubiquitous computing systems are changing the nature of our interaction with technologies. We must, however, consider the infrastructure rather than individual services or isolated functionalities to understand the potential in pervasive systems [1]. The combination of ambient technologies and internet services enables new scenarios of distributed information systems that affect design choices in many application domains. Indeed, ubiquitous computing devices and distributed services can be connected to create *ecologies* to support domain-specific user activities [2-4]. Such ecologies can be created as a networked *assembly* or orchestration of resources to serve specific purposes and be situated in diverse devices and physical locations. Furthermore, it is argued that people, supplementary to computers, should take the initiative to be constructive, creative and, ultimately, in control of their interactions with the world. Different scenarios in the Health Care domain [5-7], envision loosely-coupled connections among content and/or services and realize machine-based aggregation of services. In the latter case, the idea is to, for example, rely on automatic, semantic agents to fulfill specific user requirements on demand. This aggregation of information and a machine-based, interpreted, semantic approach are and will be, in many situations, not only possible, but also allow users to make complex queries and operations combining a number of different data sources and services.

However, there are situations wherein, from a user's perspective, a passive and hidden data aggregation and computation are not preferred. Our care scenario challenges this notion of invisible, calm computing, as proposed by Mark Weiser in 1991, and follows the implications anticipated by other, more recent contributions [8]. Ubiquitous and ambient technologies should "shift from proactive computing to proactive people" [8, p. 406] and find new modalities to engage user experiences. Specific situations in the NICU presented in this article are aligned with this idea of proactive people and end user control in pervasive systems and can be exemplified by the following use challenges:

Breakdowns and recovery – Most envisioned scenarios of a networked future deal with successful implementations and functional systems [9]. However, interaction with even the best of systems is not always as flawless as these scenarios presents. All technology runs the risk of breakdown and malfunction. To acknowledge this and to envision use-scenarios including breakdown situations become especially important in critical care scenarios and a setting such as the NICU.

Sense-making – The possibilities offered by networked devices should sustain a continuous understanding of the situation at hand from an end-user's perspective in order to support effective and meaningful use of services for the users. To allow, for example, care personnel to understand where data originates (for example, in a wireless setup where one cannot 'follow' the wire between a sensor and a display) or how it is calculated 'at a glance' can be critical in a NICU.

Dynamic construction – Construction of device and service ecologies should support specific requirements when dealing with emergency situations as well as daily care.

User Control – The notions of system automation and user control gain in importance when moving from individual to networked care (i.e., a network of devices, services, and human actors). How can a system manage access and manipulation of such a distributed information system? Indeed, to allow a network of services to not only be automated, utilizing a semantic notation for machine interpretation, but also to depend upon human actors to guide the inter-connection among device and services, can prove to be crucial for critical care scenarios.

These challenges are rather generic by nature but are of utmost importance in the critical care scenario of this paper (see section 'Scenario of current practice'). Hence, in this paper a specific perspective on the above-mentioned key issues will be provided by presenting a case study on the development and envisioned use of ambient and distributed technologies for an NICU. Inspired by Internet of Services (IoS) [10], Internet of Things (IoT) [11], and SOA [12], this paper investigates the idea to allow non-service developers (such as doctors, nurses, or patients) to work with a distributed computational network, reconfiguring it and changing connections among running software entities. This will allow completely new care scenarios due to the dynamic, loosely-coupled features of an SOA-based network of services. The user service composition strategy developed for the NICU scenario constitutes the specific contribution of the paper since the Assembly Browser, originally developed to allow navigation and composition of service assemblies, and the operative use cases will be described in detail as proper contribution of the paper.

The case study below will discuss system requirements that are manifested both at micro level (i.e., the incubator) and at macro level (i.e., the ward). This will be followed by a scenario which pinpoints some of the challenges in the current care practice and also serves as a springboard to discuss a service-based architecture with a strong focus on end-user control. A prototype will then be presented that utilizes the framework and was co-developed together with the medical staff at an NICU. The Assembly Browser, a tool for end-user composition of services in runtime at the ward will also be introduced. This will then be followed by a section related to trials we have performed with our prototypes and, finally, there will be a conclusion to our work.

2. THE NEONATAL INTENSIVE CARE UNIT

Premature birth is a traumatic event in a child's life. Premature babies experience a variety of problems depending on the developmental stage in which they are born. The time spent in the NICU is physically, psychologically, and emotionally difficult for these babies [13]. All the stimuli from the macro-environment are very stressful to their perceptive systems which are used to the protection of the mother's uterus. Moreover, many of the interventions performed on the child are very painful; during their time as patients in the NICU these children suffer a great deal, and the pains that they endure has an effect that is perceivable even in their later lives [14, 15]. Technological solutions capable of interpreting these requirements could avoid resorting to stressful interventions on the child and can support a personalized monitoring tailored on the specific needs of each baby [14].

2.1. The incubator

The incubator appears to be the main apparatus that medical staff can configure to adapt temperature, oxygen, and humidity, depending on the baby's condition (Fig. 1). A high level of re-configurability characterizes the system since each incubator should be conceived as an ad hoc entity tailored to the baby's conditions which change dynamically over time. The necessity of regulating the baby's micro-environment is based on the enormous difference between the endo- and extra-uterine experiences.

The ordinary work practice at the NICU is based on continuously combining and integrating data collected from different sources and the way in which people make sense of what is going on; this is crucial together with how the continuous process of understanding is supported and correlations are created. These aspects are fundamental for the medical personnel as they permit prompt interventions on the baby's behalf when necessary. This also concerns families involved in psychologically enduring such a delicate situation and to allow them to play an active role in the childcare [15].

Figure 1. Incubator in use at Nicu, 'Le Scotte' Hospital, Siena – Italy.

2.2. The NICU ward

To understand the work practice in such a delicate environment as an NICU, we arranged a number of user workshops in order to map the activities within the NICU and the use of tools that support the neonatal care. An additional objective was to identify the connections between the different components of this system. The results of these activities are reported in the form of an analytical description.

Current incubators cannot be intended as autonomous units (Fig. 1). Each incubator works in conjunction with a number of machines that support the different functions of the baby. The incubator is configured according to the baby's condition and is dynamically re-configured as the newborn status changes; it is a highly-malleable space of interaction, in which the medical staff continuously creates various configurations.

Devices, such as the Pulse Oximeter and the respirator surrounding the incubator, represent elements that are fundamental on a functional level. In fact, the *Pulse Oximeter* mainly allows monitoring of the baby's SpO_2 (oxygen saturation) and heart rate, and the *respirator* is a fundamental device in the incubator configuration. In an NICU, different kinds of respirators are used depending on the baby's condition and in combination with the humidifier in order to regulate the temperature of the air flow. The respirator and the Pulse Oximeter are in a strict relation so that any malfunction in one device affects the other's function, and may even change the baby's condition. Nowadays, the neonatologist performs this coupling during the interpretation of the situation. The different devices that work in conjunction with the incubator, though they have a mutual influence on the infant's status, are not integrated at all. No support is provided to show the way in which one affects the other either in normal situations or when problems occur.

The neonatal team in our project was asked to report on scenarios in which malfunction had occurred in their interaction with the current equipment in the NICU. One of these scenarios, related to the respirator's alarm, is reported in the following section.

3. SCENARIOS OF CURRENT PRACTICE

From the nurse's perspective, the sounding of the respirator's alarm is an indication that something is wrong. However, in the story reported, when the alarm sounded she couldn't determine whether the alarm was triggered by a change in the baby's condition or if there was a malfunction in the respirator. Thus, after considering the different parameters displayed, she decided to switch off the machine and then to restart it. If any change in the status of the system was verifiable, she could have even decided to disconnect the sensor in order to stop the alarm. No real understanding of the baby's condition was in this way supported. From the perspective of the system, there was an even less significant awareness of the actual situation. The respirator threshold manager detected a value that did not correspond to the configuration and thus triggered the alarm. The system was not able to indicate if the sensor was wrongly positioned or if the baby's condition was worsening. This example shows how, when interacting with technology, the modality by which information becomes visible is a fundamental aspect. Evidently, such situations can generate conflicting interpretations when problems occur in the baby, as reported by the medical staff.

The situation described above and in Fig. 2 illustrates a system that is completely opaque, and if any inexplicable variation occurs, it does not allow any hint or intuition as to what is going on [16]. The only way to overcome the situation is to apply a trial and error strategy. The medical staff first decides to control the baby, then checks the sensor placement and position, and then substitutes the sensor. Eventually they have the intuition to control the respirator. The way in which this trial and error strategy is applied depends on experiences of the nurse and of the neonatologist; no explicit or shared procedure is provided in order to support the diagnostic process. In the case of a mismatched detection, the medical staff must question the overall reliability of the system; no level of degradation is provided, and when something stops working the whole system is compromised. In other words, this can be considered an on/off device.

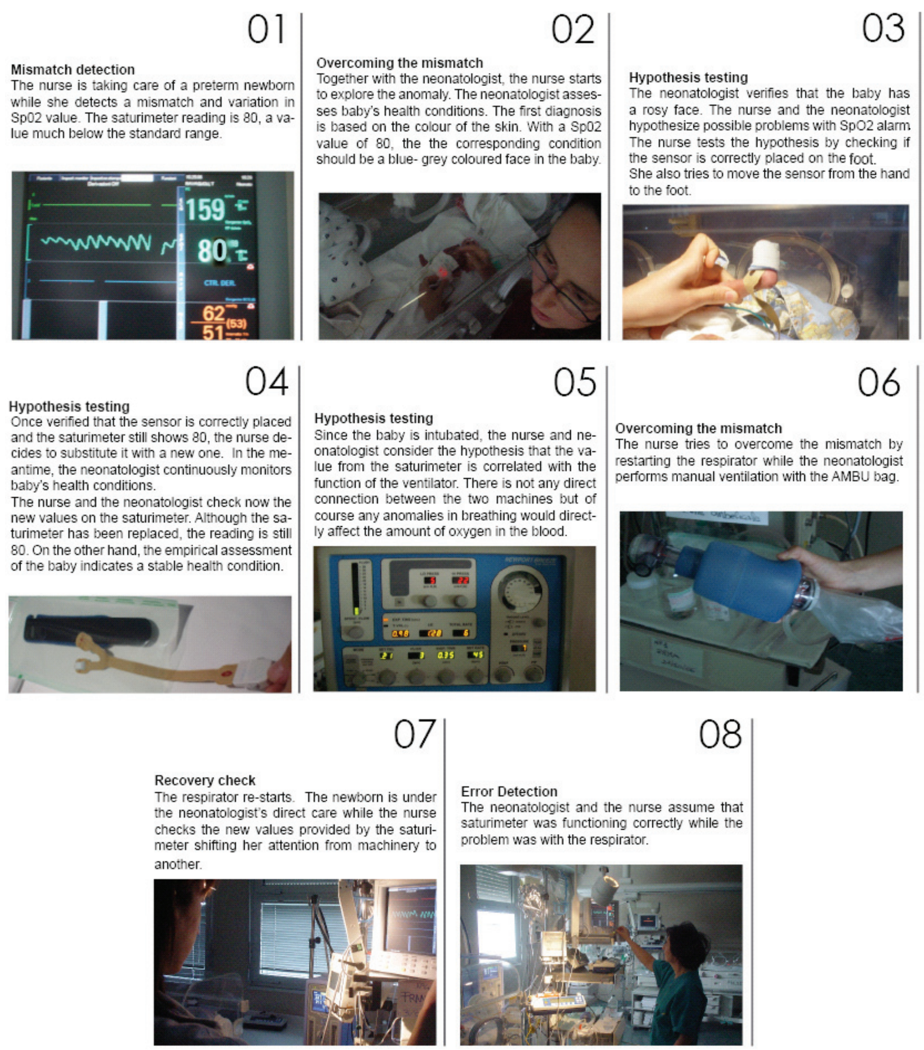

Figure 2. SpO_2 Variation Activity Scenario (Nicu, 'Le Scotte' Hospital, Siena – Italy): this illustrates the procedure that the medical personnel apply when a sudden variation in SpO_2 values (amount of oxygen in the blood) occurs in a newborn. The neonatal team (nurses and doctors) apply a trial and error strategy in order to understand the typology and the source of the problem. No functional coupling is now provided among the different machines.

Indeed, the current incubator represents a complex system in which different components play precise roles that have a strong impact on the child care. This leads to the following [14, 17]:

- The setting presents a high level of re-configurability; i.e., each incubator should be conceived as an ad hoc entity that is tailored to the baby's condition that changes dynamically over time.
- The incubator is associated with external devices that sustain the baby's vital conditions, but no functional coupling is now supported among those devices, thus making it difficult to recognize and discriminate system failure from the aggravation of the baby's condition.
- The work practice is based on the continuous combination and integration of data from different sources.
- Different NICU staff members have different access to the incubator depending on their roles, thus different access to the information being displayed.
- This setting should support the co-existence of emergency situations as well as daily care.

The scenario herein presented indicates a need to support reconfiguration and understandability from a user's perspective. The following are an introduction and an explanation of how end-user control can be achieved.

4. END-USER CONFIGURATION OF LOOSELY-COUPLED SERVICES IN NETWORKS AND DEVICES

More and more devices become uniquely addressable and connected to local networks and to the internet. This trend is on the way to fulfill the vision that we, and different artifacts, will be able to connect, track and interact with devices in our world both physically and digitally. Loosely-coupled services running in a network or in devices can connect and interact among them with or without the interference of human actors. This characteristic can appropriately support the dynamic, heterogeneous nature of critical care scenarios. The SOA perspective on autonomous services running in a cloud-network or in devices offers service providers and users an opportunity to share contents and interact utilizing static, predefined connections or temporary ad hoc orchestrations of services to cover emergent requirements. These services can run in a predefined network and in physical and potentially roaming artifacts, and they can also be composed and manipulated by the user.

To a certain extent, this orchestration is possible today through portals that allow users to aggregate and combine functionality. Microsoft Healthvault [18] and Google Health [19] are industrial initiatives based upon web 2.0 and portal technology. Aggregation and service mash-ups can be made but on an application developer's initiative. Research initiatives such as Salud! from GeorgiaTech [20] allow instruments such as a blood glucose monitoring device to send data to the system, but it is still a centralized portal aggregating functionality and data. The true power of SOA can be seen when running entities connect and interact in a more distributed manner. To allow services to connect and interact without the need of a central server or portal enables new possibilities in respect to, for example, scalability, breakdown redundancy, and flexibility. Services do not need to be ‘installed’ on a portal or added in a repository, for example, but simply need to announce their presence in the network, similar to ZeroConf networks [21] or the very idea of Internet. If one node fails, the whole system will not fail as in a centralized architecture. This graceful degradation fits well with the monitoring and correlation of data requirements existing within a critical care setting such as NICU.

4.1. Building assemblies of services

To overcome the current limitations in the scenario presented earlier and to enable end-user control of distributed services an architecture is needed. The architecture experimented with in this research is SOA-middleware [22]. The architecture allows a number of services to communicate with each other in order to provide support for both end-user applications and other services through published and discoverable interfaces. The services are autonomous and can be located on different platforms in a distributed network [23-25]. As described by Brønsted, Hansen et al. [26], not only service composition as functionality but also how the actual service composition is performed is essential. This is described below from a technical perspective.

The architecture allows distributed services to be connected through the use of Assemblies. The Assembly is the core concept of the architecture, and three middleware managers exist to support the formation, the modification, and the whole lifecycle of the assembly itself. These are the Assembly Manager responsible for the creation and lifecycle management of assemblies, the Resource Manager which maintains an up-to-date directory of all active (and if required, inactive) software resources, and the Contingency Manager which maintains resource and assembly resilience by applying both reactive and proactive compensation policies and mechanisms [27]. They are depicted in Fig. 3 for the whole computational infrastructure.

The assembly is a composition of software resources which potentially includes other assemblies. It consists primarily of services and provides additional functionality for the end users through aggregation, beyond what is provided by individual services [28]. The assemblies are relevant, both for the developer of ambient systems as a means by which to build new functionality, and for end users to dynamically tailor and augment the behavior of the system within a concrete context. The assembly may interact directly with the users or act autonomously at the user-level application. To be included in the assembly, each computational resource has to provide an XML Descriptor with essential data regarding how to deal with it (functionalities, communication channels, and features). The computational resources are discovered and composed accordingly by means of the interpretations of XML Descriptors. Any available resource in the operating environment that matches the requirements declared in the descriptors is identified and may be invoked to a particular form and assembly. They also specify the rules for the governance and replacement of a service. Composition is the ability to specify and plan a set of resources that contributes to the behavior of the assembly. Coordination describes the interaction of those resources within the context of the assembly. The model is dynamically constructed with the opportunity to break it apart and reconstitute the computational resources. An assembly may be distributed over multiple physical devices and, when an assembly is no longer needed, it can be decomposed by the users [28]. Figure 4 shows the relations among the middleware managers described in the section below.

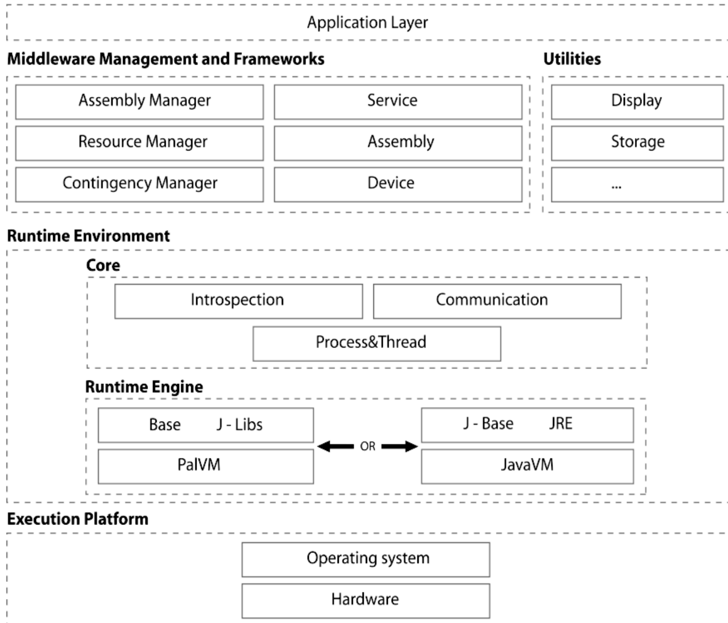

Figure 3. Layers and Functional Elements in the PalCom Infrastructure. The execution platform is the actual hardware and Operating System running on top of the hardware. The runtime environment is based on a Java-based system with a Java Runtime Environment (JRE) and libraries to run the PalCom framework or a specially developed system for small, embedded systems named PalVM. The core (rudimentary functionality such as communication and handling of processes and threads) can run on both of these runtime engines. A complete explanation of the individual components in this figure can be found in [27].

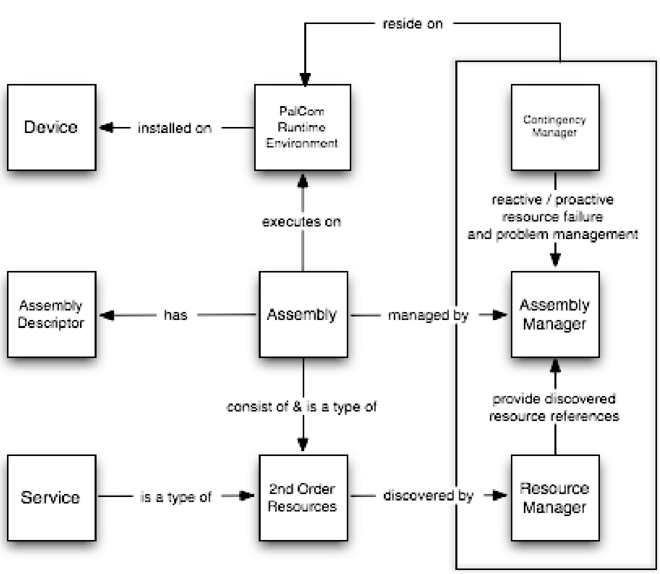

Figure 4. Middleware managers and the PalCom architectural ontology [27]

The *Assembly Manager* primarily has to deal with the construction of Assemblies according to the underlying XML-encoded Assembly Description, which will contain details of the particular 2nd Order Resources[1] and how they may be used. Together with the construction of Assemblies, an Assembly Manager is responsible for deploying the Assembly and thereafter managing its lifecycle in collaboration with the available Contingency Managers.

The *Contingency Manager* is responsible for indicating faults and problem conditions occurring in active Assemblies and 2nd Order Resources through the application of a variable set of contingency tools and mechanisms. The Contingency Manager is expected to provide a set of reactive contingency actions (i.e., compensations) that respond to unattended events. This provides that a system becomes more resilient and also capable of adapting to changing ambient conditions. The *Resource Manager* is responsible for maintaining an up-to-date directory of discoverable 2nd Order Resources. The primary operations of a Resource Manager are the discovery and monitoring of 2nd Order Resources and the match, description and provision of resources according to needs expressed by Assembly and Contingency Managers. The Resource Manager manages the lifecycle of selected resources including initiation, termination, restarting, and movement, etc. of 2nd Order Resources.

5. INCUBATOR PROTOTYPE

As indicated in the last section, how service composition is performed is of utmost importance. We will now provide an explanation of the incubator prototype and how users can work with service composition and assemblies using the prototype and the framework introduced in the last section. This research has worked with scenario-based evaluation also highlighted as preferable by Brønsted, Hansen et al. [26] due to actual testing and empirical data.

The design process aimed at addressing the characteristics of this application domain has been developed throughout iterative design phases into a redesign of the original setup. This prototype is composed by an assembly of services and devices that are able to respond to the specific requirements of the NICU [29-31]. The incubator prototype integrates dedicated technologies (i.e., the Biosensors Belt and the Mattress) with the current medical equipment at the NICU. A specific User Interface called the ‘Assembly Browser’, is used to allow end-user’s compositions of services and devices [32]. The Assembly Browser allows the medical staff to discover the available services and devices, to access and monitor data, and to create, manipulate, and visualize assemblies during the daily care activity.

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[1]1st Order Resources are low-level resources associated with a physical device including processor load, memory, bandwidth and power supply. The deployment of a service (i.e., a 2nd order resource) depends on the availability of the foreseen hardware requirements. The Resource Manager is deputed to free up resources through priority overrides, scheduling, etc., within the operational constraints of service, devices, and usage expectations

2nd Order Resources are abstractions used to describe those resources that either contain or consume 1st Order Resources. Examples include Assemblies, Services Devices, and communication channels. In order for the Palpable Architecture to be flexible and robust enough to support the user’s experience of palpability, the 2nd order resources ought to be directly manipulated and adapted.

The incubator prototype re-conceives the NICU as assemblies of services and devices that are able to respond to the specific requirements of the setting (Fig. 5). The incubator prototype can be intended as an assembly composed of the incubator itself and the surrounding machines. Specific technologies for noninvasive monitoring have been developed in order to integrate and enrich the diagnostic work of neonatal care.

The services intentionally run directly in each device's hardware but rarely does medical equipment allow for external manipulation of its firmware. Hence, we mostly 'wrapped' functionality through the use of an additional, programmable computer running the middleware and related services. The idea is, however, that the middleware shall run directly on each machine and be shipped with relevant services. The middleware today can run on embedded-size computers making this vision possible. What follows is an overview of the incubator prototype components. Beside this, it will be illustrated how and to what extent the notion of assembly can support critical care in this setting.

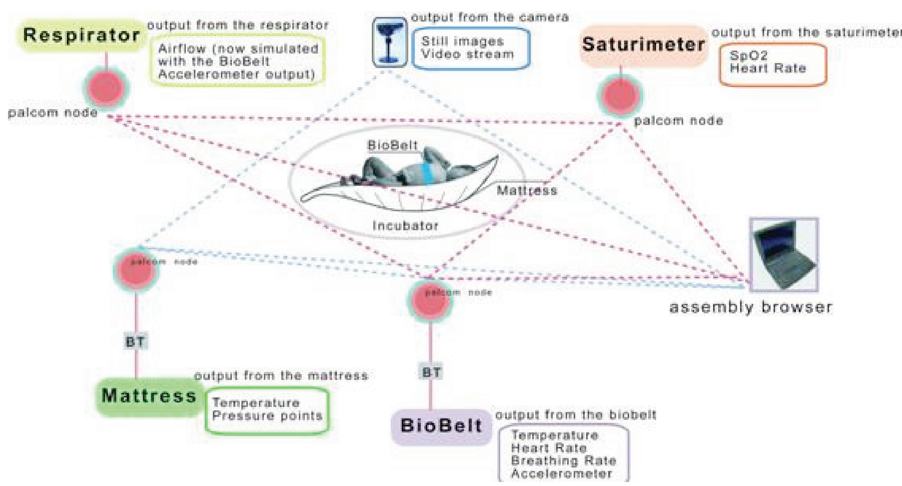

Figure 5. The incubator assembly is composed of the existing machines such as the Pulse oximeter, and technologies such as the BioBelt, the Mattress, the PalCom-node, and the Assembly Browser. BT = Bluetooth connection.

5.1. The BioBelt

The Biosensor Belt is a sensitized band (Fig. 6). The belt consists of a system of sensors inserted in textile and can be configured in combination with the parameters detected by the other devices in the NICU according to the specific monitoring needs of the infant. The belt is developed as a prototype with embedded sensors and transducers for monitoring the heart rate (HR), the breathing rate (BR), the body movements (BM), and the temperature (T). Concerning the physiological parameters, the belt aims at facilitating the continuous HR, BR, BM, and T monitoring with proper signal acquisition and pre-processing systems, while ensuring an unobtrusive measurement.

The belt can be adapted to fit the size of the baby and adjusted in a noninvasive way to avoid the direct contact of scratchy material with the baby's skin.

Figure 6. A wearable and sensitized band equipped with a set of sensors for monitoring newborn vital parameters including heart rate, breathing rate, temperature, and respiratory movements. The fabric is soft and extremely thin, and the sensors used are electrodes and extensometers, while the transducers are generic accelerometers and temperature sensors for medical use. The BioBelt permits a variety of measurements without having to paste, fasten, or position anything on the newborn but the belt itself.

Figure 7. A mat of polyurethane gel with embedded sensors for the recording of interfacial pressures of specific anatomical points, temperature, and movements. The gel has anti-decubitus-ulcer properties because it distributes interfacial pressures in a larger surface area with respect to standard foams and with isotropic behavior so relieving the contact points on the body.

5.2. The Mattress

The Mattress prototype developed features polyurethane gel with embedded sensors intended for the recording of temperature, movements, and interfacial pressures at specific anatomical points (Fig. 7). The gel distributes interfacial pressures throughout a larger surface area with respect to standard foams and with isotropic behavior, thus relieving the contact points on the body. The gel has a high thermal inertia and thus favors the maintenance of the body temperature. The pressure and temperature sensors can be embedded in a distribution matrix so that they cover the entire area under the body. These permit the measurement and monitoring of pressure, temperature, respiration (indirect measurement from the rhythmical variation of pressure in time), and physical movements. The signals are collected through a dedicated digital-to-analog converter (DAC) and forwarded to a dedicated service.

5.3. The PalCom-node

This node is an I/O-device that functions as a bridge between existing devices in the NICU and the technologies developed within the research project. Without direct access to the chipsets of the diverse medical equipment at hand in our scenario, we cannot run the architecture and hence services directly on the machines. The architecture exists for embedded devices with limited memory and processor power, but even if resource-wise we could execute the framework and services on the medical equipment, it is not practically possible within the frame of this project. Hence, by connecting a computer or another unit capable of executing the framework and related services to existing data output ports (e.g., a debug serial port) on the medical equipment, we can 'wrap' a given medical functionality. The PalCom-node is hence the interface between legacy medical systems and the rest of the system. We acknowledge that this approach is not perfect, but it allows us to work with complex medical equipment in a testing and pre-production phase.

5.4. The Assembly Browser

The Assembly Browser allows the neonatal team to discover, create, and manage running services and assemblies of services and devices (Fig. 8). In this way, the doctor can establish new correlations among the services and inspect the status of all the devices, both those that are running the architecture and those that are integrated in the incubator setup through PalCom-nodes. The user interface of the service browser shown in Fig. 8 has been co-developed with the medical personnel.

Through a discovery protocol, services continuously announce themselves on the network and hence a mechanism to discover and trace services in the browser (left side of Fig. 8). To allow this functionality, a device allows services to execute directly on the framework or, in the case of existing hardware, the services execute on a node bridging closed hardware and framework-ready devices. The user creates an assembly among two services by selecting the two services on the left side of the interface. By doing so, they appear in the 'sandbox' (right side of Fig. 8). The services expand in the sandbox, presenting their different I/O possibilities. An alarm-condition (output) offered by one service can be connected to a display-service that takes text as parameter (input). When executed, the assembly feeds the display with alarm messages as they are raised by the first service due to some specific conditions in that particular service, e.g., a heart rate value being too low or too high. A number of assemblies can exist in parallel, and they can be individually altered in runtime through support from the framework. If a service disappears or is no longer reachable (for the discover mechanism), it is 'greyed out' and is no longer an active component in the interface. As it re-emerges (utilizing the discovery mechanisms), it is once more a usable component among the others. Hence, users (e.g., a doctor) will choose a number of services from a list (left side menu in Fig.

8). These are dragged into the work area (right side of Fig. 8) where each service will reveal its available communication possibilities. The work, as perceived by the users, is therefore to match input and output capabilities among services currently in the shared work space. This is all done in runtime and does not require any reboot or system adaption.

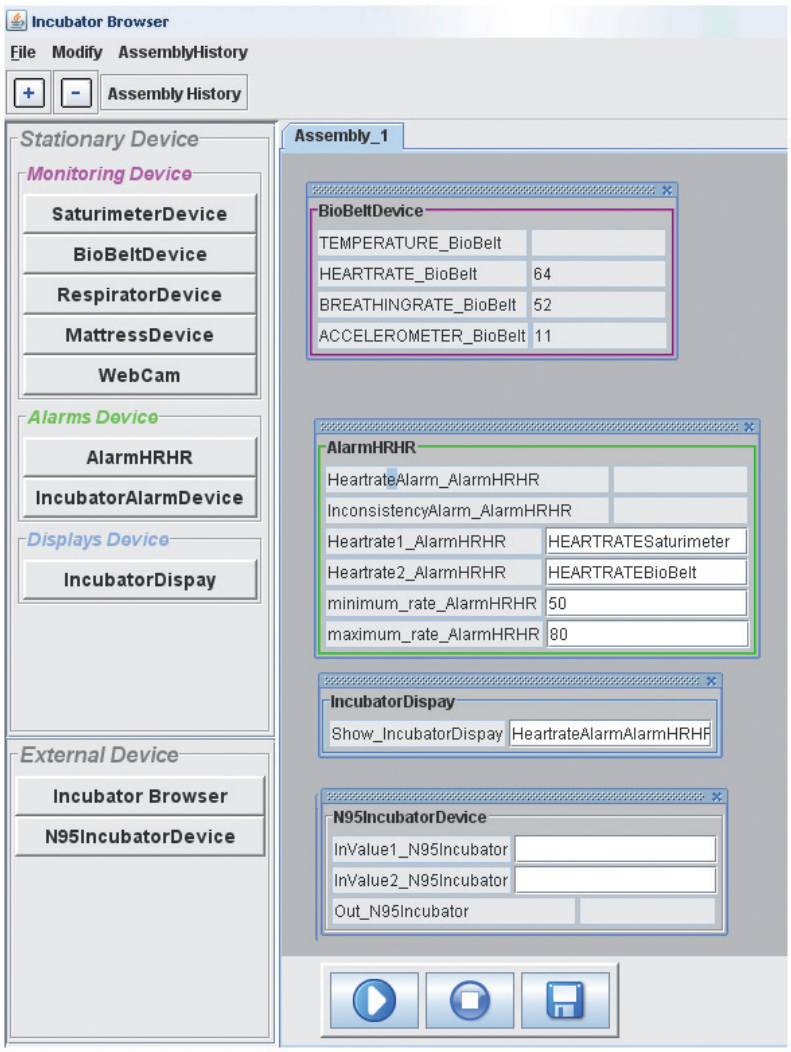

Figure 8. The Assembly browser. Using the browser, the doctor can survey the available tools and services, construct assemblies of tools and services, and obtain specific correlations between data. The doctor also has access to the data being monitored on various types of devices (screens, laptops, cell phones, PDA) and can visualize and inspect the function of the assemblies and components in the assemblies.

In this case study, the assembly is a fundamental mechanism for service coordination. A system that is constructed by means of assemblies can be inspected in a service browser which makes its inner structure visible at a certain level. This gives a better understanding of the system, and it is particularly important when a system breaks down as it allows users to not only perceive which system component is faulty but also to substitute malfunction components with functional ones. Furthermore, the assembly concept targets construction of systems from services that were not originally created for cooperation with each other. The dynamic construction and deconstruction of assemblies imply that the available services are distributed and able to discover and interact with each other.

6. ASSEMBLIES AND INTERNET OF SERVICES: SUPPORTING CRITICAL CARE

The incubator prototype enables the neonatal doctors to dynamically bring together individual computational resources to create a loosely-coupled system model that fulfills the premature infant's necessities in an easy and flexible way. This application supports the demand of a noninvasive monitoring system capable of anticipating the occurrence of complications and to avoid resorting to painful interventions for the infant.

The configuration of the assembly components is defined at two different levels: (a) combination of specific devices, e.g., the BioBelt, the Pulse Oximeter and the Respirator, and (b) combination of specific services to support precise monitoring necessities, e.g., alarm and comparison services that trigger events when an input value deviates too much from a preset value (see Fig. 9). Such configuration of the assembly components allows the neonatal doctor to put into perspective the values captured by individual devices, to investigate new correlations among the monitored values, and to experiment with novel usages of the existing devices. An assembly is a specific implementation of the concept of Internet of Services applied to a critical care scenario. Also, it allows non-service developers (such as doctors and nurses) to experiment with a distributed computational network, to reconfigure it, and to change connections among running entities.

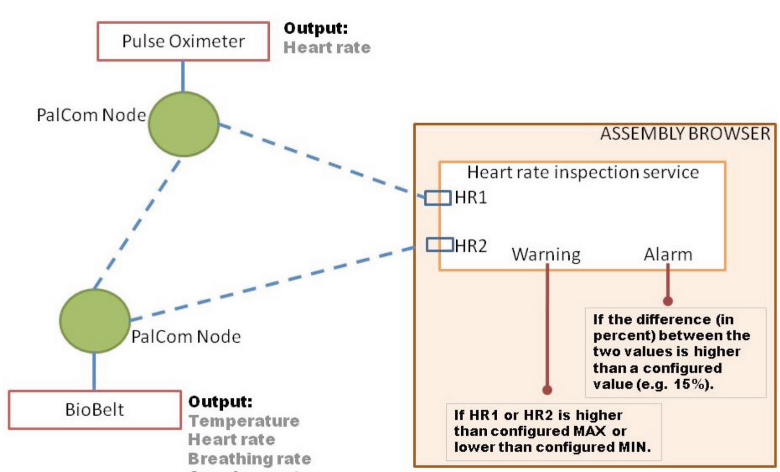

Figure 9. An assembly that compares and can trigger alarms during potential signal inconsistency situations.

6.1. The assembly configurability that addresses the specific needs of application domain

First, the assembly concept supports users in creating different ecologies of services in order to sustain their daily activities. Assemblies can be easily reconfigured when necessities change and when emergencies occur. It is possible to visualize and navigate assemblies dedicated to the monitoring of precise correlations. In this way, the feedback from the monitoring activity becomes more precise and more informative as it not only provides an indication of having exceeded the values of a certain threshold, but also sustains the possibility of understanding the meaning of that variation according to the more complex logic of the possible correlations between the parameters identified. For example, the neonatal doctor can compare the values of the SpO_2 registered by the Pulse Oximeter with the diaphragmatic movements of the child monitored by the BioBelt in order to improve the monitoring of hypoxias/apneas.

Furthermore, the incubator assemblies define systems of different components that allow novel forms of inspection by relying on the networking among the assembly components [16]. A sufficiently complex system can be expected to have many unanticipated failure mode interactions, making it vulnerable to normal accidents. The notion of assemblies offers the setting to experiment with a network-based inspection. If a component fails, the other components of the assembly can notify the user. Indeed, while using dynamic assemblies, users can discover and detect connection breakdowns and inspect a failure of a component that for some reason does not respond any more to its neighbors in the assembly. Each constituent in the assembly is aware of and becomes 'responsible' for its neighbors, and this feature can be used to check whether a constituent is properly receiving signals and data from the others. In this way, each component of the assembly can communicate with the others about the state of its neighbors. An example of such an application is breathing-rate monitoring where the respirator provides the infant with oxygen while the breathing rate, which correlates to the respirator function, is monitored by the BioBelt, and the SpO_2 is monitored by the Pulse Oximeter. Using the notion of assembly to make these devices communicate to each other, whenever the respirator malfunctions, the discovery protocols enabled by the PalCom nodes will propagate the information on the missing signal from the respirator to the whole assembly. This creates a novel inspection opportunity for the user to understand what is causing the problem and at which level of the system [16].

Finally, graceful degradation and recovery of (some) functionality in case of, for example, hardware failure can be supported through the middleware. The framework supports resilience in case of functional breakdowns. If part of the system fails, some functionality should still be available and working. It allows the user to reconfigure the system to create temporary work-arounds through reconfiguration of running assemblies.

Consider the following two scenarios:

(a) The Pulse Oximeter used to measure the oxygen level in the infant's blood has a broken display due to an accident earlier in the day. A substitute Pulse Oximeter will not arrive until later of the day. In this situation, the Pulse Oximeter would be of no use, even if the sensor and data acquisition part still work fine. Around the incubator, there are a number of displays with different usages. The doctor or nurse might even have a smartphone. Here, the service-oriented approach and end-user-configured assemblies could prove essential. The doctor could, while waiting for a new Pulse Oximeter, create an assembly connecting the sensor data service running in the Pulse Oximeter to, for example, a display normally showing less critical data such as the infant's temperature, or even connect the sensor data stream to the display on his smartphone.

(b) A doctor of an infant needs to go to a meeting. Even if he or she formally hands over the monitoring responsibility to a colleague, the doctor is still interested in knowing how the infant's health status develops in the next few hours. The doctor could have an option to have the monitoring data of one or all infants in the NICU displayed on his or her smartphone real time. This option is made possible through a new, temporary assembly including sensor data from the patient and a service running on the smartphone.

These two scenarios exemplify the opportunities offered by the user-configurable, loosely-coupled, distributed services in critical care, both during component breakdown and in normal operating situations.

7. EXPLORATORY TRIALS

Introducing new technologies in an NICU is a heavy and quite complicated task. It is therefore necessary to perform a number of clinical trials before testing the designed solutions with the users in a setting that is as realistic as possible [5]. The present incubator prototype has been submitted to a set of exploratory workshops with the neonatal team at the NICU of Siena Hospital [21]. These trials experimented with the use of the assembly browser and aimed at exploring the different scenarios that could support critical care settings, elaborating and refining the logic of correlations supported by a service-based approach and the inspection strategies supported. The particularity of the application domain, the conditions of the users (i.e., neonatal patients at NICU), and the specific Italian legislation greatly limited the extent to which the system could be tested at a 'prototype-stage'. For this reason, the evaluation has been mainly focused on trying to capture the qualitative aspects of interacting with this technology and understanding the support these can provide the neonatal team's work. In addition, a preliminary functional evaluation was conducted for the BioBelt prototype, which after a pre-assessment from the medical board was judged to be tested in a semi-realistic setting.

Therefore, a set of preliminary trials were performed in order to evaluate the feasibility of applying the paradigm of unobtrusive and wearable monitors on preterm or ill-term newborns admitted to the NICU [33]. The study was conducted in collaboration with the NICU at the Hospital of Siena "Le Scotte" and the Bioengineering Department of Milan Polytechnic Institute. The evaluation has three objectives:

a) To evaluate the service composition approach presented above.
b) To understand the usability of such technologies through a qualitative evaluation.
c) To evaluate the reliability of measurement using wearable and unobtrusive monitoring.

Even though the system has been assessed at the stage of proof of concept prototype, it was possible to explore with the users a spectrum of issues such as management of breakdown and support to recovery actions, support for sense-making in the diagnostic work, dynamic construction of assemblies, and user control over the undergoing automated processes. Therefore, the prototype evaluation was organized as follows:

a) Service composition approach: assessment through scenario based evaluation.
b) Usability evaluation through user workshops.
c) BioBelt functional evaluation.

7.1. A service composition approach: assessment through scenario based evaluation

Different participatory and scenario-based techniques have been experimented with throughout the design process that were directly inspired by the participatory design traditions [34]. User workshops and activity modeling, data sessions, and 'bricolage' workshops [35] were conducted with the neonatal team. Diaries [36] questionnaires, and interviews with parents, experts, and future laboratories were documented [37]. In line with the participatory design process, the service composition approach was evaluated with the user in true-to-life scenarios that describe specific and recurrent situations the neonatal team has to deal with in their daily activities. The assessment was focused on the use-challenges introduced at the beginning of the article: Breakdown and recovery, Sense Making, Dynamic construction and User control (see Section 1. INTRODUCTION). In order to explore these aspects, a scenario based on the current practice and elaborated with the neonatal team was considered. As previously described, this scenario features a variation of the SpO_2 value in the newborn and the different attempts medical personnel make in order to solve the problem. As a result of activity analysis, it is currently impossible to figure out the functional relations among the different equipment necessary for the newborn's survival, although a malfunction of one device (such as the respirator) directly affects the functioning of another device (such as the Pulse Oximeter) which in turn directly influences the baby's status (e.g., change in the SpO_2 value). Furthermore, no direct indication is provided by the system to make visible relations or even interconnections between the two devices. For these reasons, this scenario was selected by the medical personnel since it was able to embody many issues related to their work. The results of this assessment are reported below and put in relation to the existing scenario, and the solution supported by the service-based approach herein proposed. The neonatal team has experimented with these scenarios in the NICU setting through a dramatization technique. This allowed for estimating the impact of real conditions of use. The software architecture was employed in a prototype, simulating some of the inputs and the system responses.

Breakdown and recovery

The respirator provides the infant with oxygen and monitors all the parameters related to the breathing function. When the respirator breaks down, the monitoring of all these parameters is lost, and the neonatal team has to perform manual ventilation until the respirator is repaired. The manual ventilation is performed using a device called Ambu Bag. Currently, without any indications on the breathing rate of the baby, it is difficult to regulate the use of the Ambu Bag and results in a potentially invasive treatment for the newborn.

In the incubator prototype, the neonatal doctor can configure the system to create an assembly between the respirator and the BioBelt to detect BR, HR, RM, and T. Therefore, when BR signal from the respirator is no longer available, the system can automatically ‘switch’ to the BR value collected by the BioBelt, thus guaranteeing continuous monitoring of the baby. In this way, the values of BR and HR provided by the BioBelt can help the neonatal doctor in performing manual ventilation using the Ambu Bag.

Sense-Making

The assembly between the Pulse Oximeter and the BioBelt can show how a service-based architecture supports the inspection strategies of the users. In this situation, a classic redundant error-handling strategy is applicable. The heart rate detected by the Pulse Oximeter (HR1) is continuously compared with the heart rate detected by the BioBelt (HR2). An ‘inconsistency alarm’ is triggered whenever the difference between the two values exceeds a defined threshold for a predefined number of pulses. This may indicate a fault in the set-up following a classic inspection strategy which compares the same signal from different sources. Such comparison is currently performed by the medical staff without any external support.

By means of the assembly, the alarms can be configured differently by the neonatal team based on the risk that is presented. Such flexibility proved to be particularly appreciated by the medical staff because the thresholds—each corresponding to a different level of alarm (from a softer to a more acute sound)—can be set by the user when creating the assemblies. The configuration of the alarms and the prevention of faults have been considered a valuable support for the interpretation of dynamic changes.

Dynamic Construction

The quality of dynamic construction is illustrated by another recurrent situation. For instance, the neonatal doctor is called to assist a delivery in the maternity ward, and he/she would like to transfer the output of the monitored data from the central display in the NICU to his/her mobile device, such as a PDA. However, this feature of distributed monitoring is currently not available to the doctors. In the incubator prototype, the neonatal doctor can reconfigure the assembly of devices that supports monitoring of the baby by adding his/her PDA as a display device. In this way, the doctor can continue monitoring the baby while absent and can promptly intervene if necessary.

User Control

The assembly browser was evaluated with the users to allow the neonatal doctor to explore the assembly possibilities. It is possible to create novel assemblies dedicated to the monitoring of various precise correlations. For instance, a neonatal doctor can create a new assembly among the Mattress, the web cam, and the BioBelt to have an accurate monitoring of the baby’s breathing function when the newborn starts to breath autonomously. Indeed, the expansion of the chest—involved in each respiratory act—can be registered by the body pressure applied on the Mattress when the infant breathes.

Complemented by the data from the BioBelt and the recordings of the web cam, this information can offer a closer monitoring of the infant.

7.2. Usability evaluation through user workshops

The present incubator prototype has been submitted to a set of exploratory workshops with the neonatal team at the NICU of Le Scotte Hospital in Siena [30]. These trials tested the use of the assembly browser and aimed at exploring different scenarios that could support critical care settings, elaborating and refining the logic of correlations supported by a service-based approach and the inspection strategies supported. Different sets of design workshop activities were conducted with the Neonatal team of Siena Hospital in order to evaluate the usability of the assembly browser interface and of the BioBelt and Mattress prototypes on premature newborns, from a medical personnel's perspective.

Usability of the Assembly Browser

The assembly browser has been used by a doctor and a nurse at the NICU of Siena Hospital. The tests focused on the following applications:

- To build an assembly for breathing monitoring.
- To build an assembly using the Mattress device in order to monitor newborns' spontaneous movements.

The testing was repeated over one week in order to monitor the learning of the system and error occurrences. Although the system was completely new to the users, they found it easy to use. The general understanding of the possible action paths and of the warning information was clear as well.

Usability of the BioBelt and the Mattress

The Mattress and the BioBelt prototypes was evaluated in one exploratory trial at the NICU in collaboration with a physician, a nurse, and a premature baby under stable and controlled conditions. However, due to ethical and safety restrictions, both the devices were completely non-functional and the child was monitored with the standard equipment. Therefore, this initial evaluation was solely devoted to the understanding of major usability problems in the design of the devices.

The outcomes of this activity informed the project by providing several indications for the redesign. It appears necessary to provide different BioBelt sizes in order to fit newborns of different weights. The contact area between the electrodes and the body has to be improved in order to maintain a stable signal. Thickness and elasticity of the textile fiber must also be improved in order to achieve a better and comfortable adherence to the baby's body.

7.3. The BioBelt functional evaluation

The prototype for preterm bio signals unobtrusive monitoring was evaluated in pre-clinic trials at the NICU of Le Scotte Hospital in Siena [33]. The subjects for this experiment were aged 2 to 12 months, selected among patients just dismissed from the NICU. The incubator was set up to comply with that of an actual clinical setting, although the testing was considered only a preliminary assessment.

The evaluation protocol was based on 15-minute sessions of continuous monitoring using the belt prototype and a commercial Pulse Oximeter. During each session, data collected by an accelerometer and an ECG were processed through a complex algorithm that instantaneously provided HR and BR of the infant. These indicators, together with the body's temperature acquired by a calibrated temperature sensor, gave an accurate overview of the patient's general conditions. The experimental setup also suggested application of a standard Pulse Oximeter on the babies' feet or hands to measure beat-to-beat SpO_2 and HR. The simultaneous application of several devices to measure the same clinical parameter (e.g., HR) represents a standard methodology of inspection in critical environments such as NICU where the additional information helps to prevent errors.

The preliminary results achieved with the use of the unobtrusive monitoring prototype in a controlled experimental setting suggest the potentiality of a successful introduction of wearable computing in critical settings such as the incubator where current devices generally produce high-level noises and often corrupted output signals. Although this experimentation is considered only a preliminary assessment of the BioBelt, the successful overall results prompt a further development of the device, especially concerning its reliability, some design aspects, and the textile extensometer sensitivity. Together with the evaluation of end user defined assemblies of services, our preliminary results suggest that implementing loosely-coupled services and devices in critical settings, such as the NICU, is both feasible and beneficial.

8. CONCLUSIONS

The combination of ambient technologies and advanced internet services is breaking new grounds for distributed information systems whereby users can access, treat, and manipulate 'information resources' in order to support their activities. The case study presented in this paper challenges this notion by presenting an SOA perspective on the design of technologies for critical care with a strong focus on end-user configurability.

An incubator prototype was developed in order to create different ecologies of devices and services to support the neonatal team in their specific monitoring requirements. Through the middleware platform, service composition was experimented with the end users (i.e., the neonatal team), and the exploration of the concept of assembly provided specific inputs challenging the key issues of ambient computing highlighted in this paper. The following conclusions are based on the results of our research:

Breakdown and Recovery: The assembly browser allows the neonatal doctor to manage the dynamic configurations among the different services and devices available in the system by providing means for inspecting the assembly and exploring the status of the different devices (e.g., Respirator, Pulse Oximeter and BioBelt) connected in the assembly.

Sense Making: Assemblies offer a way to access, treat, and manipulate data and information in order to establish novel 'meaningful' connections among the incubator equipment and making visible the functional relations among the assembly components.

Dynamic Construction: The possibility of manipulating the inputs and the outputs through the use of the assembly browser can create new modalities for monitoring the newborns and exploring diagnostic strategies.

Automation vs. User Control: In a critical care setting, the technological solutions have to find a balance between automatic system processes and user control. This balance should occur between what the system offers and what the users specifically necessitate.

The NICU prototype developed in this study is the result of a participant-driven design process. The prototype has been validated by users in close-to-real situations. The delicacy of the intended-use setting challenges the development and, more importantly, the testing of new technological support systems. Still, the architectural support for end-user configuration and the possibility to create ad hoc bindings to support both everyday situations and breakdowns align well with and support actual situations at the NICU.

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