Mobile Patient Monitoring for the Pediatric Intensive Care Unit
Work Domain Analysis and Rapid Prototyping Results

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Abstract—Detection of patient deterioration and triage (prioritization of care) are two critical tasks in the high risk environment and interdisciplinary care model of patients in an intensive care unit. To make decisions and plan treatments, clinicians need to observe, integrate, communicate, and understand a wide range of information from various devices located at the bedside of multiple patients. However, several technological and physical limitations prevent them from optimally performing these tasks, which negatively impact the capabilities of healthcare teams. The Monitoring Messenger concept was developed to overcome some of these challenges by integrating information on a mobile device and supporting team decision-making and information exchange. Results from the initial phases of this project: requirements definition using Cognitive Work Analysis and rapid device prototyping are presented in this paper.

Keywords—Device alarm, alert, and communication systems; Design and development; Human factors

I. INTRODUCTION

The assignment of priority of care and the early detection of deterioration of critically ill patients in the intensive care unit (ICU) represents an enormous source of preventable morbidity, mortality and cost [1], [2].

A. Problem statement

There are a limited number of nurses, respiratory therapists and physicians in an ICU at a given time. To make decisions and plan therapies, these clinicians need to observe, assimilate and interpret a vast array of information originating from various devices located at the bedside of multiple patients [3], from diagnostic centers spread throughout the hospital (e.g. radiology), and from the expertise of several care providers that are not always co-located or available at the same time.

This complex sociotechnical system presents several shortcomings in existing technology, limiting their capacity to multitask and collaborate in the care of multiple patients: a) the fixed location of monitoring devices at the bedside; b) information overload from a multitude of devices, each with its own display and overlapping alarms; c) the lack of integration and interaction between these devices; d) the use of visually cumbersome displays, which were historically created for monitoring during anesthesia but never optimized for users in the ICU; and e) lack of context specific information (such as historical trends) to support patient data interpretation and clinical decision making.

B. Proposed solution

To address these challenges in ICU monitoring and communication, a unified, portable, and intelligent device: the Monitoring Messenger, is currently being developed in a partnership between the Electrical and Computer Engineering in Medicine research group (ECEM) at the University of British Columbia and the Advanced Interface Design Lab at the University of Waterloo. By integrating information from multiple monitoring devices, mechanical ventilators, infusion pumps and clinical information systems on a mobile device called the Monitoring Messenger (see Fig. 1 for the system context) we will allow nurses, respiratory therapists and physicians on- or off-site to continuously monitor critically ill patients, thereby improving response time, quality of care, and patient safety.

The Monitoring Messenger has the potential to significantly increase clinician’s Situational Awareness (SA) [4] and decision-making ability by providing tailored and integrated information, allowing synchronous and asynchronous collaboration, and maximizing the potential of healthcare teams by creating the possibility of virtual collaborations. The development of this prototype will be modeled after a similar project conducted by the ECEM group in which we developed and evaluated a mobile device for anesthesia assistants in the operating room: telePORT [5]. Experience gained during the development of telePORT will be used as an additional guide in this project and the software development framework,

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and the decision support engine will be revamped for the Monitoring Messenger.

C. Aim of this paper

To identify information needs of physicians and nurses in a pediatric ICU (PICU), characterize their work domain, and create rapid paper prototypes based on the identified requirements and constraints for future evaluation of the usability of such a system in a simulated environment.

II. METHODS

An inter-professional team of nurses, physicians, engineers, and human factors experts followed a user-centered design process [6], [7] to obtain the system requirements, and obtain feedback during the rapid prototyping phase of the system development. The objective was to quickly develop a prototype, allowing design feedback and early user evaluations, without overburdening the users with extensive observations and interviews. Previous adult ICU observation experience of the first author [8], [9] allowed quick and effective collection of unit- and setting-specific data for the generation of a work domain analysis, task analysis, scenarios, and finally the prototype. The following steps were performed:

A. Observations

In-situ, immersive, and non-obstructive observations [10] of PICU nurses and physicians were performed. An expert researcher shadowed PICU healthcare team members for two consecutive day shifts to observe their collaborative tasks and take detailed notes of all activities. Task frequency and information needs reported for nurses in an adult ICU setting [9] were used to focus specifically on the differences versus a pediatric setting, such as a higher nurse to patient ratio, the lack of cardiovascular disease in these patients, and the increased emphasis on ventilatory information. Participants were asked to explain actions they were performing and to state their goals during each task when appropriate. Finally, the observer asked unstructured clarifying questions, to elicit information requirements for tasks, task frequencies, perceived challenges and potential suggestions to improve their current work in the middle and at the end of each shift. Results from these observations were organized in sample scenarios that served as an input to the Cognitive Work Analysis (CWA) modeling component of this complex sociotechnical system.

B. Modeling the work environment

CWA [11], [12], specifically work domain analysis [13] and control task analysis [14], was performed to develop hierarchical models representing the work domain. CWA is a technique initially introduced by Rasmussen [15], and later solidified by Vicente [6]. It provides a formative framework based on identifying, evaluating, and incorporating needs from constraints on the analysis and interventions of complex sociotechnical systems. CWA is composed of five major components, each accounting for a part of the system evaluation: work domain analysis, control task analysis, strategies analysis, social organization and cooperation analysis, and worker competencies analysis. By integrating each component into a system model can be created, which can be used to support system and interface designs.

The work domain analysis (WDA) highlights the physical constraints that define the capacity and potential of our system. Through WDA, designers can identify the boundaries of their intervention and the extents to which their new design can influence work being performed. Control task analysis (CTA) identifies how tasks performed by the workers are constrained by system states and worker responsibilities within the constraints defined by the WDA.

CWA has been used in healthcare to model and help understand nursing work in teletriage [16], for the evaluation of the use of flow sheets in PICUs [17], and for the design of clinical displays [13]. These three distinct uses of CWA were integrated into the design of the Monitoring Messenger as they provide the tenets of our design approach by including the constraints of care provider work in the PICU on the design of a novel system that has the potential to improve providers’ SA and quality of care. In our approach, we are combining team CWA [18] constraints derived from collaborative work in the PICU into collaborative requirements targeted at maximizing team SA [19] and consequently improving patient care.

The CWA modeling process included several iterations until a final model was achieved. The iterative process was important, as it created an opportunity to refine the descriptive model to yield better representations of the work domain and tasks. Expertise drawn from care providers in the PICU were vital for assuring that the models presented a good representation of the complex sociotechnical system. These models represent the intentional, functional and physical properties of the work domain at different levels of abstraction [12] and serve as a base for the development of our prototype.

C. Prototyping

Rough prototypes, incorporating the requirements and constraints obtained through the CWA process, were developed during a series of brainstorming sessions using a blackboard. Based on a combination of scenarios and models developed...
above, requirements were implemented focusing on the required system components, maximizing integration of information and potential for an increase in SA. Environmental constraints, as well as human behavioral limitations were taken into consideration to develop a robust, interactive mockup that would allow for immediate testing and evaluation by users. Mockups of potential system features were developed by the second author using Balsamiq Mockups (Balsamiq Studios, Sacramento, CA, USA) due to its ability to quickly and efficiently generate a working prototype.

The design was constantly constrained by four major factors that shaped the features embedded in the system: a) characteristics of the human operators (members of the healthcare team), b) technical system limitations (equipment data export capabilities, size and power requirements of portable device), c) institutional constraints (including privacy issues), and d) environmental constraints (geographical location of patients, equipment and healthcare providers).

We are currently developing the evaluation of our prototype in order to test its usability with experts from the field. Here, we plan to focus mainly on task triaging (assignment of priority to five patients) with limited time measuring accuracy and decision speeds in a crossover design with traditional (paper) tools and the Monitoring Messenger to gather information. However, since the process was developed through the use of expertise drawn from the PICU at BC Children’s Hospital and other ICU sources, we present the initial results of a prototype that is aligned with the system and human requirements of this environment.

III. RESULTS

Three key elements were identified from the observations and CWA modeling: a) The need for a communication layer to support team interaction, both synchronously and asynchronously, allowing timely collaboration; b) the need for a patient information layer to show relevant patient information such as vital signs, medications, and orders; and c) an information integration layer, where trends, automated decision support tools, and multiple data are integrated into visualizations and supported by an early warning system. The combination of the elements above would strongly support the decision making process, allowing both a more efficient triaging process in-situ (with all healthcare team members co-located) and quick consultations (with one or more team members in remote locations). This would increase SA of the remote healthcare team members and provide an effective communication layer to support information exchange.

A. Work Domain Analysis

Using data collected from observations, both in the pediatric and adult settings, the developed work domain analysis (see Fig.2) showed a highly interconnected tree (as expected from a CWA of such a complex sociotechnical system). Important features of the WDA are described below:

- There was a significant need for non-collocated collaborations considering that care providers that are not always available at the bedside (pharmacists, respiratory therapists, or specialists), identified by their location being highlighted as an important physical form, while still having important expertise to contribute to the triaging process.
- Recorded vital signs, medication orders, and exam results, that should be made available on the monitoring messenger are accessible from different sources across the institution (exams and tests), as their location was highlighted as an important physical form, requiring the integration of our messenger system with already existing technologies.
- The Monitoring Messenger would have to include three major layers derived from the physical function level (equipment, staff, and environment): a patient information layer allowing access to vital sign feeds from bedside equipment (Fig.3, on the left), a decision support layer to maximize the potential of the care providers (Fig.3, on the right), and a communication layer with direct communication channels between team members to account for user expertise and subjective assessments (Fig.4).
- Although we are focused on improving patient care, there are supporting aspects that need to be accounted for to maximize the benefit to the patient through efficiency and quality of care: environment, logistic, and equipment processes.

B. Control Task Analysis

- There was a need for immediate collaboration and information sharing, as tasks are significantly interconnected (by links between decision ladders). Numeric pagers or simple phone calls do not resolve this problem due to constraints of the low media richness of these channels.
- The decision making required multiple members of the healthcare team participating in the process at the same time. This may require movement of healthcare team members throughout the unit and potentially across the hospital as some important information is currently only available at the bedside. By adding a layer that provides this information remotely, we reduce the time spent waiting for other healthcare team members and may also avoid the need to have a team member present at the bedside when their presence is not critical.
- The decision making process was highly dependent on higher cognitive processes of specific team members. The Monitoring Messenger could play an advanced support role in the decision making process by presenting integrated patient information with embedded automated decision support. Record of tasks conducted by physicians, nurses, and pharmacists would be greatly beneficial for bedside and just-in-time decision-making support from the proposed device.
- Different care providers have distinct needs regarding patient vitals and exam results, which alerts they are dependent upon, and the support they need from the system. Therefore, a “one size fits all” solution encompassing all needs would not be readily applicable as it would create a cluttered and noisy interface.
C. Prototyping

Using the results from the CWA, the rapid prototyping process yielded a prototype in a portable document format (PDF) demonstrator file, which allowed the end users to navigate between different screens using links: one tabular unit overview screen, four overview screens in a map layout, five screens with patient information, eight communication screens, two screens for reminder setup, and six screens for subscription to patients and delegation task support. Examples can be seen in Fig. 3 and 4. This prototype will allow validation and refinement of designs prior to moving towards a functional system. Additionally, it can guide the definitions of decision support mechanisms that are being developed. Major functions, in addition to patient information and vital signs (patient layer) derived from results of the CWA are outlined below:

- Location was identified as a physical form for care providers, in addition to the highly integrated decision-making process outlined on the CTA, showcasing that care providers are not always collocated, as well as the need for strong and constant information exchange. This combination led to the design of a strong communication layer for both patient-centered communication and general tasks (Fig. 4), since care providers necessary to the care process are not always available at the bedside.
- The CTA showcased that the triaging process is dependent on higher cognitive processes of certain care providers as they are responsible for integrating the available knowledge and devising a treatment or diagnostic course for each patient. This requirement led to the incorporation of decision support and trend analysis for early detection of patient deterioration to guide therapy decisions (Fig. 3, on the right). Automated decision support systems could reduce the load on care providers, also benefitting from prediction and modeling capabilities of computer systems.
- The identification of providers’ skills on the WDA as an important physical form, allied to the need for provider-tailored information as identified on the CTA, demonstrate that providers will have distinct roles and different informational requirements for their tasks. This resulted in the incorporation of interface features allowing the setup and configuration of personalized and user-defined alerts and reminders that do not add to existing ICU noise and improve on the awareness of patient condition, focusing...
on the patients the provider is assigned and provider-specific information. In addition, the integration of multi-patient views with notifications for messages and task reminders (Fig. 4, on the left and Fig. 5, on the right) creates a comprehensive view of the patients assigned to each care provider, consequently increasing SA and incorporating collaborative tools to maximize knowledge integration.

IV. DISCUSSION

Information obtained by shadowing healthcare providers in the PICU was used in the identification of design goals and information requirements using a WDA. The modeling results were used to quickly start the rapid prototyping process of the Monitoring Messenger device. This approach allowed the direct integration of domain constraints and work requirements into the prototyping phase, by generating a working prototype including domain constraints and work requirements in as few as a couple weeks, maintaining the domain constraints fresh in the designer’s prototyping process.

This process ensures the active involvement of nurses, respiratory therapists, physicians, experts in engineering, and designers early in the process where design changes are cheap and easy to implement. This allows the incorporation of design suggestions and usage ideas, which would otherwise never have been deemed necessary or possible by designers. Furthermore, by basing the development on grounded theory instead of the designer’s ideas, one avoids potential pitfalls with respect to human factors, intuitiveness, and usability.

The results of the CWA, developed as a stepping-stone for the prototyping phase, present a model of the work constraints in a PICU, as well as the tasks surrounding triage. These results alone will benefit projects to come, providing a descriptive model of the PICU, a complex sociotechnical system encompassing multiple care providers, subsystems, and patients.
Considering the ultimate goal of healthcare, this model will facilitate the development of systems that can now benefit from awareness of multiple constraints that can impact patient care and patient safety.

The development of bedside integrated ICU information displays have been reported in the adult setting [20] and approaches to optimally transition paper records into electronic health records have been described [21]. Additionally, it is known that patient information displays using graphical trends and integrated configurable displays improve nurse performance in detecting abnormal physiological states in comparison to tabular data presentation, commonly used in electronic health records [22]. However, given the current growth in mobile device prevalence, this area of information exchange and communication among healthcare providers is currently underutilized. The Monitoring Messenger will make use of the availability of hospital-wide secure wireless networks, vastly improve computational capabilities of current mobile devices, and provide intuitive information presentation and abstraction, to provide healthcare team members with a one-stop shopping solution for their patient monitoring needs. This will improve workflow in the ICU and decrease worker stress, especially among nurses, who are increasingly regarded as key decision makers in the healthcare team [23].

From a human-factors perspective, the Monitoring Messenger would significantly increase the levels of SA by providing a portable and centralized patient-information device. Higher levels of SA have been linked to improved performance [4], [24] and patient safety [25], and will positively impact the triaging and diagnosis processes. The decision support mechanisms will unload part of the cognitive burden onto the device, by moving some of the team’s workload into a reliable and user-defined automated warning system.

Future work includes a) the development of early warning systems using context-appropriate feature extraction, b) display refinement and the development of a small mobile tablet prototype device, c) prototype evaluation using a simulated ICU environment to evaluate the performance of the prototype’s speed and accuracy on a triaging task, and d) using the system to evaluate mechanisms to improve trust in collaborative teams.

V. CONCLUSION

Following a rapid prototyping development with a highly interdisciplinary team, a formal design approach based on a CWA can be a successful pathway for the development of mobile applications in a clinical setting.

REFERENCES


