Abstract—Intelligent Nursing Cart (iNuC) is a mobile, point-of-care medication administration tool for the purpose of preventing medication errors and enhancing patient safety. It provides its user with work and time management and record keeping capabilities as well as a web portal to hospital services and information system. In addition, iNuC has several labor-saving and automation capabilities, including generating shift report from data and notes collected during the user’s shift, tracking medication and medical supply usages and automating requests for medication replenishment.

I. INTRODUCTION

This paper describes an intelligent, mobile, nursing cart, called iNuC (Intelligent Nursing Cart) for short. Its primary user (or simply the user) is someone (usually a nurse) who uses the cart as a point-of-care medication administration and patient record keeping tool. The cart has all the basic functionalities that are often provided by existing mobile medication carts listed in [1, 2], including bar-code activated interlock for ensuring the administration of right medications to the right patients and bookkeeping functions for updating patients’ personal records, billing records and medication inventory of the hospital. In addition, iNuC has several advanced and unique capabilities. As an example, its scheduling and planning tools can help the user make the medication preparation and administration schedules of the user’s patients central to the user’s workday plan. Another example is the intelligent monitor, alert and notification (iMAN) tool designed for error prevention. Like similar tools for safety critical systems, iMAN also enables the user to analyze and determine the causes of errors after they occur. iMAN is unique in its capability to alert the user when it detects events and action sequences that have a high likelihood to cause error. Any hospital personal can login an iNuC as a guest and use the cart as a web portal, a point of access to hospital services and information system.

Being a user-centric device, iNuC is designed to be easily configurable and customizable: The current version is configured to support manual, centralized medication dispensing and delivery workflow processes illustrated by part (a) of Figure 1. Such processes are still in use in most hospitals today.
Its component based architecture and implementation should allow the cart to be easily configured to support fully distributed and automated medication dispensing and delivery processes illustrated by part (b) of Figure 1. Distributed and hybrid (partly centralized and partly distributed) are becoming more and more widely adopted each day. Moreover, the cart can be customizable by the user for not only the general workflow process and medication use rules of the institution, but also different processes and rules of individual departments and user groups within an institution.

Following this introduction, Section 2 describes background and motivation of developing iNuC and related work. Section 3 presents the capabilities of iNuC. Section 4 describes the approach and method to capture iNuC requirements and define NuC functionalities. Section 5 describes iNuC architecture, major components and development environment. Section 6 summarizes this paper and discusses the future work.

II. BACKGROUND AND MOTIVATION

Despite tremendous progress in quality of health care worldwide, recent publications (e.g., [3-9]) on the subject still report alarming statistics on occurrences and consequences of preventable medication errors. This fact has motivated many projects on identifying and preventing medication errors (e.g., [9]) and the advent and use of an increasingly broader spectrum of information systems and smart devices as tools for prevention of medication errors and improvement in compliance (e.g., [10-18]).

Medication errors can occur at any stage of the medication use process, from ordering, transcription and dispensing to administration. Today, computerized physician order entry (CPOE), electronic personal health record (PHR) and medication administration record (eMAR) systems (e.g., [10-14]) are widely deployed by world class hospitals. Pharmaceutical distributors and hospital equipment industry now offer all sorts of medication carts and smart cabinets (e.g., [1, 2, 15-18]) for dispensing medications in a controlled manner and tracking the use and inventory of medications managed by them. In particular, distributed, automated medication dispensing systems, such as MedSelect offered by AmerSourceBergen [1] and MedStation by Pyxis [18], can help reduce errors and improve efficiency in medication management, preparation and delivery.

iNuC focuses on intelligent devices and tools designed specifically for prevention of administration error, i.e., errors occurring in the last stage of the medication use process. Administration errors, contribute a significant percentage (25 – 40%) of all preventable errors. The rate of error can be as high as one in six doses, even in prestigious, world-class hospitals. Such an error rate is not surprising as the tedious nature and unavoidable disruptions of medication administration process can overtax even the most well trained and disciplined medical care professionals. Currently available mobile point-of-care medication carts do not provide sufficient help on this respect. Take the one described in [2] as example. It is among the best mobile carts available today. It does provide bar-code activated interlock for the purpose of ensuring that right medications are given to right patients and support automatic updates of patient medical records, billing records and pharmacy inventory records. Still, it does not support automation and integration to the degree required for error-free medication administration [15]. None of the available carts provides the users with modern planning, time management, reminder and alert tools that they can be easily customized to conform to the workflow processes of the institution and individual departments and personalized according to their own preferences.

iNuC is built on the foundation established by our research on smart consumer electronic, assistive devices and service robots for the elderly. The keystones of the foundation include medication scheduling models and algorithms; prescription algebra and authoring tool; smart medication dispensers for home use; component model, software components and prototyping and evaluation tools; flexible integration framework; and workflow-based architecture and middleware for embedded systems and service robots. In addition to references [19-26], other publications on our work and links to software components can be found at project SISARL (Sensor Information Systems for Active Retirees and Assisted Living) homepage (URL: http://sisarl.org).

III. iNuC CAPABILITIES

Figure 2 shows the structure and the major components of iNuC, together with the environment for integration of the cart with supporting devices and record systems of the hospital. We will return in Section 5 to provide the names and describes the functions of the components in part (a) of the figure. The integration environment shown in part (b) of Figure 2 supports experimentation and evaluation of alternative record keeping tools, protocols and process and their integration. The gateway server isolates the prototype tools from hospital information and record systems on the one hand, and allows iNuC to have access to real-life data and interfaces of the hospital systems on the other hand.
Having these tools available to management, calendar and information access tools are degree chosen by the user. Functions so that updates can be automated to the with customizable update tool and user interface

Records at bedside but also further provides the user not only supports automatic update of electronic patient records and inventory records. iNuC supports for either automatic or manual updates of capability described shortly below.

This reason, the cart must have the monitor/alert mechanism
can be circumvented, however. Busy users are known to work around it. For this reason, the cart must have the monitor/alert capability described shortly below.

Similarly, many existing medication carts provide supports for either automatic or manual updates of electronic patient records and inventory records. iNuC not only supports automatic update of electronic records at bedside but also further provides the user with customizable update tool and user interface functions so that updates can be automated to the degree chosen by the user.

As stated earlier, modern time and schedule management, calendar and information access tools are integral parts of iNuC. Having these tools available to the user through iNuC makes it more likely for the medication preparation and administration schedules of the patients cared by the user to be the central core of the user’s workday plan. This is an advantage of this choice over using separate personal portable devices or office facilities for this purpose.

We want to make iNuC well suited to serve not only hospitals that treat critically injured and seriously ill patients but also long term care and assistive living facilities for people with chronic deceases and functional limitations. A nurse in such an institution often cares for a relatively large number of patients. Flexible medication schedules that do not require waking patients from their naps, interrupting family visits, etc. are clearly preferable. Flexibility in this situation can place immense stress on the care provider and increase the potential for errors without the help of a smart medication scheduler. A smart medication scheduler can take full advantage of the sizable ranges in dosage parameters typically allowed by directions of modern medications to make the medication schedules fit better with daily activities of respective patients without risking loss of rigor in compliance and without demanding noticeably more attention and time of the care provider. We have developed models and algorithms for computing from constraints defined by medication directions such schedules that are sufficiently rigorous [21, 25, 26]. The scheduler and planner provided by iNuC enables us to experiment with these algorithms.

The iNuC intelligent monitor, alert and notification (iMAN) tool to be provided by iNuC is novel and unique. It has good potential to be one of the most effective tools for prevention of medication errors. Like similar tools (e.g., flight and data recorders) for safety critical devices and systems, the event monitoring and logging functions of iMAN will also enable the user to analyze and determine the causes of errors after they occur. iMAN is unique in its capability to alert the user to take action for prevention of error when it detects event and action sequences that have a high likelihood to cause error. As mentioned above, some users are known to take shortcuts and circumvent bar-code operated interlocks provided by medication carts and cabinets in order safe time and effort. Circumvention should not be disallowed completely and may or may not lead to errors. We want iNuC to be capable of determining when potential of errors is present and alert the user accordingly. User-centric devices are often semi-automatic: They rely on the user to perform some essential functions. Yet their users may have little or no training in its use. While the users of iNuC are well trained in medication administration, they may not be as well versed in the some mechanisms (e.g., interlocks) offered by the cart. One way to prevent harm and abuse is to have the device monitor its user’s actions and prevent itself from entering states in which it cannot operate safely and correctly.
Finally, we have placed special emphasis on the design, construction and evaluation of the user interface of iNuC. This work is motivated by two factors. First, user interfaces of existing mobile medication carts and medication management and dispensing equipment look and feel old fashioned. They fall far short of what can be achieved with today’s choices of input/output devices and interface design technology. Second, a technologically advanced device is unlikely to be a successful tool without friendly user interface to provide the user with easy access to its sophisticated capabilities.

IV. METHODS FOR REQUIREMENT CAPTURE

We have adopted two practices in the process of capturing and documenting iNuC requirements. We want to ensure the effectiveness and usability of the cart for hospitals.

The first is to involve the end-users (i.e., the actual users) from the start of the process. This widely advocated practice was motivated by the fact that insufficient attention to eliminate misunderstanding in requirements between the users and developers can lead to inconsistencies between views of the user and the system and such inconsistencies are sources of errors known to occur when new automated systems are deployed. As pointed out by studies on this problem, including [14], this and other causes of errors can be avoided to a great extent by involving end users throughout the requirement definition, design and development process. Following this practice, we presented the iNuC concept and functions in a meeting attended by over 40 National Taiwan University Hospital nursing staffs from many departments. They provided us with guidelines to follow and deeper insight into users’ wishes and views.

The second practice is to use a mockup, sometimes called rapid prototype, as a requirement solicitation, evaluation and documentation tool. Requirements of intelligent tools such as iNuC are typically specified in textual and diagrammatic forms, and sometimes, augmented by more precise and formal representations for the benefit of the designers and developers. Such requirement specifications are ineffective as a communication channel between the end-users and developers. In the case of iNuC, a mockup is a virtual iNuC. Except for the absence of the physical medication drawers with interlock mechanism and fake patient data and nurse ids used in during evaluation, the mockup gives the look and feel of a real cart. We use it as a tool for acquisition of accurate information on what the users want the cart to do and what not to do, how the users want the cart to interact with them, how they want the display to look, what their preferences in input/output devices and modes are, and so on.

Through the process of this evaluation involving the actual users using a mockup, we indeed obtained valuable feedback and suggestions. More importantly, it enabled us to identify and eliminate numerous view inconsistencies between the user and the system. The design defects and potential bugs thus exposed would likely to remain unnoticed until the prototype is put to use.

V. ARCHITECTURE, DEVELOPMENT AND MAJOR COMPONENT

Clearly, a major component of iNuC is the cart. The left side of Figure 3 shows its overall physical appearance. The structure of the medication drawers are illustrated by the picture in the right side of the figure. The electronics components of cart consist of an embedded computer, a touch screen display, a keyboard underneath the cart top, and a barcode scanner.

Figure 3 Physical appearance of iNuC and medication drawers

A. Medication Drawers and Cart

The design assumption is that the medication drawers fit iNuC as well as supply carts used to deliver medications from pharmacy to individual wards. At the back of each drawer, there is a tag containing the RFID of the drawer. Each drawer holding medications of a patient has the bar-code identifier of the patient placed inside the drawer, in addition to the printed textual name of the patient.

Each iNuC has a RFID reader at the back of the drawers. To put the medication drawer of a patient under the control of an iNuC, the user of the cart first scans the bar-code patient id in the drawer to capture the id and then puts the drawer in any empty drawer slot of the cart. Sensing a drawer is placed in the slot, the RFID reader reads the tags on the drawers. In this way, the cart acquires the RFID and location of the new drawer and creates the mapping between the drawer id and location and the patient id. Later, when the patient is due to take some medication(s), the user can have the cart open the patient’s drawer by scanning the patient’s bar-code id that is also available in the
wristband worn by the patient. The cart maintains the drawer location and patient id mapping until either the drawer is removed from the cart or the patient is released from the hospital and her/his bar-code id is deleted.

When a user logs in an iNuC as a primary user, the records of the patients assigned to the user are downloaded into the cart along with their medication schedules and appointments and user’s own schedule. Based on the drawer-location and patient-id associations of all drawers in the cart, iNuC can detect missing medication drawers and alert the user accordingly.

B. Software Components

Part (a) of Figure 2 shows the structure of the iNuC software system, major components and the support environment. As it is evident from the figure, iNuC structure is modular. The functionalities of the cart are provided by user interface (UI), work and time manager (WTM), lockers and interlock mechanism (LIM), data refreshing mechanism (DRM), record keeper (RK), authentication and authorization (AaA) module, intelligent monitor, alert and notification (iMAN) module, and cart and user event logger (CUEL).

User Interface (UI) is clearly one of the most important components of iNuC. It is one of the most visible parts of the cart. Most of the tasks done by the cart on user behalf are dispatched from there.

Work and Time Manager (WTM) is responsible for generating and maintaining schedules of the patients cared by the user (and hence served by the cart), as well as the personal schedule of the user. Its responsibilities also include sending reminders prior to scheduled events, checking schedule changes for correctness (i.e., conforming to rules) and sending alerts and logging the occurrences when scheduled tasks are overdue.

Lockers and Interlock Mechanism (LIM) provides easy-to-use functions for other modules (e.g., the UI) to manage medication drawers. Functions provided by LIM include those for querying status of medication drawers and unlocking medication drawers specified by drawer id or location. In this way, LIM module hides the control of electronic and mechanical devices used to manage medication drawers.

Data Refreshing Mechanism (DRM) module is responsible for data transmissions between carts and the server. It guarantees reliable data transmission and specified quality of service when network is available.

Record Keeper (RK) provides the record semantics on top of the DRM module. It provides functions other modules calls to upload and download patient records, schedules, prescriptions, and other types of files to and from the server.

Authentication and Authorization (AaA) module authenticates the user during login. It checks the user for authorization to control user’s access to data generated and maintained by iNuC.

Intelligent Monitor, Alert and Notification (iMAN) is a run-time monitoring tool. It provides the capabilities for real-time monitoring, capture and analysis of events and conditions that indicate the potential for occurrences, or actual occurrences, of errors, and issuing alerts and notifications to trigger error handling or prevention actions. It also provides notification functions other modules can call to send reminders and alerts.

Cart and User Event Logging (CUEL) system provides custom event logging services to all iNuC modules, enabling each module to have a separate custom event log.

C. Development Environment

We have chosen to run the iNuC software system on Windows Embedded Standard and .NET Framework. There are several reasons for this choice. As examples, using Windows Forms enables us to minimize and manage the technical challenges in programming as complex a user interface as iNuC user interface. Consequently, we were able to concentrate on its design and functionalities. By using minilogon, iNuC can skip the usual Windows login and directly displays the iNuC login screen.

We are mindful of the desire to port iNuC to a less expensive platform in the future, however. This is one of the reasons that we have chosen to write all the modules in C, except the user interface, which is written in C#. Indeed, we strive to make iNuC software easy to maintain and port so as to reduce future effort in technology transfer.

As illustrated by part (b) of Figure 2, iNuC carts rely on the support of a server. The carts access some hospital services (e.g., for making appointments) and information (e.g., drug data) via a web portal. Except for this, iNuC interact almost solely with the iNuC server (called iNuC Gateway in the figure) during development. The server maintains a relatively small number of fake patient records that were set up for experimentation and testing purposes.

In addition, the server also maintains patient and user calendars (schedules), user authorization and access rights, preference setting parameters, and so on. By management information, we mean data needed to support functionalities specifically for head nurses and users with head-nurse authorization. We have
structured these data in ways best suited for iNuC operations.

VI. SUMMARY AND FUTURE WORK

The primary goal of iNuC is to prevent medication administration errors and enhance patient safety. As a secondary goal, the cart provides its user with work and time management support for the purpose of increasing efficiency, improving quality of care and reducing workload and stress. A unique attribute of iNuC is flexibility: A web-based tool enables users with authorization to easily configure the cart to support the workflows, enforce the rules and perform desired sentinel functions of their institutions and individual departments of an institution. The next step is further take advantage of its component-based structure to support the configuring the cart for different medication dispensing and delivery processes.

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