Intensive Care Window: Real time monitoring and analysis in the Intensive Care environment

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***Abstract*—This paper introduces a novel, open source software named *Intensive Care Window*, ICW. ICW enables communication with intensive care unit bedside installed medical devices over standard and proprietary communication protocol stacks, facilitates the acquisition of vital signs and physiological parameters exported from patient attached medical devices and sensors. Moreover, ICW provides run-time and/or post analysis procedures for data annotation, data visualisation, data query and analysis. The ICW application can be deployed as a stand alone solution or in conjunction with existing clinical information systems providing a holistic solution to inpatient medical condition monitoring, early diagnosis and prognosis.**

I. Introduction

MODERN Intensive Care Unit infrastructures are facilitated with sophisticated medical devices installed at the bedside for the monitoring and supporting patients' physiological state. Most of these medical devices export large amount of data over customized and in most cases non-standard protocol stacks. This introduces design, implementation and deployment overhead to designers and lack of interoperability among medical devices and installed *Clinical Information Systems* (CIS) infrastructures. The need for standardisation has been identified since the mid 80's, (IEEE 1073 Committee for the Standard for Medical Device Communications was formed in 1984) and several standards have been formed since then (the emerging family of *International Standards Organazation* (ISO)/*Institute of Electrical and Electronics Engineers* (IEEE) standards [1], [2], [3], [4], *European Committee for Standardization* (CEN) *VITAL* [5] standard).

However, current medical device and medical sensors provided solutions are still far from being standard compliant. Instead they introduce in their majority inhouse, proprietary communication protocols, data definitions and medical information definition languages. Lack of interoperability among medical devices and/or third party hospital information system solutions introduces communication overhead, imposes the installation and provision of complex network designs and limits the monitoring capabilities while moving inpatients for diagnostic examinations. Furthermore, the fact that the medical information is spanned among the data series collected from the medical devices the requirement of computational demanding algorithms arises for processing such large amount of medical data.

Current paper's contribution and proposed solution addresses communication interoperability problems faced with medical devices that utilise standard or proprietary communication protocols and more specifically interoperability problems among the clinical information systems, the physiological monitors, the medical devices and the bedside computers. Furthermore, the proposed solution facilitates current infrastructures with un-interruptible data acquisition, long term data storage and advanced data processing, analysis and annotation functionality.

This paper is organised as follows: Section II describes the problem under investigation and the motivation that drives our work. Section III presents the related work. Section IV presents the related work and the solution proposed and in section V the pilot application deployment of the Intensive Care Window at the main referral hospital of Cyprus is described and the results are analysed. The paper concludes with section VI which further presents the future work.

II. Motivation

MONITORING the critically ill patient is an extremely challenging and demanding task mainly due to the inherent acuity of the critical illness, the complexity and the wide range of physiological derangements, the rapid changes of the patients status and the "noise" produced by the ICU environment and nursing routine. Further to these, it is important to note that in the intensive care setting there is, at the moment, lack of a real integrative monitoring technology that will acquire the physiological parameters from the different organ systems and analyse and present them in correlation to each other in an interactive environment that will facilitate the physician to extract the best conclusions for the patients treatment. It is deemed necessary to say that at the moment, the most invaluable, interface monitoring tool in the intensive care setting is the ICU nurse. The use of information technology aims to cover at least a part of this lack with the use of clinical information systems in the intensive care setting. However the huge amount of the required resources associated with the purchasing, the deployment and the maintenance of the commercially available systems is currently a prohibiting factor for the wide spread use in the intensive care. Another restrictive factor is the fact that the commercially available systems use proprietary code which is not made available to the customer and in some cases may lead to further complexities and hidden costs especially when expandability is required. Furthermore, the clinical systems commercially available at the moment focus more on the management of the everyday clinical work instead on the in-depth analysis of the acquired physiological parameters. Although this is very useful for the everyday clinical practise in an ICU, it does not offer the in-depth interactive analysis environment often required by the physicians. The aforementioned restricting factors motivated us to create a software solution for use in the intensive care setting that would provide bedside network and clinical information system connectivity, medical data processing and information extraction. The software solution is aimed to have an interactive environment and to be capable for in-depth analysis of the acquired vital parameters. Also, it is aimed to be of low deployment cost, easily expandable and to comply with open source code standards.

III. Related Work

SIMILAR efforts that attempt to address the aforementioned challenges over the past years can be found in literature. In [6] the authors present a process management system for ICU monitoring management and patient data analysis, using the expert system developing tool *OPS/83* that was able to connect and retrieve data from the bedside monitoring devices. In [7] researchers have designed a system to collect parametric and waveform type information in pediatric Intensive Care Units and in [8] the design of a tele-medicine system based on Vital Signs Information Representation (VITAL) and *Digital Imaging and Communications in Medicine* (DICOM) standards was introduced. Another work was presented in [9], [10] where researchers provided embedded solutions to address the medical device interoperability problem and succeeded to develop a wireless (bluetooth network) medical device subnetwork for home treatment infrastructures. In [11] the authors provide a study for an ubiquitous healthcare service and corresponding based on the ISO11073 and ubiquitous sensor networks. Also in [12] the authors present the implementation of an end-to-end standard based patient monitoring solution able to extract information from the bedside environment and transfer it to an electronic healthcare record server.

IV. System Description & Architecture

THE main contribution of the proposed work described in the following paragraphs:

A. ICW bedside controller

The controller is build based on the *Medical Information Bus* (MIB) standard network model. The controller's modules used to communicate with standard or proprietary protocol medical devices introduce an object oriented run-time library (named *Medical Device Infrastructure Library* (MDIL)) that can be used independently from application level software executables. The framework (via the software development kit) provides solutions to medical device communication interface software developers, hides the communication complexity to medical information system developers and interfaces with installed hospital information systems using standard protocol interfaces. Three of the most important contributions of the ICW bedside controller as far as run-time execution is concerned are:

- *Automatic and Semi-Automatic medical device configuration*. The application is using a build-in feature for automatic and semi-automatic medical device connection parameter configuration. The application utilises a dynamic configuration mechanism which loads corresponding software libraries at run-time. Users are facilitated with simple procedures to select the appropriate device communication component, select the communication path (serial, ethernet, other) and configure the corresponding communication channel accordingly.
- *Establishment of standard compliant communication paths*. The ICW bedside communication controller(depicted in figure 1) establishes in parallel multiple communication channels with a variety of medical devices over standard protocol stacks.
- *Hides proprietary protocol complexity*. The bedside communication controller establishes connection with medical devices using proprietary protocol stacks, groups the information based on standard medical languages and transmits the data over standard communication channels to storage servers or other hospital information systems.

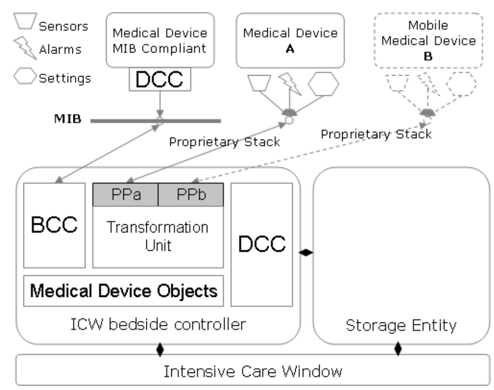

Fig. 1. Intensive Care Window architecture

B. ICW application

The *Intensive Care Window* (ICW) application (with an end user graphical user interface) serves the need for human-machine interaction providing, among others, functional and graphical components for real time monitoring. The ICW application is able to communicate with the ICW controller and retrieve exported signals and parameters and perform real-time or post process analysis. The most important functions in the ICW application can be summarised as follows.

- *Real time monitoring and supervision(figure 2)*. The application depicts retrieved medical information in real time. The depiction of the numerical information retrieved from medical devices is in textual and graphical format. ICW application users are enabled to mark events, set watermarks and supervise critical incidents via alarm mechanisms.
- *Playback functionality*. Retrieved data are formalised in time series which enables playback functionality of

each individual scenario in offline mode. Using the playback functionality practitioners can review the status of inpatients and enrich scenario information. Playback functionality can be also applied during scenario run-time execution without disrupting normal reception and storage procedure.

- *Data collection annotation*. Each single medical information datum is identified with a unique key using value type identifier and the reception time value (this is valid for values in the same space; in this case a value space consists of all the available information retrieved from medical devices attached to a single *Intensive Care Unit* (ICU) bed). Using data identifiers the application is capable of annotating singe or multiple occurrences of interesting incidents in one-to-many or many-to-many relationships.
- *Local search capability* (figure 2). Reconfigurable, expandable A simple but helpful search mechanism has been designed which serves the need for information abstraction among large data sets. The application is enhanced with a *Graphical User Interface* (GUI) editor which can be used for composing logical criteria information filters. These logical criterions, defined as a single or a group of conditions based on boolean algebra, are fed to the search engine to product a collection of time sensitive values matching the criteria.

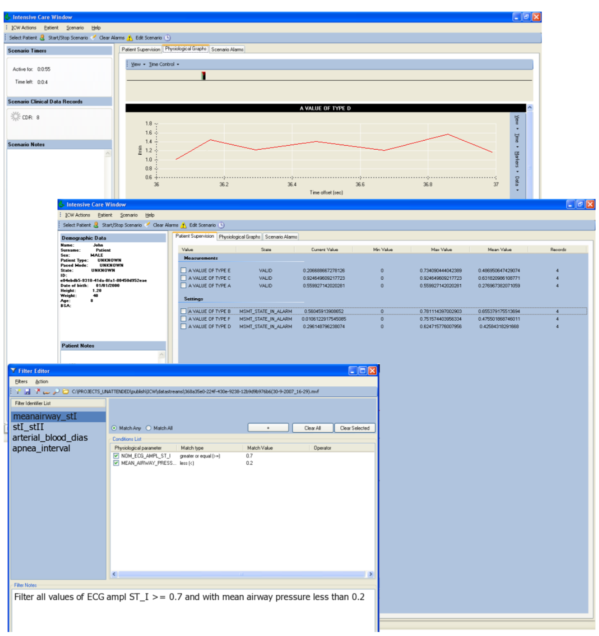

Fig. 2. Vital signs real time monitoring - graph and textual representation

V. Real life scenarios deployment

A. System Deployment

A real life scenario deployed in *Nicosia's General Hospital* (NGH)'s ICU is depicted in figure 3. The ICW application was installed on normal portable PCs running Microsoft Windows XP operating system. Physical connections with *Recommended Standard 232* (RS-232) interfaces were established using RS-232 to Universal Serial Bus (USB) converters. When needed (connection with N medical devices, where N $>$ Available USB ports) USB hubs were installed and used. This configuration serve us the need for maintaining mobility until the system is deployed in full scale.

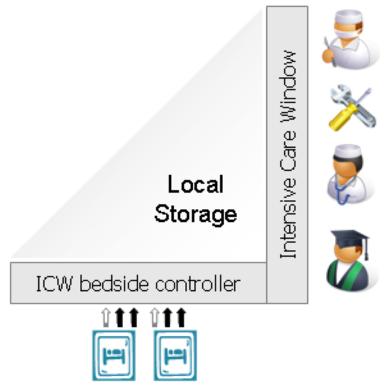

Fig. 3. Nicosia General Hospital Intensive Care Unit deployment

We installed the *ICW bedside controller* in two ICU beds and established a connection with two major medical devices (monitor and ventilator) and communicate over raw data path with a blood gas analyser. For the monitoring procedure we used the *Philips Monitor MP70* which is facilitated with international standard communication protocols and languages (MIB and *Medical Device Data Language* (MDDL)). The *Puritan Bennett Ventilator 840*, though a state-of-the-art medical device it does not export physiological parameters using proprietary communication protocols. Further parameters (blood glucose and SjO_2) were retrieved by the automatic blood gas analyser *ABL800 Flex* utilising the raw data format path over the serial communication channel. For the needs of this experiment an hourly blood sampling rate was applied.

The ICW bedside controllers were configured to retrieve information from the attached medical devices and store it in local storage elements for further processing. The following motivating scenarios are under investigation to identify life threatening conditions:

- *Multiple Organ Dysfunction Syndrome* (MODS). MODS is a life threatening complication of many acute diseases involving several medical specialties. MODS is defined as the presence of multiple organ dysfunction in acutely ill patients such that homeostasis cannot be maintained without intervention(s). An example of a life threatening condition in this scenario is the co-incidence of more than two *high risk* physiological derangements i.e. mean blood pressure $<$ 60mmHg, SaO2 $<$ 90% and blood glucose $>$ 160 mmol/lt. This syndrome is considered to be one of the most demanding for trainees and young professionals.
- *Traumatic Brain Injury* (TBI). Our understanding of pathophysiology of traumatic brain injury (ischemia, oedema, neuronal damage and regeneration) is surprisingly poor. New insights into brain tissue metabolism reveal complex associations between clinical, physiologic, imaging, metabolic and genetic data that can predict

outcome and offer clinical decision making. Another example of a life threatening conditions in this scenario is the co-incidence of more than two *high risk* physiological derangements i.e. cerebral perfusion pressure $<$ 60mmHg, SjO2 $<$ 60% and blood glucose $<$ 60 mmol/lt.

B. Results

Practitioners were able to monitor in real time inpatient's state or execute post analysis procedures to identify and annotate clinical interesting episodes using the ICW. The system was configured to retrieve and store all available information (measurements and settings) provided by the three medical devices. Table I lists the physiological parameters and vital signs monitored during the evaluation phase of the system. In total, the selected parameters and vital signs were retrieved on 12 seconds interval basis. Detailed information regarding the metrics during the evaluation phase are listed in table II.

TABLE I
REAL TIME VITAL SIGNS AND PHYSIOLOGICAL PARAMETERS

Philips Monitor MP70	
Vital Sign	**Type**
Arterial blood pressure diastolic	Measurement
Arterial mean blood pressure	Measurement
Arterial blood pressure systolic	Measurement
Arterial oxigen saturation	Measurement
Central venous mean pressure	Measurement
Cerebral perfusion pressure	Measurement
SaO_2	Measurement
Electrocardiograph parameters	Measurement
Heart rate	Measurement
Non-invasive blood pressure diastolic	Measurement
Non-invasive blood pressure systolic	Measurement
Pulse rate from plethysmogram	Measurement
Perfusion indicator	Measurement
Pulse rate	Measurement
Puritan Bennett Ventilator 840	
Exhaled minute volume	Measurement
End inspiratory pressure	Measurement
End inspiratory pressure	Measurement
Exhaled tidal volume	Measurement
Constant during rate	Setting
Flow pattern	Setting
Inspiratory pressure	Setting
Inspiratory time	Setting
Mean airway pressure	Measurement
O_2	Setting
Peak flow	Setting
Peep setting	Setting
Pressure support	Setting
Plateau time	Measurement
Respiration rate	Measurement
Spontaneous minute volume	Measurement
Tidal volume	Setting
Total respiratory rate	Measurement
ABL800 flex	
Blood glucose	Measurement
SjO_2	Measurement

TABLE II
EVALUATION PARAMETERS AND METRICS

Evaluation Metrics	
Metric Type	**Value**
Evaluation period duration	3 Months
Total number of patients	10
System users (ICU practitioners)	2
Parallel sessions	2
Average session time duration	72 hours
Average data throughput between *Medical Device* (MD)s and ICW bedside controller	2 Kbps
Average data throughput between ICW bedside controller and ICW application	4.5 Kbps
Average information stored per hour per patient	0.5 MB per hour

VI. CONCLUSIONS

IN this paper we introduce a novel application which provides the Intensive Care Unit physicians with the essential tools and functionality to retrieve and analyse the physiological state of ICU inpatients. The ICW bedside controllers retrieve the physiological parameters, alarms, settings which are exported from beside installed medical devices. The exported information is analysed and depicted in real time using textual and graphical views for purposes of accurate diagnosis or early prognosis. Long term storage capability of retrieved information along with playback functionality enable training and long term education which in turn will improve treatment of patients facing life threatening complications.

Future work aims to deploy the system in full scale in NGH's ICU for a longer period of time and evaluate information extraction procedures correctness and accuracy. Furthermore, it aims to initiate an open source project for the MDIL runtime framework and software development kit.

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