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Clinical-HINTS: Integrated Intelligent ICU Patient Monitoring and Information Management System

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Abstract. Clinical-HINTS (Health Intelligence System) is a horizontally integrated decision support system (DSS) designed to meet the requirements for intelligent real-time clinical information management in critical care medical environments and to lay the foundation for the development of the next generation of intelligent medical instrumentation. The system presented was developed to refine and complement the information yielded by clinical laboratory investigations, thereby benefiting the management of the intensive care unit (ICU) patient. More specifically, Clinical-HINTS was developed to provide computer-based assistance with the acquisition, organisation and display, storage and retrieval, communication and generation of real-time patient-specific clinical information in an ICU. Clinical-HINTS is an object-oriented system developed in C++ to run under Microsoft Windows as an embryo intelligent agent. Current generic reasoning skills include perception and reactive cognition of patient status but exclude therapeutic action. The system monitors the patient by communicating with the available sources of data and uses generic reasoning skills to generate intelligent alarms, or HINTS, on various levels of interpretation of an observed dysfunction, even in the presence of complex disorders. The system's communication and information management capabilities are used to acquire physiological data, and to store them along with their interpretations and any interventions for the dynamic recognition of interrelated pathophysiological states or clinical events.

1. Introduction

High technology medicine has been making rapid progress in supporting health care, and particularly so in relation to the critically ill patient in high dependency environments (HDE). These latter include intensive therapy, renal dialysis, transplantation, and open heart surgery hospital units. The benefit that high technology medicine offers is that it has introduced a mathematical element into the reasoning processes underlying clinical judgement, making the diagnosis and management of an observed problem, and hence patient care, less of an intuitive art form and increasingly more of a science [2, 3]. As a consequence, diagnostic investigations and monitoring can now be readily embarked on and repeated, resulting in an increasing yield of patient data and potential knowledge particularly about dynamic aspects of various complex conditions. This has implications both in terms of medical procedures as well as in terms of the development of computer-based systems for clinical decision support [2, 3].

Although biomedical diagnostic investigations involve the observation of dynamic phenomena that take time to run their course (e.g. biochemical alterations induced by a disease stimulus), the current facilitated visualisation of physiological function is removed from its clinical and temporal context, thereby yielding a large number of raw data that must be interpreted within the clinical context to provide interpretations appropriate to the context [3, 12]. Consequentially, the management of the data generated as a result of scientific and technological developments is a major problem for modern clinical medicine with repercussions on both the quality and cost of health care. In the last decade or so, studies of the data generated in critical care medical environments have reported dramatic increases in the both the number and frequency of measurements performed [5, 21]. Although the availability of patient data from the above sources aims to improve the quality of care, the large number of variables and frequency of measurement can overwhelm clinicians. Therefore, the benefits that high technology promises in postponing death and reducing disability are not met with an equal ability to restore health and exact too high a price on hospital resource management. This is particularly true of the critical medical care environment [5] and especially so in relation to the clinical laboratory, which can be regarded as an exemplar of what holds true for the wider health care system [11, 12].

What is required is a transition from a technology of diagnostic tests to a technology of advanced intelligent instrumentation providing decision support [4, 5, 14]. With such means the data acquired by existing instrumentation can be intelligently displayed and transformed in a manner which converts them to information, making it easier for the clinical team to avoid the misinterpretation of numerical data [13]. The objectives underlying this primary requirement are:

1. To develop intelligent instrumentation systems, seeking to maximise the decision support facilitated by biomedical measurement technology by interpreting the generated data in the evolving clinical context using knowledge based inference techniques, thereby enhancing the yielded information content.

2. To optimise the assistance offered to the clinical team, by means of the provision of interpretative support that is geared to the real-time information management needs of the clinician decision maker [6, 10].

3. To develop improved software architectures, and to address the inferential problems associated with the diagnosis of complex clinical events [4, 14], in the context of the wider problem of integration with the information management infrastructure [6].

2. System description

Clinical-HINTS is an object-oriented embryo intelligent agent for ICU monitoring, which encompasses a generic task-specific [7, 8, 9, 14] knowledge-based system (KBS) architecture for intelligent patient monitoring [14]. The system was designed with the aim to develop a system that:

1. Provides a basis or a shell for intelligent real-time clinical information management.
2. Demonstrably performs and coordinates the full range of intelligent behaviour required for effective critical care monitoring.
3. Provides facilitated access to the underlying structures of data, knowledge, and information generated.
4. With minimum development effort, will scale up to satisfy all of the needs for decision support in critical care medicine. This includes the full range of information management and decision support activities encountered in the targeted environment.

2.1. Top level system organisation

To satisfy the above requirements for inference, genericity of inference, integration, adaptivity, and extensibility, the Clinical-HINTS architecture was designed and developed in layers. The top-level organisation of the Clinical-HINTS system is depicted in **Figure 1**.

The kernel of the system consists a central data structure which integrates the three classes of AIM-based, DSS information structure listed below, in a global memory of persistent models. The Clinical Object Base (COB) is what makes Clinical-HINTS stand out from previous KBS architectures and approaches to knowledge-based clinical decision support. It consists three classes of persistent models: the Patient Record Model (PRM), the General Domain Model (GDM), and the Patient-Specific Model (PSM). These in turn form the structure of the system knowledge base, data base, and reasoning base respectively. Thus, apart from serving as a global memory of persistent clinical information models, the COB also serves as a framework for the development of system facilities. Current system facilities include:

1. Acquisition, organisation and display, storage and retrieval, communication and generation of real-time clinical information.

2. Monitoring, detection, interpretation, documentation, retrieval, and display of clinical events and disorders in the ICU patient's chart.

Communication with the environment is handled by a generic Object Communication System (OCS). The OCS is an independent process which interfaces ICU instrumentation with the COB. Each instrument requires its own dedicated computer to provide access to the object base server. The object base server is an Object-Oriented Data Base System (OODBS) [19] that uses the persistent model interfaces described below to create and maintain the COB. The COB was implemented using the POET pre-compiler. The server can also be accessed at any time via the integrated Intelligent Clinical Information Management System (ICIMS) user interface described below.

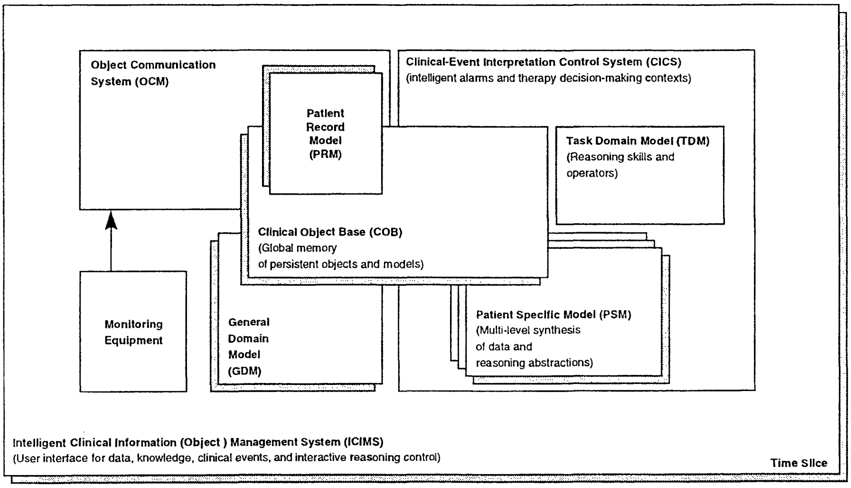

Figure 1. Top-level organisation of the Clinical-HINTS system.

2.2. Intelligent user interface

The integrated ICIMS is an intelligent top-level user interface to the information managed by Clinical-HINTS. This includes acquired and inferred information. The ICIMS comprises a number of system-user dialogues which are accessed via the Clinical-HINTS main menu.

The ICIMS interface comprises two classes of system-user dialogue: the Data Base Management System (DBMS) dialogues and the Knowledge Base Management System (KBMS) dialogues. Each class is further divided into two parts: views and queries. A view provides direct access to the information structure while a query provides information search facilities. A patient view includes the parameters being monitored for that patient, the patient's clinical features, and the patient's status. Currently the patient's status is displayed as a state-space trajectory comprising a high-level summary of clinical events. The user may evaluate the patient's status by selecting the evaluate button. By doing so the user instantiates a generic blackboard-based qualitative reasoning architecture (GQRA), based on the Task-Domain Model (TDM) described below and controlled by a Clinical Event Interpretation Control System (CICS). CICS produces a number of dialogues with the user which display the current state of the instantiated GQRA (TDM and PSM) and also allows the user to probe the constructed PSM during the reasoning process. The monitored patient parameters are inserted into patient objects directly via the OCS.

A knowledge base view includes the disorder in view, its links with other disorders in the classification hierarchy, expected results of investigations, and the disorder's clinical classification in terms of the patient's clinical features. Other parts of the current KBMS include a vocabulary of terms and clinical parameter statistics such as minimum and maximum values, mean value and standard deviation. Currently there is no facility for graphical display of the COB structure but such a facility should be added to Clinical-HINTS.

2.3. Information structure

An intelligent instrument comprises epistemological models of monitored qualitative processes and behavioural models of task-specific interpretations or manipulations of those models. The architecture of knowledge-based machine intelligence comprises the following structural ingredients [7, 8, 9]:

1. An epistemological model is a GDM of some system under observation (e.g. the respiratory-buffer-metabolic control system of acid-base balance). The model comprises qualitative abstractions which encapsulate any structural and structural-support knowledge available in the modelled domain.

2. A behavioural model or Task-Domain Model (TDM) comprises procedural abstractions which encapsulate the mechanisms, or operations and strategies, by which the structure of a process is brought to bear on the simulation of a process. Reasoning control knowledge is represented either in the inference structure of the behavioural model [7] or as a separate model of strategic concepts [9].

3. A PSM comprises qualitative as well as quantitative abstractions which encapsulate the state of a simulation at any one time.

A generic KBS architecture must provide a conceptual description of these components and of the mechanisms that will be used to implement the identified components. These conceptual descriptions or models are represented in the COB of Clinical-HINTS. Generic Model Building Interfaces (MBI) are used for the construction and maintenance of the PRM, GDM and PSM. In terms of their physical structure, each of these information bases comprises a number of persistent objects which are constructed according to their respective MBIs. All system models are represented as object-oriented relational networks (hierarchies and transitional graphs). Inference procedures can thus be described in terms of reasoning operators for placing nodes and links in the PSM. In IMC systems, temporal PSMs linked as state-transition diagrams emerge as a fourth structure or class of models. Furthermore, integration of the reasoning models with a clinical information base becomes an absolute requirement in the case of IMC systems.

2.4. Task domain model for generic qualitative reasoning

Clinical-HINTS generates patient-specific information by instantiating a blackboard-based [18] generic qualitative reasoning architecture which can be applied to any class of disorders given access to the necessary GDM. The system monitors the patient by communicating with the available sources of data in the ICU and uses generic reasoning skills, or abstract operators, to generate intelligent alarms, or HINTS, on various levels of interpretation of an observed dysfunction, even in the presence of complex disorders. The system's communication and information management capabilities are used to acquire physiological data, and to store them along with their interpretations and any interventions for the dynamic recognition of interrelated pathophysiological states or clinical events. Patient-specific information is generated in real-time by CICS. For each observed clinical problem class, CICS will instantiate an appropriate controlled GQRA for the construction of a pathophysiological PSM from the GDM of domain pathophysiology and patient data, by means of the successive application of reasoning operators to the blackboard memory. Current generic reasoning skills include perception and reactive cognition but no action.

Clinical events are known domain disorders represented at three levels of perceptual abstraction: parameter abstractions, pathophysiological states, and disorder aetiologies. Thus clinical-HINTS recognises an organ system dysfunction by means of deviations from expected patterns on these three levels. The qualitative abstraction of monitored patient parameters confers the ability to identify significant or probable observed physiological abnormalities. Parameter-based problem abstractions are obtained by a process of probabilistic data classification. Further interpretation of the generated qualitative abstractions within the clinical context confers the ability to diagnose the most likely cause of an observed clinical problem and thereby to identify known pathophysiological states of the represented domain. State-based problem abstractions are obtained by a process of disorder classification by evidence aggregation in a hierarchical belief network [20]. Belief networks [16] have already demonstrated their power in providing a unified framework for qualitative modelling and reasoning under uncertainty [15, 16], and are now being applied to the task domain of intelligent monitoring and control for diagnosis as well as prediction. Complex disorders are further diagnosed by projecting the PSM onto the clinical context. The recognition of complex clinical events is further facilitated by observing state-space trajectories formed by time-ordered persistent PSMs.

The ultimate benefit of developing clinical DSS must be an improvement of the quality and cost-effectiveness of health care. This must be demonstrated by an improvement of diagnostic accuracy coupled with a reduction of redundant and negative investigations, patient management decision making errors, and consequentially a reduction of rates of stay in the hospital and overall patient morbidity and mortality [13]. The evaluation of DSS is a complex undertaking which has only recently been formally addressed [1] and as such the literature contains only a small number of evaluations of the performance of medical DSS, both in narrow domains and in the broader field of internal medicine [1].

So far, Clinical-HINTS has been subjected to a retrospective evaluation with cases from the ICU and reported studies. The system was in agreement with the diagnoses provided by peer systems, including those generated by the Siggaard-Andersen & Radiometer Oxygen Status Algorithm (OSA). In a retrospective evaluation of 60 challenging cases selected from the COB, the system agreed with 53 (88%) of the cases, either with the expert or senior clinician involved in the study. The display of state-space trajectories comprising diagnosed pathophysiological states was found very useful in working towards eliminating diagnostic ambiguities and facilitating the management of the monitored patient [17].

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