A Survey of Agent-Based Intelligent Decision Support Systems to Support Clinical Management and Research

Darren Foster[1], Carolyn McGregor[1], Samir El-Masri[1]
[1]Health Informatics Research
School of Computing and IT
University of Western Sydney
dsfoster@cit.uws.edu.au, c.mcgregor@uws.edu.au,
s.elmasri@cit.uws.edu.au

Abstract. The research into agent-based intelligent decision support systems is important to the medical industry because these systems can be used to improve the quality of healthcare in many ways. The areas these systems can be used in are diverse from the storage of medical records to the examination and evaluation of real-time data gathered from monitors. These systems are helpful to doctors and nurses in the diagnosis and treatment of patient with all kinds of conditions. This paper is a survey of the current research into agent-based intelligent decision support systems to support Clinical Management and Research, in order to first determine the current state of research in the area, second to help derive the key features and problems with these systems in the medical industry, and thirdly to use these key features and problems to explain how the current research would effect the development of a neonatal intensive care unit agent-based intelligent decision support system.

1 Introduction

The use of agent-based intelligent decision support systems (IDSS) to support decision making is important within the medical industry because they allow doctors and nurses to quickly gather information and process it in various ways in order to assist with making diagnosis and treatment decisions. The areas these systems could help in is diverse from the storing and retrieval of medical records, storing and retrieval of key substances in medicines, examination of real-time data gathered from monitors, analysis of X-Rays, analysis of patient history for the purposes of diagnosis, analysis of family history (for cardiac conditions for example), and in many other areas [1-3].

The motive of this research is to survey existing research in the area of agent-based IDSS within medicine, to review current trends and assess the ability of current agent-based intelligent decision support research to support the needs of clinical research within the neonatal intensive care unit setting.

This paper presents a survey and comparison of recent research on the use of agent-based IDSS to support the two functional areas within medicine of clinical management and clinical research.

This paper is designed to give an overview of the current research into medical agent-based IDSS. This will involve looking at agents, decision support systems (DSS) and current agent-based IDSSs both inside and outside the medical industry. The information gathered in this research will help with identifying potential issues with agent-based IDSS particularly with our intended future work on an Agent-based IDSS for neonatal analysis and trend detection.

This paper will first review Agents, including what they are, what they are used for and how they could be used in the medical sector. Then it discusses DSSs including what they are, the differences between DSSs and IDSSs and how they relate to Agent-based IDSS. Then the paper presents medical Agent-based IDSSs in detail including current systems. We then compare and contrast the current systems in detail in order to expose issues with medical Agent-based IDSSs as well as open areas of research. Finally we analyse the current research in light of an intended Neonatal Intensive Care Unit (NICU) Agent-based IDSS in order to discover any possible issues and desired features. The paper concludes with an overview the current state of research and discuss where future work on the NICU Agent-based IDSS.

2 Agents

2.1 What is an Agent?

The word Agent has many definitions in artificial intelligence circles some of the more common definitions are presented in this section. One of the most common definitions for agents is that the agent itself is merely an umbrella term for a group of more specific types of agents. They can be classified by attributes. Some commonly used attributes are reactivity, autonomy, learning, cooperation, reasoning, communication, and mobility [4-9]. The American Heritage Dictionary definition of an agent is *a system that acts or has the ability to act or represent another*. This essentially is using the term agent in the same manner as it is used with real estate agents and travel agents [10]. Another common definition is that an agent is anything that can autonomously interact with its environment and an intelligent agent perceives its environment and makes informed decisions based on its perceptions and acts accordingly [11, 12]. For the purposes of this research we use the definition that an intelligent agent is defined, as a system that perceives its environment and acts upon the information it perceives.

2.2 Multi-Agent Systems

Unlike agent definitions, the definition of Multi Agent Systems (MAS) is well known and accepted as a loosely coupled network of agents that work together to find answers to problems that are beyond the individual capabilities or knowledge of each agent and there is no global control system [13, 14]. The problems being beyond the individual capabilities of an agent could mean that the domain requires multiple different agent types each focussed in a different area, meaning they can only solve

part of the problem [13, 14], or it could mean that each agent is only capable of solving a subset of the domains problems [15]. There is a need for mechanisms for advertising, finding, fusing, using, presenting, managing, and updating agent services and information.

Most MAS use facilitator agents to help find agents, agents to which other agents surrender their autonomy in exchange for the facilitator's services. Facilitators can coordinate agents' activities and can satisfy requests on behalf of their subordinated agents [13, 14]. Other methods also exist including Mediators, Brokers, Matchmakers and yellow pages and Blackboards [13, 14, 16]. Another method also exists that is called scenes, where the roles are predetermined and each agent is told where the rooms are that they need to be in [17].

There are essentially two kinds of MAS. Closed MAS contain well-behaved agents designed to cooperate together easily toward a global goal. Open MAS can contain agents that are not designed to cooperate and coordinate [18]. Most open MAS of cooperation and coordination mechanism are designed to assist the agents to working together. The most common kinds of these mechanisms are for negotiations [19] and auctions [20]. One example of negotiations is where an agent barters either services, money, etc in exchange for assistance on a particular task or subtask by another agents [19]. One example of an auction would be where you have a group of tasks and agents that you would like distributed as efficiently as possible. You would let the agents bid on the tasks they want to do [20]. Assuming the agents are configured correctly they will only bid on tasks that they can complete for less then the other agents.

2.3 What are Agents used for?

Some of the activities that agents have been used for include as Internet shopping assistants [21, 22], game playing agents like for example soccer agents [23, 24], non player (NPC) characters [25, 26]or even at a strategic level [27], personal assistants [11, 28], text-learning [29] and also for assisting decision support systems both outside [30, 31] and inside of the medical domain, as detailed later in this paper.

Agents are normally used in similar circumstances, in that they are used to observe the current situation and knowledge base, and then make a decision on an action consistent with the domain they are in, and finally perform that action on the environment.

3 DSS/IDSS

3.1 What is a DSS

There are many definitions of what a DSS is but according to Turban and Aronson [32] the central purpose to a DSS is to support and improve decision making. Little [33] defines DSS as a “model-based set of procedures for processing data and judgements to assist a manager in his decision-making.” He argues that to be successful such a system needs to be adaptive, easy to use, robust and complete on important issues. These features are desired but not required in a DSS. Bonczek et al.

[34] defines a DSS as a computer-based system consisting of three interacting components a language system, a knowledge system and a problem-processing system. This definition covers both old and new DSS designs, as the problem processing system could be a model-base or an ES or an agent-based system or some other system providing problem manipulation capabilities. Keen [35] applies the term DSS to situations where a 'final' system can be developed only through an adaptive process of learning and evolution. Thus he defines a DSS as the product of a developmental process involving the builder, the user and the DSS itself combining to evolve into a combined system.

For the purpose of this research the definition of a DSS is based on the definitions of Turban and Aronson and Bonczek in that a DSS is a system to support and improve decision making. However, it also must contain the three subsystems that Bonczek describes, that is it must have a database of some kind attached (data subsystem), it must have a mechanism for processing the data (model subsystem) this could be models, rules, agent-based subsystem or some other techniques and it must be capable of receiving and acting on requests from users (user interface subsystem) for example the user might request the detail that allowed a specific recommendation to be formed in order to see for himself if it is justified.

3.2 Difference Between an IDSS and a DSS

There are several different definitions of the differences between a DSS and an IDSS. This is due to the fact that there are multiple different kinds of IDSS (or Knowledge-Based DSS as they are also known), these include those that replace the model base management system with the Expert Systems (ES) or other intelligent decision making functionality, those where the functionality is added to enhance the model-base management system (MBMS) to make it intelligent, and improved user interfaces can be achieved using other parts of artificial intelligence, including natural language processing or similar techniques [32, 36]. IDSS also allow for supporting a wider range of decisions including those with uncertainty. So that rather than just making a recommendation it can also give a confidence level that the recommendation is a good one. It can also handle domains where the decision process is more complicated and requires expertise as well as assessment of the impact of the proposed solution [32]. Some other advantages proposed by Marakas [37] gives the advantages of using intelligent components with DSSs as opposed to plain DSSs as increased timeliness in making decisions, improved consistency in decisions, improved explanations and justifications for specific recommendations, improved management of uncertainty, and formalisation of organisational knowledge. The most useful of these advantages is the improved explanations and justifications which is an extremely useful feature particularly in fields like medicine, etc where it helps if the real expert can validate the machines reasoning. McGregor [38] uses a Agent-based decision support system that has the intelligence section attached to the model base as opposed to replacing it. This is normally done when the purpose of the intelligence section is to enhance and supplement the models as opposed to replacing them, this can be a very useful method of increasing the accuracy and consistency of decisions. In the context of this research the definition of an IDSS is that the IDSS has an intelligent component, which either replaces or enhances the model subsystem.

4 Existing Healthcare Systems

4.1 Agents

There are multiple areas in the Medical Industry that would benefit from agent-based systems designed to support a range of decisions from diagnosis assistants, to treatment recommending systems, to patient history examination systems. These systems could be used for any purpose like examining patient history for previous medical treatments on the same of similar condition, to examining EKG or X-Rays to diagnose the exact problem with a patient [2]. Some examples of applying agent research within the medical industry include an agent that searches the patient databases in an attempt to discover family relationships [39] and a system that involves multiple cooperating agents in order to decide on treatments [40]. Larssan and Hayes-Roth present [41, 42] another agent that's entire purpose is for medical monitoring and diagnosis of a patient. Meunier [43] detail a mobile agent system for gathering together medical data from different hospitals and other data sources. Silverman et al's [44] agent based system is used to remind doctors of important events such as surgery or follow up examinations. A multi–agent system was proposed by Vicari et al [45] that diagnoses patients in a similar manner to doctors for the purpose of teaching of medical students and providing an alternate opinion if asked. They have also be used to verify that medical protocols are being followed correctly [46]. Medical image analysis agents are described by McInerney et al [47]. Agents have also been used to gather enhanced information about certain conditions, etc to enhance the electronic patient record [48]. A patient advocate system was defined by Miksch et al [49] where the patient has an agent assigned to them that attempts to ensure the patient gets the best possible treatment and reminds the patient about follow-up tests, etc. They can also be used for data mining to determine trends [50]. Ouali [51] describes agents used to represent people for virtual training purposes. A multi-agent patient scheduling program was proposed by Decker and Li [52] This system attempts to increase hospital efficiency using global planning and scheduling techniques.

4.2 DSS

IDSS and DSS are used in the medical industry to store and allow for patterns in the data to be analysed by models or other methods. An overview of some of the systems currently being used is given. One example of how these systems are used is a hospital statistic analysis, which can be used for long term strategic planning of where to put limited hospital resources as well as for analysing hospitals performance in relation to other similar hospitals [53]. Another system proposed by Warren, Beliakov and van der Zwaag [54] is used to help evaluate the clinical guidelines to assist doctors in finding alternative courses of treatment and diagnosis. Prather, et al [55] present a system that identifies similar factors between different cases that lead to complications or a difficult to diagnose illness. A IDSS was proposed by Catley, et al to diagnose babies in neonatal intensive case unit and to determine ethically which if any treatments to perform [56-60]. Bolinger, Price and Kyner [61] developed an IDSS to help determine if a treatment would be safe given patient history and known allergies for example in the treatment of diabetics in a diabetic clinic.

5 Medical Agent-based IDSS

This section introduces the research included as part of this survey. The research method used to select the papers is first described. The following two subsections introduce the medical agent-based IDSS research within the broad categories of clinical management and clinical research.

5.1 Research Method

The medical agent-based IDSS systems papers where found by looking for "agent", "intelligent agent", "medical", "healthcare", "clinical", "multi-agent systems", "MAS", "DSS", "IDSS", "active DSS" and combinations of these search terms. While this research concentrated on papers from the last 5 years, others were included if they were deemed still relevant. Again predominately the searches were mainly from IEEE and ACM conferences and journals however some ScienceDirect conference and journal papers were also used. Also some of the key papers were found on PubMed. One interesting fact to note is that many agent-based IDSS call themselves agent-based systems in the abstract and titles and only in the body of the paper do they admit they are agent-based IDSS. Gross-Portney and Watkins [62] definitions of Clinical Management and Clinical Research are used to group the papers within these terms as presented in the next two subsections.

5.2 Clinical Management

Clinical Management systems are systems that are designed to assist doctors in diagnosis and treatment using existing already established methods of diagnosis and accepted treatments [62].

Coffin et al [63] describe a reminder system. It uses intelligent agents to monitor looking for circumstances that require notifying healthcare professionals about events. These events can include giving shots, vaccinations, surgeries, follow-up checks and other important events. These events are found by the analysis of administrative data as opposed to clinical data. The case study presented was tested on determining who should be give pneumonia vaccinations however it can be used in much wider areas.

Cohen and Hudson [64] present an agent-based IDSS which is used for diagnosis involves three levels. The lowest level is called agents, which contains multiple kinds of agents including user interface agents, data mining agents and problem solver agents. The second level are communicators which act as translators between the task-managers and the agents to ensure that every agent gets the information in their desired format. The top level is task-managers, which break the task up into sub problems that are assigned to agents.

The Intelligent Healthcare Knowledge Assistant is a healthcare knowledge procurement system, which has six different agent types. These types are the user interface agent, an agent to convert the search result into a viable format for passing to the UI agent, a query optimising agent which optimises the query, the knowledge retrieval agent that performs the query, the knowledge adaptation agent to adapt the

knowledge to the current circumstances and the knowledge procurement agent which if all else fails searches the web for the knowledge [65].

Godo et al [17] define an agent-based IDSS for the prescription of restricted use antibiotics, the system works by having multiple agent types. These types include UI agents, agents involved in the procedure of revising therapy, and a special kind of agent called a guardian angel. The agents involved in the procedure of revising therapy come in two types, which are laboratory assistants that handle lab result and pharmacy experts that handle using their knowledge of pharmaceuticals and the current situation to propose alternative treatment strategies. The guardian angel is assigned to a specific patient and takes care of the patients stay aiming to get the patient the best possible treatment.

The EMG Analysis system is a data mining system that is used to mine electromyography (EMG) data the system contains three different agent types. These are the task agent which is the user interface agent, the sub-agent which has information about a specific part of anatomy and the data agent which is used to mine one specific field from one specific table [66].

The Clinical-HINTS system is a decision support system designed to meet the requirements for intelligent real-time clinical management in critical care medical environments such as intensive care units (ICU). The system is a single agent based system where the agent is used to analyse the data and activate any alarms that are required [67].

5.3 Clinical Research

The definition of Clinical Research used in this paper is the one provided by Gross-Portney and Watkins [62], which is a structured process of investigating facts and theories and exploring connections. It proceeds in a systematic way to examine clinical conditions and outcomes, to establish relationships among clinical phenomena, to generate evidence for decision-making and to provide an impetus for improving methods of practice.

Chen et al [68] outline an agent-based IDSS clinical research that performs data mining on biomedical literature in order to gather papers relevant to the indicated topic in the case study they used this system on papers about cancer genes research. The system searches for data on multiple databases like PubMed in order to gather the most up to date data as possible.

Hudson and Cohen [1] describe a agent-based IDSS that actually supports a combination of clinical management and clinical research and is used for the diagnosis of cardiac disorders this was done using five different agent types. The first of these type is called EMERGE and is used to analyse chest pain. The second is an evidence based medicine (EBM) agent used to enhance the results from the first agent. The third is called HyperNet, which gathers information from clinical databases. The fourth is called CATS, which analyses signals in particular the electro-cardiogram (ECG). The final agent is the image analysis agent, which analyses

images like MRI, ultrasound, etc. The system also contains two other agents one called agent 0 which represents the medical practitioner and is used to get input from him about the decisions and possibilities as well as to send the results to him and one which is a coordination agent called the task manager it assigns tasks and translates the results from each of the agents so the other agents can use them [1]. The clinical research is done by the EBM agent, which searches for relevant medical literature and provides in to the medical practitioner as well as using it to improve the rules used by the first agent.

The Multi Agent-based Data Mining Info-Structure (ADMI) system [69, 70] was designed to preform data mining on medical data using four types of agents. These are the interface agent, the data collection agents, the data-mining agents and the service generation agents, which are used to give strategic advice and decision support about the mined data.

6 Comparison of Medical Agent-based IDSS

This section presents the comparison of the research introduced in the previous section. The comparison framework is first presented. The comparison of the research based on the framework is then presented. A discussion of the results of the comparison is then presented. The purpose of this comparison is to discover open research questions, common system components, and the common structure of an agent-based IDSS to further our research into a agent-based IDSS for use in the NICU context.

6.1 Comparison Framework

The motive for the construction of this comparison framework was to determine key functional requirements for later development of the NICU agent-based IDSS, based on existing agents-based IDSS research applied within the medical domain. The comparison framework, used to compare the research introduced in the previous section, was developed using broad IDSS features, which include what kind of decisions the systems support, the purpose behind making the given IDSS which is either decision speed or quality and the time sensitivity of the decisions. Time sensitivity is important as Panniers [71] has stated that only low and medium urgency decisions are suitable for computerization into a decision support system, this does not mean high urgency decisions cannot be computerized, just not as a decision support system. Then the individual subsystems of the IDSS as described in section 3 were used to lead to other points of comparison. The data subsystem was compared upon data handling features that at least one of the system examined supported. The categories are is the data distributed, accuracy of the data, whether there are any real-time data streams in the input data and whether or not there support for distributed data mining. The agent subsystem can be compared on the following features that were mentioned in at least one of the examined systems. The language the agents are coded in, whether they are open or closed MAS, the structure of the agents which is either a single agent or either functional or layered multi-agent structures, the coordination method used which is not applicable for single agent systems and whether the clinical research IDSS have there agents output rules to enhance existing

clinical management systems. There are many other dimensions that the agent subsystem could be compared on such as for example what means of assisting agent cooperation and coordination was used however none of them would be appropriate to this specific paper as unfortunately all of the systems examined either did not use these mechanisms or if they did use them they did not mention them. This was probably a result of all the examined system being closed MAS. The (user interface) UI subsystem can be compared on several features the first is the utility of the user interface which is that it is either request/response where each request results is a response which can then lead to another request or an interactive UI where the human can clarify and enhance his requests at any time and the computer can ask for clarification if required. The other feature that was chosen was what devices the UI was available through, such as for example PC, PDA, etc. The final remaining point of comparison that was chosen was evidence-based information this was chosen in order to see how many of the systems actually documented the results of implementation of the system.

6.2 Medical Specific Implementations

Broad IDSS Features

Paper Number	What does it support?	What decision time is allowed for the decision?	Is the aim to improve decision speed or decision quality?
[63]	Treatment	Time Insensitive	Decision Quality
[64]	Diagnosis	Time Insensitive	Decision Quality
[65]	Diagnosis/Treatment	Time Insensitive	Decision Quality
[17]	Treatment	Time Insensitive	Decision Quality
[66]	Diagnosis	Time Insensitive	Decision Quality
[67]	Diagnosis	Low Urgency	Decision Quality
[1]	Diagnosis/Research	Time Insensitive	Decision Quality
[68]	Research	Time Insensitive	Decision Quality
[69, 70]	Research	Time Insensitive	Decision Quality

Data Subsystem Features

Paper Number	Any info on the quality/ accuracy of the source data?	Is the data distributed?	Are there data streams in the source data?	Is there support for distributed mining?
[63]	No	No	No	No
[64]	No	No	No	No
[65]	No	Yes	No	Yes
[17]	No	No	No	No
[66]	No	No	No	No
[67]	No	No	Yes	No
[1]	No	No	No	No
[68]	No	Yes	No	Yes
[69, 70]	No	Yes	No	Yes

Agent Subsystem Features

Paper Number	What language were the agents coded in?	Is the subsystem an open MAS or a closed MAS?	What is the agent organisational structure?	What coordination method do they agents use?	Clinical Research Only: Do the agents output the rule sets to be integrated back into clinical management?
[63]	Not Specified	Closed	Functional	Facilitator	N/A
[64]	Not Specified	Closed	Layered	Facilitator	N/A
[65]	Not Specified	Closed	Layered	Facilitator	N/A
[17]	Not Specified	Closed	Layered	Scenes	N/A
[66]	Java	Closed	Layered	Facilitator	N/A
[67]	C++	N/A	Single Agent	N/A	N/A
[1]	Not Specified	Closed	Layered	Facilitator	Yes
[68]	Not Specified	N/A	Single Agent	N/A	No
[69, 70]	Not Specified	Closed	Layered	Facilitator	No

UI Subsystem Features

Paper Number	What sort of UI is it?	What device(s) is the UI available through?
[63]	Request/Response	PC
[64]	Request/Response	PC
[65]	Request/Response	PC
[17]	Request/Response	PC
[66]	Request/Response	PC
[67]	Request/Response	PC
[1]	Interactive	PC
[68]	Request/Response	PC
[69, 70]	Request/Response	PC

Evidence-Based Information

Paper Number	Where there clinical trials performed and are the results presented?
[63]	Yes
[64]	No
[65]	No
[17]	No
[66]	No
[67]	Yes but is a very limited trial just tests accuracy
[1]	Yes
[68]	No
[69, 70]	No

6.3 Discussion

As can be seen the agent-based IDSSs examined cover the full range of potential uses in the medical domain treatment, diagnosis and research. All of the systems examined are time insensitive or in one case medium urgency this is consistent with what Panniers discovered with her research into appropriate problems for decision support systems in the neonatal intensive care unit [71]. All of the systems are focussed on improving decision quality as opposed to speed as they are either time insensitive or of at most medium urgency.

None of the agent-based IDSSs give information on the accuracy of the data used to make decisions. Only a few of the systems use distributed data but of those that do all of them are capable of distributed data mining. Of the three clinical research systems two of them handle distributed data and data mining. Only one of the systems is capable of handling streaming data, which is crucial to the solving of certain decision support problems in the medical industry, particularly in intensive care units.

Only two of the system descriptions include what language was used to program the agents, which were JAVA and C++, this while not crucial information is fairly important for maintenance and enhancement purposes. Most of the systems for both clinical management and clinical research have UI agents; in fact the only clinical research system without a dedicated UI agent is a single agent system. Most of the systems overviewed had multiple agent types specialized to work at different layers or for different purposes in the case of the functional structured system. Of the two kinds of multi-agent IDSS the majority of the systems are layered as opposed to functional. This is done to simplify the system and to make modifying and enhancing the agents or the framework simpler. Most of the systems use facilitator agent to handle coordination of multiple agents. Of the three clinical research papers only one of them contains a method to turn the discovered trends and patterns into rules for the enhancement of a clinical management system this is a piece of very important functionality for clinical research systems as it is key to actually enhance knowledge for diagnostic and treatment decisions.

Most of the systems examined use a request/response system, which is where the system is given instructions from the user and then gathers the required information and responds to the user and awaits further commands. Only one uses an interactive system which is were the system might ask for or automatically provide clarification in a real-time manner. None of the systems has any alternate forms of UI such as PDA, etc.

Only three of the papers provided any evidence-based information about effectiveness and efficiency of the new system. Only three of the systems examined were clinical research which coincides with Roddick's [72] discovery that there are much fewer exploratory data mining systems (which includes clinical research systems) then explanatory data mining systems (which includes clinical management systems).

All of the systems examined dealt with closed MAS. This means that the agents were designed to work cooperatively together easily and with few problems. Therefore no conflict handling mechanisms were included, nor were any additional cooperation mechanisms such as auctions or negotiations.

6.4 Implications on NICU agent-based IDSS Research

An agent-based IDSS needs to include a Clinical Research component, which will be focussed on improving decision quality and being of at most moderate urgency. The system should be able to handle distributed data and data mining as well as streaming data as this has not been done before with any of the systems. It should include UI agents to handle user interaction, as this is a common accepted method of simplifying interaction between the user and the agents. It should also be layered in order to simplify the agents the coordination between the agents should be done using facilitator agents. The system, as it is to be used for Clinical Research, should also provide agents to turn discovered trends and patterns into rules to enhance the NICU Clinical Management component. The NICU agent-based IDSS should support at least request/response UI if not totally interactive UI that is accessible through devices other than desk top computers. There should also be tests performed once the system is established to provide evidence-based information about effectiveness and efficiency in discovering new trends. A high level diagram of the e-Baby Solution Manager Service is shown in Figure 1.

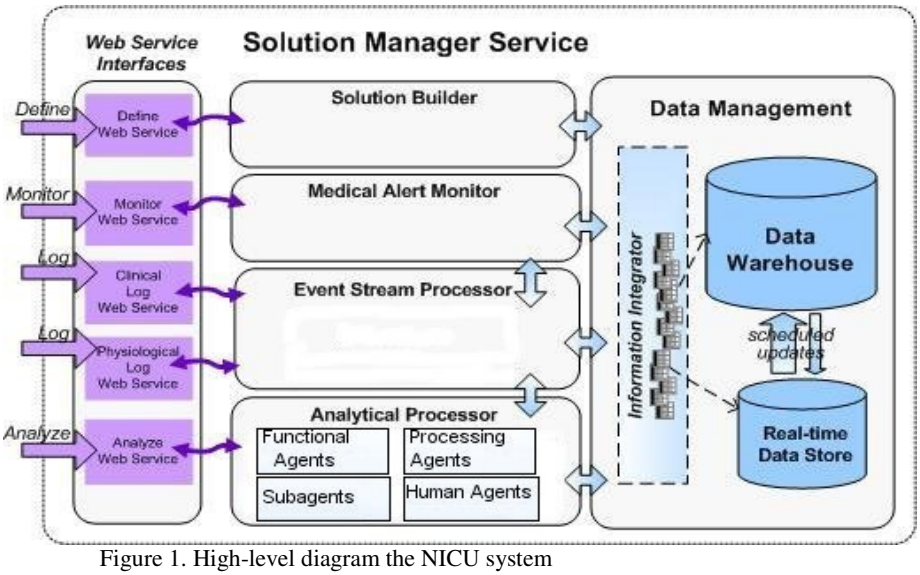

Figure 1. High-level diagram the NICU system

The Solution Manager Service (SMS) is an Intelligent Decision Support System (IDSS) to support neonatal clinical management and research. The SMS was originally developed within the context of its use for business performance measurement [73, 74]. The e-Baby research collaboration is reapplying this research within the domain of health and medicine. Figure 1 is a modified version of the SMS from related work [73-75]. The main component of the diagram that relates to the research presented here is the agent-based IDSS contained within the analytical processor, which is being developed as part of this research. This will gather data on the patients in near-real time and process that data looking for trends and patterns. Detected trends and patterns will be used to develop rules to enhance the clinical management within the NICU. The rules engine that will store these rules is shown in figure 1 as an arrow between the Analytical Processor and the Event Stream Processor. The event stream processor provides a scalable data staging environment to continuously integrate real time data using the rules that were generated by the agent-based IDSS to decide whether an alert is required. The Medical Alert Monitor still enables Neonatalogists to define and change complex medical alert rules and the Solution Builder is still used to setup and initialise the runtime components and the data management layer. Historical physiological and clinical data are stored in the Data Management Layer. Interaction with the solution management service is via a series of web services [73].

7 Conclusion and Future Work

This paper has presented a survey and comparison of recent research on the use of agent-based intelligent decision support systems to support clinical management and clinical research with the view of assessing the ability of current research to support decision-making within a neonatal intensive care unit setting.

As can be seen above medical agent-based IDSS research can be separated into two categories Clinical Management and Clinical Research. Clinical Management covers all clinical systems that are designed to help the doctor with diagnosing and deciding on treatment for medical conditions. Clinical Research on the other hand covers systems that are used to research facts and connections in attempt to detect new trends and patterns. The research into Clinical Management is wide reaching as it covers systems for both diagnosing patients and treating them. The research into Clinical Research is less extensive and most of the systems are merely used to collect research data on a specified topic and allow mining of the data in order to discover new trends and patterns. Only one of the Clinical Research systems is configured to update a Clinical Management system in order to increase the accuracy, reliability and coverage of the system. None of the systems examined handled time critical decisions or made attempts to reduce the decision time merely to attempt to increase the decision quality. Few of the agent-based IDSSs examined contained any kind of evidence-based information about effectiveness and efficiency of the system most of the papers referred to innovative systems with no substantiating data. In addition, few of the agent-based IDSSs examined contained support for distributed data mining except for Clinical Research systems where two of the three systems support distributed mining. Only one of the systems gathers data from any real-time data streams and it is a Clinical Management System. This is just one area that could use future research particularly in the Clinical Research area where no such systems seem to exist. This research is currently being extended through the further development of the framework for the agent-based IDSS for use within neonatal intensive care units. An Australian Research Council (ARC) Linkage Project supports this research project: LP0349279.

8 Reference

1. Hudson, D.L., and Cohen, M. E., *Use of intelligent agents in the diagnosis of cardiac disorders.* Computers in Cardiology, 2002: p. 633 - 636.
2. Anderson, J.G., *Clearing the Way for Physicians Use of Clinical Information Systems.* Communications of the ACM, 1997. **40**(8): p. 83-90.
3. Dick, R.S., and Steen, E.B., *The Computer-Based Patient Record.* 1991, Washington, D.C.: Institute of Medicine. National Academy Press.
4. Nwana, H.S., *Software Agents: An Overview.* The Knowledge Engineering Review, 1996. **11**(3): p. 205-244.
5. Bresciani, P., Perini, A., Giorgini, P., Giunchiglia, F., and Mylopoulos, J., *Tropos: An Agent-Oriented Software Development Methodology.* Autonomous Agents and Multi-Agent Systems, 2004. **8**(3): p. 203-236.
6. Wooldridge, M., *What Agents Aren't: A Discussion Paper.* IEEE Colloquium on Intelligent Agents and Their Applications, 1996. **101**(2): p. 1-2.
7. Willams, A.B., *Learning to Share Meaning in a Multi-Agent System.* Autonomous Agents and Multi-Agent Systems, 2004. **8**(2): p. 165-192.
8. Boudriga, N., and Obaidat, M. S., *Intelligent Agents on the Web: A Review.* Computing in Science & Engineering, 2004. **6**(4): p. 35-42.
9. Nourani, C.F., *lntelligent And Multi Agent Object Level Computing: The Priliminary Overview.* ACM SIGPLAN Notices, 1995. **30**(2).

10. Bradshaw, J., *An Introduction to Software Agents*, in *Software Agents*, J. Bradshaw, Editor. 1997.
11. Kazma, J., *Intelligent agents: Getting others to do your work for you.* IEEE Potentials, 1998. **17**(2): p. 16-19.
12. Vidal, J.M., and Durfee, E. H., *Predicting the Expected Behavior of Agents that Learn About Agents: The CLRI Framework.* Autonomous Agents and Multi-Agent Systems, 2003. **6**(1): p. 77-107.
13. Flores-Mendez, R.A., *Towards a Standardization of Multi-Agent System Frameworks.* Crossroads, 1999. **5**(4): p. 18-24.
14. Ahmad, H.F. *Multi-Agent Systems: Overview of a New Paradigm for Distributed Systems*. in *7th IEEE International Symposium on High Assurance Systems Engineering*. 2002.
15. Hegazy, I.M., Al-Arif, T., Fayed Z. T., and Faheem, H. M., *A Multi-Agent Based System for Intrusion Detection.* IEEE Potentials, 2003. **22**(4): p. 28-31.
16. Luck, M., McBurney, P., and Preist, C., *A Manifesto for Agent Technology: Towards Next Generation Computing.* Autonomous Agents and Multi-Agent Systems, 2004. **9**(3): p. 203-252.
17. Godo, L., Puyol-Gruart, J., Sabater, J., Torra, V., Barrufet, P., and Fàbregas, X., *A multi-agent system approach for monitoring the prescription of restricted use antibiotics.* Artificial Intelligence in Medicine, 2003. **27**(3): p. 259-282.
18. Parsons, S., and Klein, M. *Towards robust multi-agent systems: Handling communication exceptions in double auctions*. in *Autonomous Agents & Multi Agent Systems*. 2004. New York.
19. Guttman, R.H., and Maes, P. *Cooperative vs. Competitive Multi-Agent Negotiations in Retail Electronic Commerce*. in *Second International Workshop on Cooperative Information Agents II, Learning, Mobility and Electronic Commerce for Information Discovery on the Internet*. 1998.
20. Bertsekas, D.P., *Auction Algorithms*, in *Encyclopedia of Optimization*. 2001, Kluwer.
21. Lee, R.S.T., and Liu, J. N. K., *iJADE Web-miner: an intelligent agent framework for Internet shopping.* IEEE Transactions on Knowledge and Data Engineering, 2004. **16**(4): p. 461-473.
22. Subramanian, K.R., Shiang, T.K., Lee, S., and Sue, G.B. *Intelligent Agent Platform for Procurement*. in *IEEE International Conference on Systems, Man, and Cybernetics*. 1999. Tokyo, Japan.
23. Ito, N., Shinoda, K., Nakagaw, K., Iwata, K., Du, X., and Ishii, N. *Action Decision with Incomplete Information: A Temporal Database Approach.* in *IEEE International Conference on Systems, Man and Cybernetics*. 1999. Tokyo, Japan.
24. Zhang, B., Chen, X., Liu, G., and Cai, Q. *Agent Architecture: A Survey on RoboCup 1999 Simulator Teams*. in *3rd World Congress on Intelligent Control and Automation*. 2000.
25. Maes, P., *Artificial Life Meets Entertainment: Lifelike Autonomous Agents.* Communications of the ACM, 1995. **38**(11): p. 108-114.

26. Nareyek, A. *Intelligent Agents for Computer Games*. in *Computers and Games, Second International Conference*. 2000. Marsland, T. A.
27. Kraus, S., and Lehmann, D. *DIPLOMAT, an Agent in a Multi-Agent Environment: An Overview*. in *Seventh Annual International Phoenix Conference on Computers and Communications*. 1988.
28. Maes, P., *Agents that Reduce Work and Information Load.* Communication of the ACM, 1994. **37**(7): p. 31-41.
29. Mladenic, D., *Text-Learning and Related Intelligent Agents: A Survey.* Intelligent Systems, 1999. **14**(4): p. 44-54.
30. Wang, H., *Intelligent agent-assisted decision support systems: Integration of knowledge discovery, knowledge analysis, and group decision support.* Expert Systems with Applications, 1997. **12**(3): p. 323-335.
31. Yu, H., Zhang, S., Yang, N., Ding, H., and Wang, X. *Intelligent agent-based distributed heterogeneous database system*. in *International Conference on Machine Learning and Cybernetics*. 2003.
32. Turban, E., and Aronson, J. E., *Decision Support Systems and Intelligent Systems*. 6th ed. 2001: Prentice Hall. 867.
33. Little, J.D.C., *Models and Managers: The Concept of a Decision Calculus.* Management Science, 1970. **16**(8).
34. Bonczek, R.H., Holsapple, C. W., and Whinston, A. B., *The Evolving roles of Models in Decision Support Systems.* Decision Sciences, 1980. **11**(2).
35. Keen, P.G.W., *Adaptive Design for Decision Support Systems.* Data Base, 1980. **12**(1 and 2).
36. Sauter, V., *Decision Support Systems: An Apllied Managerial Approach*. 1997: John Wiley & Sons, Inc.
37. Marakas, G.M., *Decision Support Systems in the 21st century*. 1999: Prentice Hall.
38. McGregor, C., and Kumaran, S. *An Agent-Based System for Trading Partner Management in B2B e-Commerce*. in *12th International Workshop on Research Issues in Data Engineering: Engineering e-Commerce/ e-Business Systems (RIDE™02)*. 2002: IEEE.
39. Swain, M., and Kim, Y., *Finding Family Relationship in Hospital Database Using Intelligent Agent.* IEEE Proceedings, 2004: p. 194-199.
40. Lanzola, G., Gatti, L., Falasconi, S., and Stefanelli, M., *A framework for building cooperative software agents in medical applications.* Artificial Intelligence in Medicine, 1999. **16**(3): p. 224-249.
41. Larssan, J.E., and Hayes-Roth, B., *Guardian: intelligent autonomous agent for medical monitoring and diagnosis.* IEEE Intelligent Systems, 1998. **13**(1): p. 58-64.
42. Hayes-Roth, B., *Integrating real-time AI techniques in adaptive intelligent agents.* Annual Review in Automatic Programming, 1994. **19**: p. 1-11.
43. Meunier, J.A. *A virtual machine for a functional mobile agent architecture supporting distributed medical information*. in *12th IEEE Symposium on Computer-Based Medical Systems*. 1999.
44. Silverman, B.G., Andonyadis, A., and Morales, A., *Web-based health care agents; the case of reminders and todos, too (R2Do2).* Artificial Intelligence in Medicine, 1998. **14**(3): p. 295-316.

45. Vicari, R.M., Flores, C. D., Silvestre, A. M., Seixas, L. J., Ladeira, M., and Coelho, H., *A multi-agent intelligent environment for medical knowledge.* Artificial Intelligence in Medicine, 2003. **27**(3): p. 335-366.
46. Alsinet, T., Ansótegui, C., Béjar, R., Fernández, C., and Manyà, F., *Automated monitoring of medical protocols: a secure and distributed architecture.* Artificial Intelligence in Medicine, 2003. **27**(3): p. 367-392.
47. McInerney, T., Hamarneh, G., Shenton, M., and Terzopoulos, D., *Deformable organisms for automatic medical image analysis.* Medical Image Analysis, 2002. **6**(3): p. 251-266.
48. Lowe, H.J., Walker, W.K., Polonkey, S.E., Jiang, F., Vries, J.K., and McCray, A. *The Image Engine HPCC Project. A Medical Digital Library System using Agent-Based Technology to Create an Integrated View of the Elctronic Medical Record*. in *Third Forum on Research and Technology Advances in Digital Libraries*. 1996.
49. Miksch, S., Cheng, K., and Hayes-Roth, B. *An Intelligent Assistant for Patient Health Care*. in *International Conference on Autonomous Agents*. 1997. Marina del Rey, California, United States.
50. Ouali, A., Ramdane-Cherif, Z., Ramdane-Cherif, A., Levy, N., and Krebs, M. O. *Agent Paradigm in Clinical Large-Scale Data Mining Evironment*. in *Second IEEE International Conference on Cognitive Informatics*. 2003.
51. Hubal, R.C., Frank, G. A., and Guinn, C. I. *Lessons Learned in Modeling Schizophrenic and Depressed Responsive Virtual Humans for Training*. in *International Conference on Intelligent User Interfaces*. 2003. Miami, Florida, USA.
52. Decker, K., and Li, L. *Coordinated Hospital Patient Scheduling*. in *International Conference on Multi Agent Systems*. 1998. Paris, France.
53. Berndt, D.J., Fisher, J. W. , Hevner, A. R., and Studnicki, J., *Healthcare Data Warehousing and Quality Assurance*. 2001.
54. Warren, J., Beliakov, G., and van der Zwaag, B. *Fuzzy logic in clinical practice decision support systems*. in *33rd Hawaii International Conference on System Sciences*. 2000. Hawaii.
55. Prather, J.C., Lobach, D.F., Goodwin, L.K., and J.W. Hales, Hage, M.L., and Hammond, W.E. *Medical Data Mining: Knowledge Discovery in a Clinical Data Warehouse*. in *1997 Annual Conference of the American Medical Informatics Association*. 1997. Philadelphia, PA: Hanley and Belfus.
56. Catley, C., and Frize, M. *A Prototype XML-Based Implementation of an Integrated 'Intelligent' Neonatal Intensive Care Unit*. in *4th IEEE Conference on Information Technology Applications in Biomedicine*. 2003. UK.
57. Catley, C., Frize, M., Walker, C. R., and St. Germain, L. *Integrating Clinical Alerts into an XML-Based Health Care Framework for the Neonatal Intensive Care Unit*. in *25th IEEE EMBS*. 2003. Cancun, Mexico.
58. Yang, L., Frize, M., Eng, P., Walker, R. C., and Catley, C. *Towards Ethical Decision Support and Knowledge Management in Neonatal Intensive Care*. in *26th IEEE EMBS*. 2004.
59. Catley, C., Frize, M., and Petriu, D. C., *Software Performance Engineering of a Web Service-Based Clinical Decision Support Infrastructure.*

60. Catley, C., Frize, M., Petriu, D. C., Walker, C. R., and Yang, L., *Towards a Web Services Infrastructure for Perinatal, Obstetrical, and Neonatal Clinical Decision Support.* 2004.
61. Bolinger, R.E., Price, S., and Kyner, J. T. *Use of a Computerized Clinical Decision System in a Diabetic Clinic*. in *Proceedings of the annual conference*. 1973. Atlanta, Georgia, United States.
62. Gross-Portney, L., Watkins, M., *Foundations of Clinical Research, applications to practice*. 2nd ed. 2000: Prentice Hall.
63. Coffin, C., Saunders, C., Thomas, C., Loewen, A., Campbell, N., and Ghali, W. *Using intelligent agents to repurpose administrative data in fostering disease prevention in an outpatient context: the case of pneumococcal vaccination*. in *37th Annual Hawaii International Conference on System Sciences*. 2004.
64. Cohen, M.E., and Hudson, D. L. *Meta neural networks as intelligent agents for daignosis*. in *2002 International Joint Conference on Neural Networks*. 2002.
65. Hashmi, Z.I., Abidi, S. S. R., and Cheah, Y. *An intelligent agent-based knowledge broker for enterprise-wide healthcare knowledge procurement*. in *15th IEEE Symposium on Computer-Based Medical Systems*. 2002.
66. Balter, J., Labarre-Vila, A., Ziebelin, D., and Garbay, C., *A knowledge-driven agent-centred framework for data mining in EMG.* Comptes rendus biologies, 2002. **325**(4): p. 375-382.
67. Kalogeropoulos, D., Carson, E. R., and Collinson, P. O., *Clinical-HINTS: integrated intelligent ICU patient monitoring and information management system.* Studies in health technology and informatics, 1997. **43 Pt B**: p. 906-910.
68. Chen, S., Tsai, J. J. P., Chen, W. *An intelligent agent-based biomedical literature mining system for cancer-related genes*. in *Fifth International Symposium on Multimedia Software Engineering*. 2003.
69. Zaidi, S.Z.H., Abidi, S. S. R., and Manickam, S. *Distributed Data Mining From Heterogeneous Healthcare Data Repositories: Towards an Intelligent Agent-Based Framework*. in *15th IEEE Symposium on Computer Based Medical Systems*. 2002. Maribor, Slovenia.
70. Zaidi, S.Z., Abidi, S. S., and Manickam, S., *Leveraging intelligent agents for knowledge discovery from heterogeneous healthcare data repositories.* Studies in health technology and informatics, 2002. **90**: p. 335-340.
71. Panniers, T.L. *Selecting Appropriate Problems for Decision Support System in the Neonatal Intensive Care Unit*. in *1999 AMIA Annual Symposium*. 1999.
72. Roddick, J.F., Fule, P., Graco, W. J., *Exploratory Medical Knowledge Discovery: Experiences and Issues.* ACM SIGKDD Explorations Newsletter, 2003. **5**(1): p. 94-99.
73. McGregor, C., Heath, J., and Wei, M. *A Web Service Based Framework for the Transmission of Physiological Data for Local and Remote Neonatal Intensive Care*. in *IEEE International Conference on e-Technology, e-Commerce and e-Service*. 2005. Hong Kong: IEEE.

74. McGregor, C., *e-Baby: On Demand Web Service Based Intelligent Decision Support for Local and Remote Neonatal Intensive Care*. 2005, Health Informatics Research, University of Western Sydney.
75. McGregor, C., Purdy, M., and Kneale, B. *Compression of XML Physiological Data Streams to Support Neonatal Intensive Care Unit Web Services*. in *IEEE International Conference on e-Technology, e-Commerce and e-Service*. 2005. Hong Kong: IEEE.