A Scalable Multi-Agent Architecture in Environments with Limited Connectivity

Case study on individualised care for healthy pregnancy

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Abstract— **Technology advancement has motivated researches and studies in different domains which have enormous impact on the quality of life including healthcare domain. Among the challenges that hinder effective realization of these technologies in healthcare domain are heterogeneous nature of patients, limited internet connectivity – especially in developing countries – , and high costs of healthcare services resulting from hospitalizations and treatments of critical health conditions. In this paper we have addressed the solution to these challenges by using a case study of pregnant women. We firstly present the current status in the management of pregnancy complications, which motivates the need for improvement. We then describe analysis and design models by following agent-oriented modelling, which considers man-made agents (software agents) and human agents. Finally we present and discuss multi-agent architecture which addresses a solution to the outlined above healthcare challenges by considering (1) scalability of the provided healthcare service in environments with limited connectivity (2) providing patient care in accordance with the characteristics of individual patients such as allergies, medical history and hobbies (3) prediction of critical health conditions by using multi-parametric machine learning algorithms, which aim to provide early diagnosis of critical health condition, and (4) providing home care that enables patients to collect their physiological data and submit them to the hospital information system for continuous monitoring and analysis.**

Keywords—**Multi-agent system, individualised care, critical health conditions, limited connectivity.**

I. INTRODUCTION

According to the report by the United Nations Children's Fund (UNICEF), it is estimated that half a million women die from pregnancy complications annually [1]. Furthermore, the report describes that women in developing countries are 300 times more likely to die than those in developed countries as a result of child birth or pregnancy complications. Among others, pregnancy complications include preeclampsia, caesarean section, hypoglycaemia, abruption placentae, prematurity of the foetus, first trimester and re-current miscarriages, and excessive foetal growth. These pregnancy complications result from uncontrolled physiological conditions such as blood glucose, blood pressure, and weight gain, which lead to critical health conditions such as diabetes, hypertension and obesity. In healthcare domain, regular monitoring of physiological conditions is considered as one of the approaches for prevention and management of critical health conditions [2], [3]. Furthermore, the medical guidelines suggest the importance of monitoring blood glucose, blood pressure, and weight gain before and during pregnancy for the purpose of providing early diagnosis of critical health conditions, reducing the possibilities of pregnancy complications, and improving pregnancy outcomes (reduced infant and maternal mortality rate).

Advancements in the use of technologies have improved the quality of life in different domains including healthcare. This has motivated the development of software intensive intelligent systems referred as Multi-Agent Systems (MAS) [4], which can assist humans in their daily activities including decision making processes. These systems are designed in the way that they can perceive changes occurring in the environment by using sensors, reason, and perform meaningful actions by means of actuators. In this paper we address the application of MAS in countries which are characterized by majority of population living in rural areas [5], limited internet connectivity [6], and substantially low patient to physician ratio especially in rural areas [7].

According to our vision, each patient will be presented by an ordinary low-cost mobile phone for the purpose of regular transfer of physiological data for continuous monitoring and analysis. The patient will be connected to the rest of the system through the use of Short Messaging Service (SMS) or Unstructured Supplementary Service Data (USSD) available for all kinds of mobile phones. The use of these technologies will make for the majority of patients possible real-time monitoring of physiological data as well as generation of patient profile consisting of allergies, medical history, and hobbies. The physiological data collected from a patient is analysed by a software agent who is an expert in a particular health condition such as blood glucose or blood pressure. Following that, the software agent executes multi-parametric analysis algorithms [8] and may then notify a similar software agent representing a physician – a physician intelligent assistant – with information about the possibilities of critical

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health conditions for a given patient. The physician intelligent assistant will use the information contained in the received notification to further analyse the patient profile, which consists of allergies, hobbies, and medical history, for the purpose of providing patients with individualised recommendations on life style changes depending on allergies and hobbies of a given patient. The described MAS has to be understood as a decision support system, which has no goal of replacing human medical experts, but rather aims at enforcing their role by furnishing them with software agents that continuously monitor patients' data and analyse it, providing physicians with meaningful suggestions about the health condition of a given patient.

The rest of this paper is organized as follows. Section II discusses the related work by considering the existing applications of MAS in healthcare domain as well as healthcare solutions developed in environments with limited connectivity. The models for the analysis of problem domain and design of the solution presented in this paper are then discussed in Section III with the help of Agent-Oriented Modelling (AOM) approach. Section IV describes in detail the architecture of the proposed multi-agent system, and discusses its strengths in addressing the challenges of healthcare domain. Section V draws the conclusions of the presented work.

II. RELATED WORK

According to the existing literature, there are several completed and on-going research efforts on the application of MAS in healthcare domain. The proposed solutions include a MAS for executing personalized treatments suggested by physicians to home care patients [9], decision making on insulin dosage for pregnant women with gestational diabetes mellitus [10], remote monitoring of vital signs from elderly people for the purpose of generating necessary alerts such as reminders for medication [11], and a MAS for detecting malnutrition in children for the purpose of recommending nutritious diets [12]. This review has revealed the need for more studies on the application of MAS in environments with limited connectivity, as most of the existing works have considered software agents being situated in environments with guaranteed internet connectivity. The consideration of SMS and USSD services in the application of MAS in countries with limited connectivity as introduced in Section I of this paper has been motivated by impressing results on the use of these services in healthcare projects [13] such as a SMS based alert system for monitoring pregnant women in Rwanda [14], [15]. Although some related work has addressed the need for individualised care [9], [10], we believe this paper provides important contribution by considering the use of the capabilities provided by SMS and USSD services to MAS by providing a scalable individualised care to patients living in environments with limited connectivity.

III. ANALYSIS AND DESIGN MODELS

As was already mentioned in Section I, the envisioned system is MAS where humans playing certain roles are supported by appropriate intelligent digital assistants, which may also be termed as agents. Analysis of such systems should follow an appropriate methodology due to its complexity. There are various Agent Oriented Software Engineering (AOSE) methodologies available, such as Tropos [16], MaSE [17], and Prometheus [18]. However, they all put the emphasis on designing systems consisting of software agents rather than MAS consisting of software agents that support humans. Sterling and Taveter [19] proposed a suitable approach that includes features similar to AOSE methodologies but is geared towards designing MAS consisting of humans and software agents, which are respectively termed as human agents and man-made agents.

A MAS presented in this paper consists of humans and intelligent software agents that assist them with the aim of providing individualised care to pregnant women living in environments with limited connectivity. In this section we present two models – goal model and the merged agent and acquaintance model – that have been designed following the AOM [19] for the purpose of capturing important features of MAS.

Goal model serves as a container for three main components: functional goals commonly referred as goals, quality goals, emotional goals, and roles. Similar to other kinds of systems, MAS is described by functional requirements as well as non-functional requirements, which are respectively captured in a goal model by functional goals depicted as boxes and quality goals depicted as clouds. Goals and quality goals can further be decomposed into sub-goals and sub-quality goals, where each sub-goal represents some aspect of achieving its parent goal. Apart from capturing functional goals and quality goals, Fig. 1 has also considered the emotions of the users of MAS which are represented by hearts and referred as emotional goals. Emotional goals aim at capturing the feelings of users towards the system, which plays a huge part in the user acceptance of many systems, particularly healthcare-related systems. The purpose of the goal model is to serve as communication medium between technical and non-technical stakeholders and provide both with a better understanding of the problem domain.

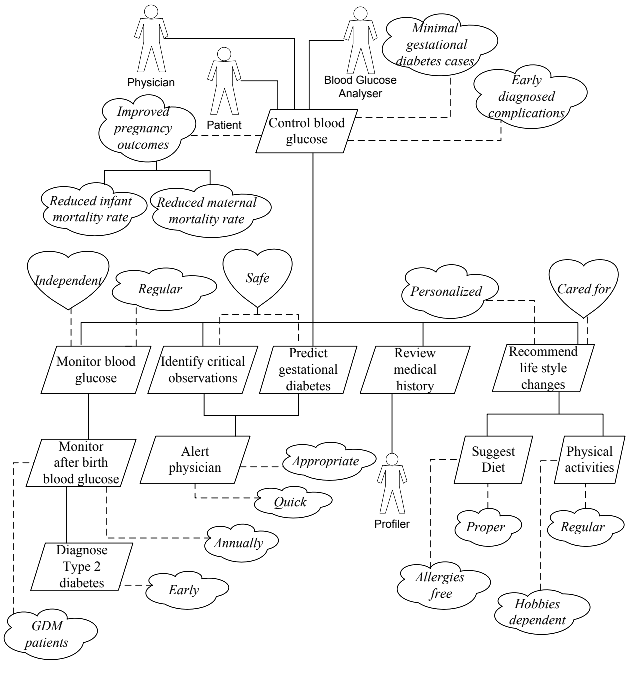

Fig 1: Goal model for the problem analysis

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Figure 1 describes the goal model of individualised care for pregnant women. In this case, we consider only one health condition, which is blood glucose but the model could be adapted to other health conditions important for pregnant women, such as blood pressure and gain in body weight. The top level goal represents the purpose of the system, which is to control blood glucose. This goal is characterized by the quality goals of early diagnosed complications, reduced cases of gestational diabetes, and improved pregnancy complications. The latter is further decomposed into two sub-quality goals: reduced infant mortality rate and reduced maternal mortality rate. The overall goal "Control blood glucose" we have explained is then decomposed into five main sub-goals as is described in Fig. 1: monitor blood glucose, identify critical observations, predict gestational diabetes, review patient profile, and recommend life style changes.

The quality goal "Regular" is attached to the functional goal "Monitor blood glucose" to emphasize that tests should be performed and the corresponding results reported in a timely manner for continuous monitoring of blood glucose. This ensures early diagnosis of pregnancy-related complications. Similarly, the quality goal "Personalised" is attached to the functional goal "Recommend life style changes". Here we have considered two kinds of life style changes – appropriate diet and regular physical activities – which are the main recommendations for controlling blood glucose and preventing gestational diabetes mellitus [20]. The life style changes recommended by a physician intelligent assistant in the MAS result from the analysis of the profile of the given patient with the purpose of recommending a diet free of allergies and appropriate physical activities. According to the recent source [21], pregnant women diagnosed with Gestational Diabetes Mellitus (GDM) are more likely to have Type 2 diabetes in the future. The proposed system has considered the provision of reminders to GDM patients for annual monitoring of blood glucose after the delivery. The after birth monitoring will provide early diagnosis of Type 2 diabetes and consequently better management of Type 2 diabetes.

To achieve the "Control blood glucose" functional goal, the responsibilities of four main roles associated with it in the goal model need to be exercised. The responsibilities of the Patient role include providing information on the patient profile, such as physiological data, allergies, medical history, and hobbies. The Profiler role is responsible for continuous analysis of patient profiles and generation of reports for physicians on the criticality of received physiological data. The role Blood Glucose Analyser is responsible for regular execution of multi-parametric machine learning algorithms [8] on physiological data of different patients available in the hospital information system. The machine learning process then generates a multi-parametric model of a patient that provides a physician role with the information on the possibilities of the occurrence of GDM for the purpose of providing patients with individualized suggestions of life style changes.

As described earlier in this section, the proposed MAS consists of both man-made agents and human agents. The latter are people such as a physician and patient, while man-made agents are intelligent digital assistants implemented in software that can run on handheld devices. Both human and man-made agents exercise responsibilities of the roles modelled for the system. An intelligent digital assistant normally interacts with the corresponding human agent. For example, the intelligent digital assistant of a physician interacts with the physician human agent, when exercising the responsibilities of the role Physician in the system. The decision on mapping the roles to human agents or/and man-made agents is presented by agent models, while the design of interaction pathways between agents of the decided types is captured by the agent acquaintance model.

Figure 2 presents the merged agent and acquaintance model. According to the model depicted in Fig. 2, some responsibilities of the roles Patient and Physician are carried out by human agents, while some other responsibilities of the same roles are exercised by man-made agents of patient intelligent assistant and physician intelligent assistant. For example, a physician human agent reviews and approves recommendations suggested by the physician intelligent assistant before communicating them to the patient in question. In the same Fig. 2 agent acquaintance model represents the interaction pathways between the decided agent types. For example, physician intelligent assistant and patient assistant interact with each other. With the combination of agent model and agent acquaintance model, we have decided the backbone of the proposed MAS.

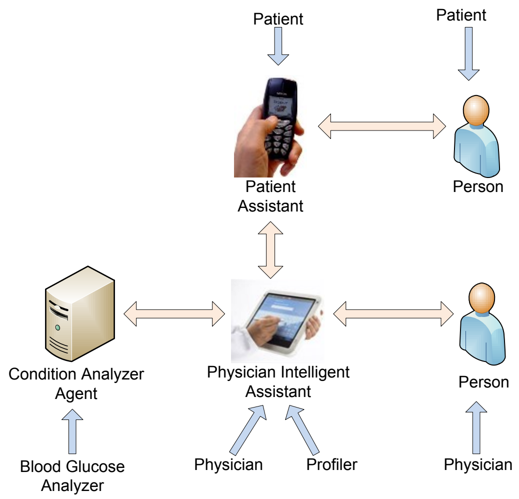

Fig 2: A merged agent and acquaintance model

IV. MULTI-AGENT ARCHITECTURE

In this section, we present the system architecture after deciding its backbone in Section III. The architecture described in Fig. 3 comprises design features that are important for providing individualised care for a large community of people living in environments with limited connectivity. As mentioned in sections I and II, the architecture suggests the use of a mobile SMS network as a communication gateway enabling the provision of healthcare services for the majority of the population in developing countries residing in rural areas.

Although the architecture proposed by us in Fig. 3 only includes monitoring the level of blood glucose of the patient, the same design can accommodate monitoring of several health conditions important for ensuring healthy pregnancy such as blood pressure and weight. When monitoring physiological data of the patient, it is necessary to include multi-parametric analysers of the corresponding health conditions. For illustration purposes, the architecture depicted in Fig. 3 represents the use of glucose meters for conducting blood glucose tests and blood glucose analyser for predicting a critical level of glucose.

The other part of the proposed system architecture includes physician intelligent assistant, multi-parametric condition analyser, and hospital information system which are situated in the environment with reliable internet connectivity. The internet connectivity provides a physician agent with the capability of continuous monitoring of the patient profile, a reliable communication channel for a blood glucose analyser, and effective computation of multi-parametric analysis models from the large amount of physiological data stored in the hospital information system.

According to the existing literature on agents and MAS [19], [22], it is important for any system consisting of more than one agent to demonstrate three main features; interactions between the agents, knowledge sharing as well as behavioural change according to the perceived changes in the environment or changes in the agent´s own knowledge. There are several communication types between agents but they are mainly categorized into client-server interactions and peer-to-peer interactions [23]. In client-server interaction the communication is between one agent requesting a service commonly referred as software agent and the other providing a service commonly referred as service agent. In peer to peer interaction each communicating agent can either request a service or provide a service. The agent types in peer to peer interactions are simply referred as software agents. The architecture presented in Fig. 3 includes both types of interactions. The communication between a Patient Assistant and Physician Intelligent Assistant follows client-server approach because all the communicated knowledge passes through Health Information System (HIS) which acts as service agent between Patient Assistant and Physician Intelligent Assistant. On the other hand, the communication between a Physician Intelligent Assistant and Multi-Parametric Condition Analyser follows the peer-to-peer approach because either of the communicating agents can trigger sharing of knowledge. Fig. 4 describes in detail a peer-to-peer interaction protocol including the following three agents: a software agent for detecting critical conditions by analysing trends, intelligent software agent for assisting a physician when monitoring physiological data, and the physician who confirms the generated alerts and recommendations suggested by software agents.

The interaction protocol presented in Fig. 4 is guided by two constructs – loop and alternative – describing the behaviours of the agents depending on their perceptions from the environment. For example, the number of iterations in the loop depends on the messages from the physician intelligent assistant perceived by the condition analyser. On the other hand, the condition analyser agent can send a message to the physician intelligent assistant for informing that the trend of physiological data is normal or abnormal. The behaviour of the

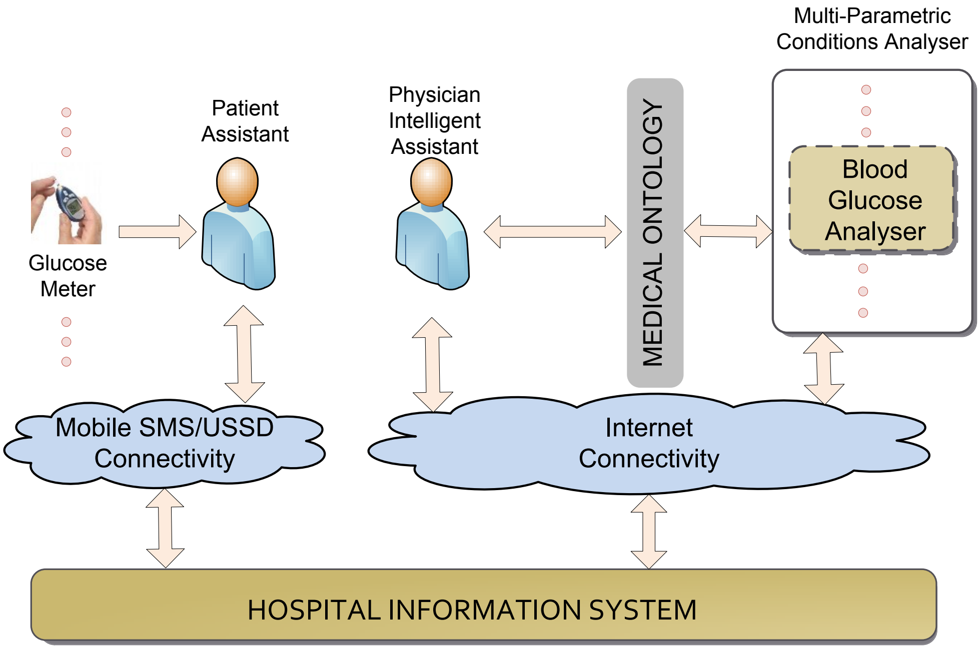

Fig 3: A scalable multi-agent architecture in environments with limited connectivity

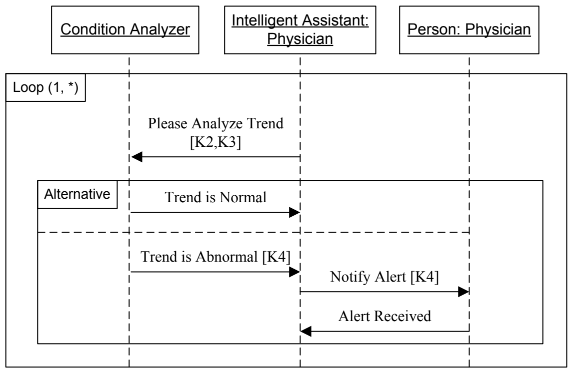

Fig 4: Interaction protocol between agents in the presented architecture

physician intelligent assistant depends on the content of the perceived message. If the perceived message informs about an abnormal trend, a physician is notified by an alert.

In order for the agents to exchange meaningful information, conceptual objects are normally used to represent knowledge handled by MAS. The knowledge can be either private or shared. Private knowledge is only known by one agent while shared knowledge is exchanged between agents during interactions for the purpose of acquiring a common understanding. Figure 5 represents a partial knowledge model for agents of the types Physician Intelligent Assistant and Condition Analyser. The knowledge model consists of the four conceptual objects K1-K4, whereby the conceptual object K1 represents a private knowledge for a physician intelligent assistant, while the remaining conceptual objects are shared between the two agents for the purpose of analysing the trends in the physiological data and generating the alerts for early diagnosis of critical health conditions.

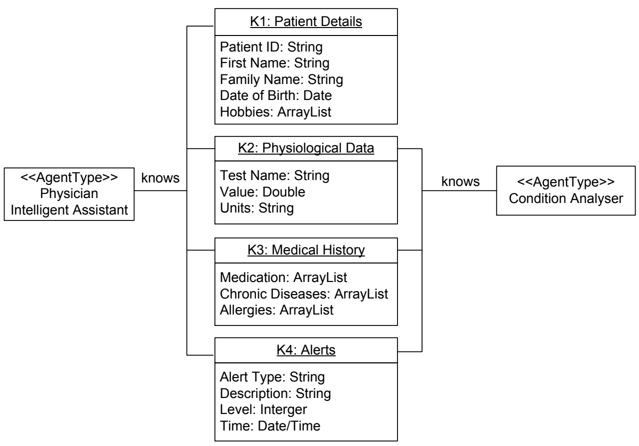

Fig 5: A partial knowledge model between agents in the presented architecture

V. CONCLUSION

In this paper, we first provided an overview of the current status in the management of pregnancy complications in the world. According to the recent report by the United Nations Children's Fund (UNICEF) and other relevant literature [1], more studies addressing solutions to pregnancy complications in developing countries were highly recommended. The characteristics of developing countries were then briefly discussed. They include (1) majority of population living in rural areas (2) limited internet connectivity and (3) significant large patient to physician ratio. Considering the characteristics of developing countries and general challenges facing healthcare delivery across the world which include heterogeneity of patients and cost of healthcare services, we presented a software intensive intelligent solution (multi-agent system) that consists of man-made agents and human-agents. The considerations of man-made agents and human agents motivated the choice of AOM [19] as a suitable approach for the analysis of the problem domain and design of the multi-agent system as was described in Section III.

In Section IV we presented the main contribution of this paper which is proposing a multi-agent architecture for promoting healthy pregnancy for women living in developing countries. The architecture addressed solutions to challenges facing healthcare delivery in developing countries as well as those facing the whole world. The architectural design addressed the need of scalable healthcare solutions and limited internet connectivity by considering the use of mobile SMS networks for the exchange of information between agents of the MAS. The world's healthcare challenge related to the heterogeneity of patients has been addressed by considering patient profiles consisting of allergies, hobbies, and medical history. The use of patient profiles enables a physician to recommend life style changes, such as appropriate diet and physical activities, which consider relevant allergies and hobbies of the patient. The proposed architecture also includes multi-parametric machine learning analysis to predict the occurrence of health-related complications which aim to provide early diagnosis and better management of pregnancy complication. Lastly, the architecture has considered the provision of home care where patients collect their physiological data and submit them to the hospital information system for continuous monitoring and analysis. This aims at reducing hospitalization costs by keeping patients out of hospitals as well as reducing costs related to the treatment of chronic pregnancy complications through early diagnosis of complications.

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