How multi-agent systems support acute stroke emergency treatment *

Beatriz López, Silvana Aciar, Bianca Innocenti, Isabel Cuevas
University of Girona
Campus Montilivi, edifice P4, 17071 Girona, Spain
{blopez,saciar,bianca,icuevas}@eia.udg.es

Abstract

Stroke is the third cause of mortality and the first cause of disability among people in western countries. A large percentage of the people who survive it live with serious physical and psychological disabilities and require permanent assistance in their daily activities. When detected, there is a limited amount of time in which treatment measures are effective. In addition, the thrombolytic treatment with rt-PA, which has shown good results, requires new extra- and intra-hospital protocols that the health-care community should be aware of. In this paper we present a multi-agent system, MASICTUS, with the aim of giving support in the diagnosis of acute stroke while coordinating ambulance services and expert neurologists to assist the patient on time. In particular, we propose the use of an auction mechanism based on trust in ambulance coordination. Moreover, the system is designed to exhibit reactive behavior when dealing with incidences occurring before the ambulance's arrival.

1 Introduction

Stroke is a cerebrovascular disease which affects the blood vessels that provide blood to the brain. It is also known as acute brain-vascular cerebrovascular accident (*ictus*), emboli or thrombosis. As a consequence of a stroke, neural cells in the affected area do not receive oxygen, cannot work, and die within minutes. There are two main kinds of strokes: ischemic and hemorrhagic; in the former, blood vessels have been internally obstructed, while in the latter, the blood has been exploded in the brain [Emsley and Tirrell, 2002]

Stroke is the third cause of mortality and the first cause of disability among people in western countries [Gil-Peralta, 1998]. A large percentage of the people who survive it live with serious physical and psychological disabilities and require permanent assistance in their daily activities. Mortality rates, which have been descending in recent decades [Bonita and Beaglehole, 1993], are currently increasing due to the growing numbers of elderly persons, who have a greater risk degree of suffering one [Broderick et al., 1989]. So, in addition to personal, family, social, and labor consequences, in the future acute stroke will represent an important health and economic burden for health systems. In Europe the importance of the illness has also been manifested by the WHO (World Health Organization), which has agreed with a set of principles aimed at finding the best stroke treatment practices (Helsingorg declaration).

Acute strokes are medical emergencies, because they occur in an acute and unexpected (but not unpredictable) way, and either the patient or their family request quick attention at the first signs of neurological defect [Egido, 1997]. Emergency treatment is particularly important because in the ischemic penumbra, the affected area, the concept of a therapeutic time window holds true. That is, there is a limited amount of time in which treatment measures are effective. This time window is not fixed, but evidence has shown that it should be no longer than 6 hours, and in the best practice, 3 hours [Fisher et al., 1995]. Specifically, thrombolytic treatment with rt-PA in less than 3 hours gives new opportunities to the patients. However, such treatment requires new extra and intra-hospital protocols that the health-care community should be aware of. So, in addition to urgency, expert neurologists are also important in the rt-Pa treatment [Davalos, 2005].

Recent studies in a given region [Davalos, 2004] have shown that the shortage of expert neurologists in health centers results in the detection of strokes outside the therapeutic time window. Expert neurologists are assigned to major hospitals, usually located in big cities. Moreover, ambulance teams responsible for moving patients from their original locations to the main hospitals are private services, so conflicts of interest can arise between patient treatment and transportation.

Given such a situation, the persons responsible for the major hospitals have considered the possibility of developing a computerized support system for coordinating expert neurologists and ambulance services. Using our experience, we have proposed and developed a multi-agent system,

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MASICTUS, with which some of those objectives have been achieved. The purpose of this paper is to describe the system.

The paper is organized as follows. First, in Section 2 we describe the protocol to follow in case of acute stroke. In Section 3, the multi-agent architecture is illustrated. The ambulance coordination method is explained in Section 4. Section 5 shows the actual implementation of MASICTUS. Section 6 comments on some related work and, finally, discussion and conclusions are drawn in Section 7.

2 The stroke protocol

In order to understand our architecture, in this section we describe the main steps required to attend to and urgently move patients who have suffered an acute stroke.

First of all, when a patient suffers an acute stroke, he or his family react in any of the following ways:

- Calling the emergency service (061) or similar (integrated health service phones)
- Going to a local health center
- Going to the emergency services of a regional hospital
- Going to the emergency service of a main hospital.

The different dependencies among health centers are shown in Figure 1.

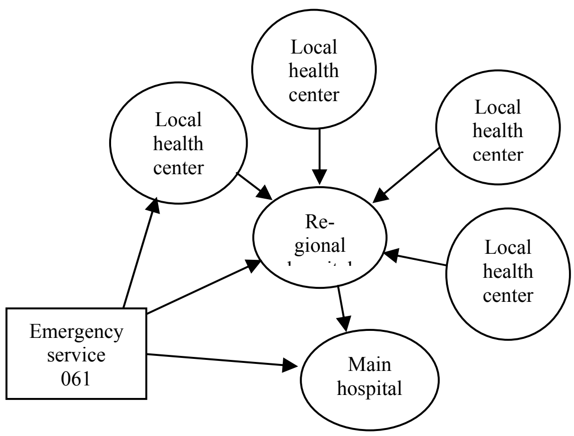

Figure 1: Health center dependencies.

The health-care staff at the center where the patient arrives should be aware of what the patient is suffering from as soon as possible. For this reason, there is a checklist provided in each center that helps the medical staff diagnose a possible acute stroke and activate the stroke protocol. The checklist includes:

- Patients less than 80 years old
- Focal symptoms (Cincinnati scale)
- Family member able to authorize medical intervention.
- Time at which the patient starts suffering the illness

Once the diagnosis has been concluded and is positive, the physician must determine whether the patient should be moved to the main hospital or not, according to the time passed since the beginning of the illness and other exclusion criteria. As stated in the introduction, the adequate treatment time window is less than three hours, but the following cases are considered:

- **Case 1:** If an acute stroke has occurred in less than 6 hours, the patient should be moved to the main hospital.
- **Case 2:** If the time window is [6-24] and the patient meet exclusion criteria (coma, epilepsy, etc.), he or she should be also moved to the main hospital.
- **Case 3:** Otherwise, the patient should be moved to the regional hospital.

At this moment, the physician knows the possible diagnosis and the destination hospital for the patient. The remaining steps should then be carried out:

- **Case 1:**
  - Activate the transfer of the patient to the main hospital with maximum priority (less than 30 minutes) so the expert neurologists can attend to him and provide the corresponding treatment.
  - Contact the expert neurologist team in the main hospital, to alert them of the arrival of a new patient (so they can prepare a TC).
  - Activate the patient transfer protocol.
- **Case 2:** Activate the transfer of the patient to the main hospital with urgent priority.
- **Case 3:** Move the patient to the regional hospital.

Note that the rt-PA administration is not performed until the patient arrives at the destination hospital. There, the neurophysicians determine with a TC (neuro-imaging) whether the stroke is hemorrhagic or not; only in the latter case is the rt-PA treatment indicated.

3 MASICTUS architecture

To give support to the stroke protocol, we have designed a multi-agent architecture in which two main kinds of agents are distinguished: agents related to the health-care service (patients, health centers, stroke protocol and ambulance teams), and supporting agents (expert system rt-PA and trust agents) (see Figure 2). On the one hand, health-care agents are in charge of assuring the correct execution of the medical protocol for the ischemia stroke treatment. In such a protocol an ambulance is required to transport the patient to the corresponding health center. On the other hand, support-

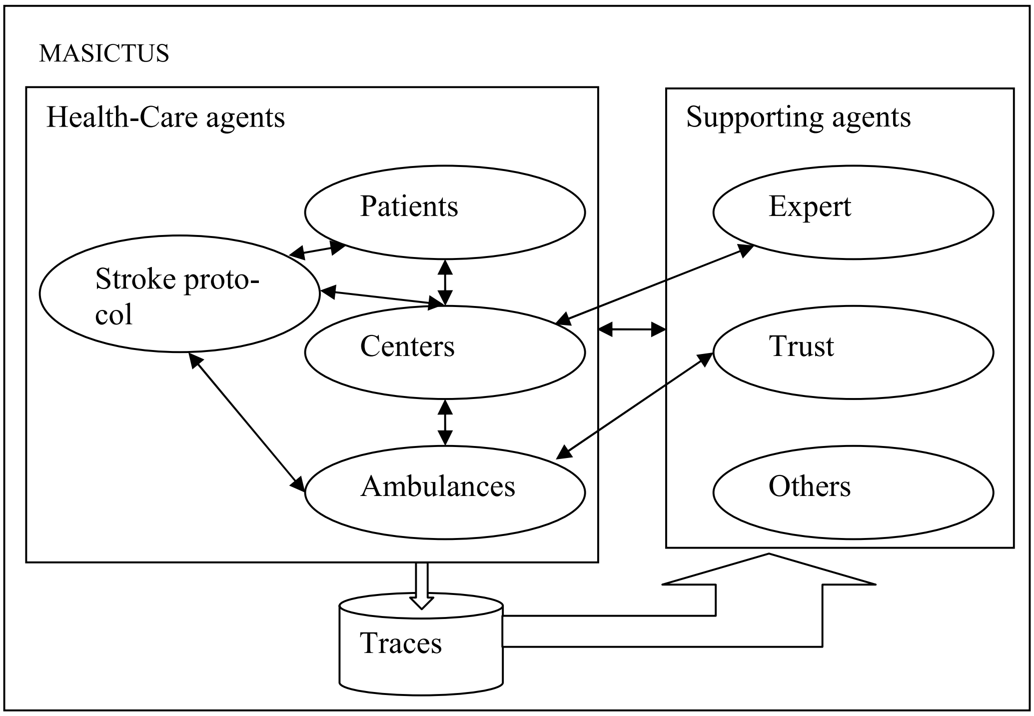

Figure 2: MASICTUS architecture

ing agents help in the process of diagnosing the disease and assessing ambulance reliability.

3.1 Health-care agents

There are four main kinds of health-care agents: patients, health-care centers, stroke protocol and ambulance teams. First, patient agents deal with all the information related to patients. When a citizen suffering from a stroke either arrives at a health center or calls an emergency phone, a patient agent is created. Such an agent keeps track of the patient until he/she is finally admitted into the hospital.

Second, there is a health-care agent for every health-care center involved in stroke attention: local centers (primary attention), regional hospitals, main hospitals and the emergency phone centers (061 phone calls). A citizen can arrive at any of these centers with an acute stroke and all of them should be prepared to detect the illness first, and then to apply the appropriate stroke medical protocol.

Each health-care agent interacts with an expert agent that helps in the process of diagnosing the patient by following a fuzzy logic approach. For the sake of simplicity, we do not provide details of the expert system development in this paper.

The outcome of the expert agent determines the kind of center the patient should be transported to: regional or main hospital. Note that in some cases, the patients can already be in the main or regional hospital, since he can be attended by the hospital emergency services. Otherwise, an ambulance team is required to transfer the citizen to a suitable hospital.

Aware of the diagnosis, the center agent now activates the stroke protocol by interacting with the corresponding stroke protocol agent. It is this agent that starts interacting with the main hospital to alert expert neurologists about the new patient. Then, he negotiates with the ambulance agents in order to assign an ambulance to transport the patient to the corresponding hospital.

Finally, ambulance agents enter the scene, providing service to the patient. Due to their complexity, ambulance agents have been conceived as abstract agents that are composed as multi-agent systems in turn (see Figure 3). The ambulance coordination at this level is described in next section.

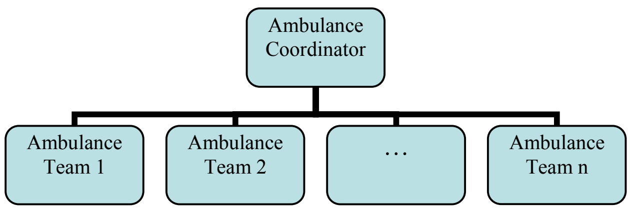

Figure 3: Ambulance multi-agent system.

4 Ambulance coordination

Coordination in the MASICTUS system is simple at the higher level: patient agents require information from center agents in a predefined way. That is, a patient agent interacts with the center agent in which the citizen has physically arrived. No choice is made at this level.

The key issue here is ambulance team coordination. As stated in the introduction, ambulances depend on private companies which are being paid for the number of services they perform. In such a situation, different ambulance companies are competing for patients. Therefore, a more sophisticated coordination mechanism is required. Specifically, we propose an auction mechanism based on trust. Auctions assure the cheapest ambulance, in terms of time, is obtained, which is crucial for our problem. In addition, trust provides a mechanism to control the veracity of the information provided by the ambulance teams in the auction process.

Due to the set deadline imposed by the acute stroke treatment time window, we have provided the ambulance teams with reactive behavior aimed at dealing with different incidences. In the case of some incidence occurring that can substantially deviate the time expected to pick up the patient, the ambulance team can contact the ambulance coordinator, so that a new ambulance auction process is started.

4.1 Auction model

At any given moment in time, there may be several patients requiring an ambulance in a given health region. Regarding the stroke medical protocol, however, it should be noted that there are principally two emergency situations:

- Case 1 with maximum priority (see section 2)
- Case 2 and 3 with urgent priority

In the first case, the stroke protocols clearly define that a patient suffering from an acute stroke has maximum priority and his transportation to the main hospital receives maximum attention. In the second case, the transportation priority is the same as with any other patient suffering from a hard attack, a traffic accident injury, etc.

In the first case, an ambulance should be assigned to the patient; in the second case there is a set of patients to be transferred in different ambulances. Since there are two different situations, two different ambulance allocation processes are distinguished. For the maximum priority case, an inverse auction is proposed, while for the later, a combinatorial auction is the appropriate technique.

On one hand, in inverse auctions (also called Contract net), the auctioneer proposes some tasks to be performed under certain conditions [Wellman and Wurman, 1998]. In our problem, the ambulance coordinator proposes to the ambulance team the task of arriving at the health-care center where the patient is located and gives a time window as the condition to be held. This time window is the result of subtracting the time estimated to transfer the patient from his or her current place to the destination hospital from the treatment time window (provided by the patient agent). Then, the bidders (ambulance teams) that believe they could perform the task in the given time reply to the ambulance coordination with a bid, containing the estimated arrival time that has been computed according to their bidding policy. Finally, using the winner determination algorithm, the ambulance coordinator decides which ambulance to allocate to the patient.

On the other hand, in a combinatorial auction, several patient locations are auctioned at a time [Sandholm, 2002]. They use the same bidding policies but a different winner determination algorithm. For the sake of length, we restrict the description of the methods we have developed to the case of inverse auctions.

4.2 Bidding policy

In order to treat the patient in the time required to ensure proper healing, transportation to the hospital becomes critical. It has to be done as quickly as possible, so traffic jams and temporally closed streets must be considered when planning the best way to arrive at the health center in which the patient is located. Then, in order to compute an estimation of the arrival time of each ambulance, the optimal path, optimal in time and the distance from the position of the ambulance to the hospital should be computed. For such purposes, ambulance teams have different components, namely the GPS module, traffic module, trajectory module and tracing module. Figure 4 shows a schematic representation of modules integrating the agents.

GPS Module
The GPS module receives the global coordinates of the ambulance. Each ambulance must have an electronic device. The outputs of this module are coordinates referring to the city/country map.

Traffic Module
From the national traffic central, this module receives information related to traffic jams, accidents and temporally closed streets. Thus, it is possible to locate in the map the points where the ambulance cannot pass.

Trajectory Module
Based on information of the GPS and Traffic modules, and on the time given by the ambulance coordinator (maximum time), the trajectory module calculates the optimal trajectory to the hospital. In this particular case, the optimal trajectory is the one that requires the least amount of time (trying to be at the hospital before the remaining treatment time elapses) and a path free of obstructions. It is also possible to use information about previous trips in order to modify current

paths that are similar to past ones that were not successful. This module must also have information about maximum speeds of the streets and the city/country map. The outcome is the estimated time of arrival according to the best path found, which is used to bid in the auction process.

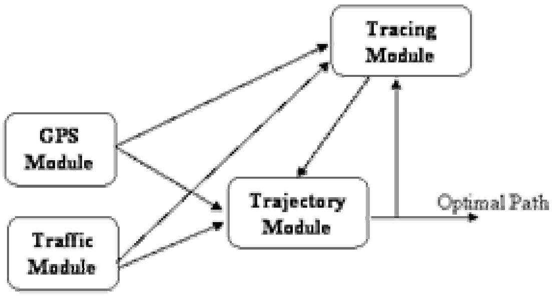

Figure 4: Modules of the reactive agent.

Tracing Module
The aim of this module is to record the optimal path, information about the traffic, the position of the ambulance, remaining time to assure effective treatment and whether the patient has been healed or not. Having a database of past ambulance experiences allows checking whether the driver has followed the optimal path or not, if there was a problem in the trajectory and why, and if the patient could be treated or not. In case there is a difference between the real and optimal path, it is feasible to analyze possible errors in the ambulance agent or in the judgment of the driver. As a summary, when the patient is finally admitted to the hospital, a resolution value is computed, which can have the following values: normal, external anomalies, and driver anomalies. This information is stored in a tracing file (see Figure 2) and can be used to modify future decisions based on ambulance reliability.

4.3 Winner determination algorithm

The winner determination algorithm is applied by the ambulance coordinator to select, among all the proposals, the best one. This process has two parameters: the bid proposals, that is, the estimated arrival time of the ambulances, and their trust.

It is not necessarily true that the ambulance with the best estimated time is the winner, because it should also have a good degree of trust.

Thus, we have used fuzzy filters to filter the information provided by the ambulance team regarding their trustworthiness. Fuzzy filters are good models for determining the trust that agents provide in their assertions in a competitive scenario [Acebo and de la Rosa, 2002]. A fuzzy filter is a Mandami inference system in which the rules have the following form:

If A_1 is S_1 and …. and A_n is S_n then F is L_1

where, A_i and F are fuzzy variables, and S_j and L_1 are fuzzy labels. A_i are called the side variables, and F the filtered variable. There is a fuzzy filter for each agent, so the assertions performed by each agent, and represented by the side variables, are then used to infer the filtered information.

For our purpose, the side variables are the estimated time (ET) and trust (t), and the filtered variable is the increasing time (IT) to be added to the estimated time. The estimated time is defined in the universe of discourse [0,TTW], TTW being the treatment time window; trust is defined in [0,1] (see the next section) and the increasing time in [0,TTW-ET]. Observe, then, that for each agent the domain of discourse of the increasing time will vary according to the estimated time provided by the agent. Therefore, the increasing time that outcome of the fuzzy filter is proportional to the ET.

For each fuzzy variable, the following fuzzy labels are defined:

- ET: {very short, short, medium, long, very long}
- T: {very low, low, medium, high, very high}
- IT: {very short, short, medium, long, very long}

Figure 5 shows the different fuzzy sets assigned to each label. Be aware that the definition is dynamic, depending on TTW and ET.

The fuzzy system consists of fuzzy rules such as:

R1: *If ET is short and Trust is low, then IT is very high*

R22: *If ET is short and Trust is very high, then IT is very short*

After applying the fuzzy filter, an increasing time is computed for each agent according to trust. That increasing time is added to the original estimated time provided by each agent, obtaining a new set of estimated times {ET'_1, ET'_2, … ET'_n}. Then, the ambulance coordinator determines the agent owner of the minimum of these new times as the winner of the auction process.

4.4 Trust model

Trust mechanisms have been applied in several fields such as e-commerce [Noriega et al., 1998], recommender systems [Montanner et al., 2002] and social networks [Yu and Singh, 2003]. Trust is defined as the beliefs of an agent about attributes like reliability and honesty of the other agents with which he has interacted [Yu and Singh, 2002]. The trust an agent, a1, has about an agent, a2, is the evaluations accumulated that a1 has of a2 from past interactions. Once an agent a1 has interactions with agent a2, its trust in agent a2 can be developed according to the degree of satisfaction with the interactions and this trust can be used to make decisions for future interactions.

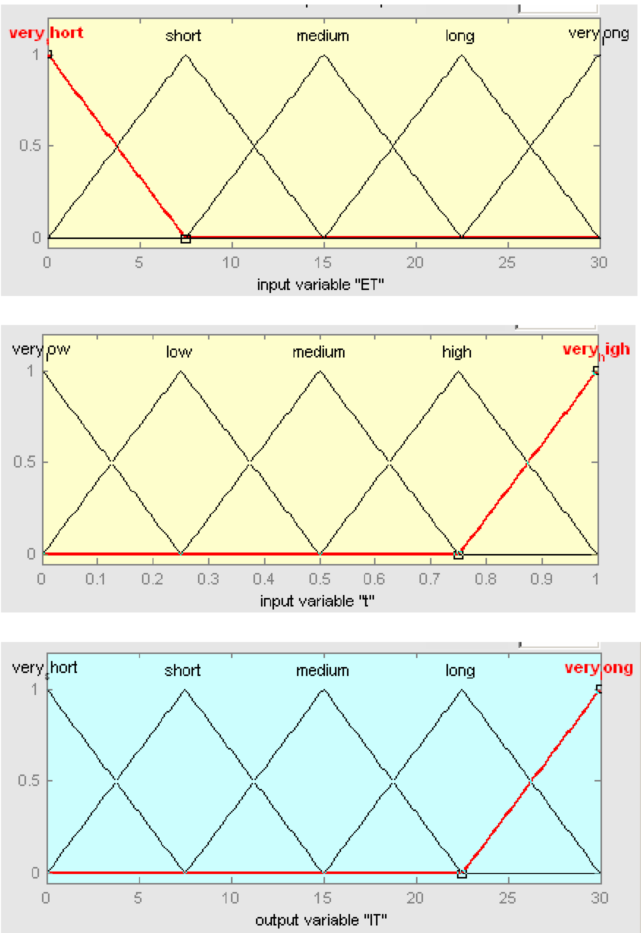

Figure 5: Fuzzy sets.

In our domain problem, trust is used by the ambulance coordinator to evaluate the reliability of the ambulance agents based in the past history of satisfying and unsatisfying services. So the ambulance coordinator has a trust value for every ambulance team, <t_1, …, t_n>. Note that it is assumed that each ambulance team has a permanent ambulance crew. This is a strong assumption that we will try to overcome in future work.

The information required to compute the degree of satisfaction is kept in the tracing file. From such information, the service provided by an ambulance can be evaluated as "satisfying" or "unsatisfying", denoted by S=1 and S=0, respectively. The following rules are used in order to determine the satisfaction values:

R1. If (estimated time = real time),
then S=1 (satisfying)

R2. If (estimated time = real time) and (external anomalies),
then S=1 (satisfying)

R3. If (estimated time = real time) and (drivers anomalies),
then S=0 (unsatisfying)

Note that the equality is computed using a fuzzy measure, so slight deviations are not considered as different.

With the information on service satisfaction we can apply the trust measure developed by Jigar Patel [Patel et al., 2005]. They define a trust value in the [0,1] interval; 0 means an untrustworthy agent, while 1 means blind reliability.

Trust between two agents, a_1 and a_2, is then computed as the expected value of a B_{a_2} variable given the parameters α and β. B_{a_2} is the probability that a_2 fulfils its obligations (see [Patel et al., 2005] for further details). Formally,

$$Trust(a_1, a_2) = E\left[B_{a_2} / \alpha, \beta \right] \quad (1)$$

E is computed as follows:

$$E\left[B_{a_2} / \alpha, \beta \right] = \frac{\alpha}{\alpha + \beta} \quad (2)$$

Parameters α and β are defined, according to the authors, as follows:

$$\alpha = m^{1:t}_{a_1, a_2} + 1$$
$$\beta = n^{1:t}_{a_1, a_2} + 1 \quad (3)$$

Where $m^{1:t}{}_{a_1,a_2}$ is the number of satisfying services, $n^{1:t}{}_{a_1,a_2}$ is the number of unsatisfying services, and *t* is the time of assessment.

The following example illustrates how trust is computed in our domain. Table 1 shows the past experiences of the ambulance coordinator with five ambulance teams.

According to the data, ambulance 001 has had 5 interactions (t=5).After applying the trust rules, 4 services were found to be satisfactory while 1 was unsatisfactory. According to equation (2), the parameters, α and β, are 5 and 2, correspondingly. Finally, after applying (1), the trust value obtained is 0.71. Table 2 shows the trust results for the complete set of ambulances.

Ambu-lance team	Date	Estimated Time	Real Time	External anomalies	Drivers anomalies
001	02/03	12:00	12:15	1	0
001	03/03	20:00	20:00	0	0
003	03/03	10:10	10:15	1	0
005	05/03	10:20	10:19	0	0
001	07/03	9:00	9:01	0	0
002	08/03	8:30	8:30	0	0
003	09/03	13:17	13:27	1	0
003	11/03	15:25	15:30	1	0
001	13/03	5:05	5:05	0	0
001	14/03	8:09	8:20	0	1
004	15/03	20:25	20:25	0	0
002	16/03	11:15	11:25	0	1
003	18/03	13:10	13:09	0	0
004	20/03	12:20	12:35	1	1
002	21/03	14:00	14:00	0	0
005	23/03	11:13	11:20	0	1
004	26/03	17:25	17:24	0	0
003	25/03	10:15	10:15	0	0
002	29/03	15:15	15:16	0	0

Table 1: Coordinator agent past experiences.

Ambulance Team	t	$m_{a_1,a_2}^{1:t}$	$n_{a_1,a_2}^{1:t}$	α	β	$Trust = \dfrac{\alpha}{\alpha+\beta}$
001	5	4	1	5	2	0,71
002	4	3	1	4	2	0,67
003	5	5	0	6	1	0,86
004	3	2	1	3	2	0,60
005	2	1	1	2	2	0,50

Table 2: Trust results.

It is possible to observe in these results, that ambulance 003 has the best degree of trust. It has performed the demanded services on time, even dealing with external anomalies. Conversely, ambulance 005, with a trust of 0.5 does not seem to have expected times which are adequate to the reality.

4.5 Reactive behavior

One important issue in our systems is the capability of showing reactive behavior to deal with different incidences. A typical incidence could be a traffic jam, in which an ambulance might be involved. Since ambulance agents have GPS information, the ambulance can be placed on the map at any moment, and then the estimated time to get to the hospital will be known.

In such a situation, the ambulance team should be able to compute another, alternative path, if possible, according to the procedure described in Section 4.2. Then, two main situations can arise:

1. The new path is consistent with the estimated time provided in the auction process.
2. The new path is significantly greater that the estimated one.

In the first case, the ambulance continues with the new path. In the second case, however, the ambulance agent should inform the ambulance coordinator about this new situation. Then, this agent can decide to start a new auction process to assign a new ambulance to the patient.

5 Implementation

Currently we have a prototype of the system running on a JADE platform (see Figure 5). Some of the functionalities of the MASICTUS have been already deployed, namely, the patient, center and stroke protocol agents. Regarding the ambulance abstract agent, the inverse auction ambulance has been developed, that is, the functionality related to the highest priority patients.

6 Related work

There is a lot of work related to the application of agents in the health-care domain. Regarding our problem, we would like to mention the research work of [Alsinet et al., 2003] on monitoring medical protocols. The authors propose a multi-agent system to assist and supervise the application of medical protocols in distributed hospital environments. The system is able to suggest actions and constraints (forbidden actions) to the medical staff. We believe that we can take advantage of their work to improve our stroke protocol agent.

Regarding coordination of medical services, [Isern and Moreno, 2004] propose an interesting multi-agent system for implementing medical guidelines, that is, sequences of actions, enquiries and decisions to be taken when faced with a patient with a certain pathology. We think that such an approach could be useful for implementing the decision support expert agent in MASICTUS. However, strokes should be detected with very little information and simple tests, without the need for time-consuming tests such as blood analysis and other medical services. So, in our case, the coordination among different medical services and regarding the patient pathology is limited to the patient record, the health center and the expert neurologist team in the main hospital.

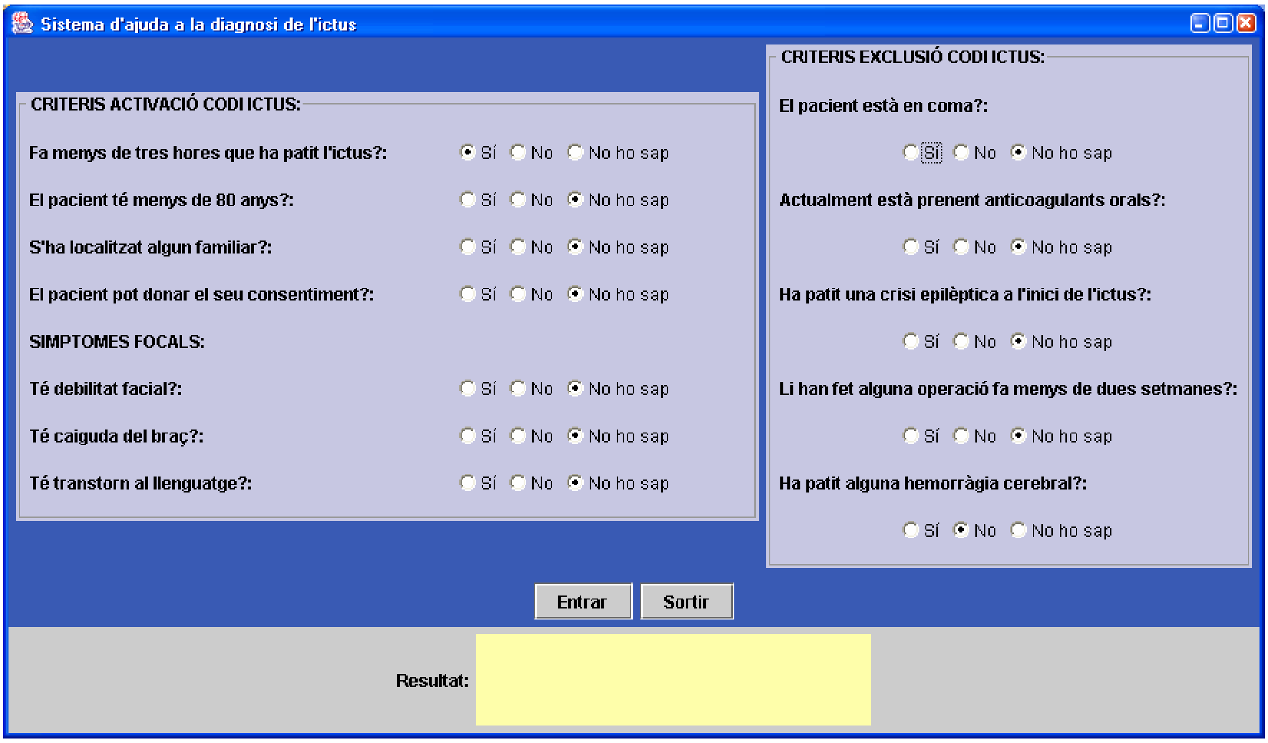

Figure 5 Acute stroke diagnosis system interface.

Other interesting applications of multi-agent systems for coordinating medical services can be found in [Decker and Li, 1998]. Both [Decker and Li, 1998] and [Isern and Moreno, 2004] replicate, to some extent, the existing human organization and authority structures in the multi-agent system. This is also our approach, and we believe that changing the organization is received with disbelief by the authorities in medical systems.

In [Ciampolini et al., 2004] a multi-agent system is proposed for coordinating medical services from an ambulance team. Here, the approach has a different focus. Instead of choosing an ambulance to transfer the patient, the ambulance proposes a hospital. The emphasis of this work is also in service coordination.

Finally, [Greenwood et al., 2004] point out the importance of strokes as one of the major social diseases and propose the ADDHealth project to provide support to treatment comparisons. We have found their work quite interesting since it opens the way to demonstrating how computing-based systems, in general, and agent systems, in particular, can improve health-care treatment.

7 Discussion and conclusions

In this paper we have presented a multi-agent system with the aim of supporting the stroke medical protocol. Two main issues are addressed: first, providing support in the diagnosis process with the help of an expert agent; and second, helping in the decision process of allocating an ambulance team to transfer the patient.

Given that ambulance teams are managed by private companies, the multi-agent system proposed, MASICTUS, uses auction techniques based on trust to deal with ambulance reliability. In addition, the system exhibits a reactive behavior to deal with incidences in the execution of the stroke medical protocol.

Currently, we have a first prototype of MACITUS. In future work, we will complete the remaining system functionalities and integrate them into the health-care system.

Acknowledgments

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