EMIKA System: Architecture and Prototypic Realization*

Günter Müller, Torsten Eymann, Norbert Nopper, Sven Seuken
Department of Telematics
Institute of Computer Science and Social Studies
Albert-Ludwigs-University of Freiburg, 79085 Freiburg
{mueller, eymann, nopper, seuken}@iig.uni-freiburg.de

Abstract – *Life critical applications in hospital environments have got special requirements concerning IT support: a real-time cooperation is necessary to ensure a continuous workflow. This article describes the prototypic realization of the EMIKA project, a real-time controlled mobile information system for clinical applications. The EMIKA architecture is comprised of three layers: first of all, the Communication Layer provides wireless device interaction. Secondly, the Middleware Layer establishes a common service platform for automated service provision and access. Finally, the Application Layer implements a multi-agent-system for the real-time coordination needed for a self-organizing patient logistics environment.*

Keywords: Ubiquitous computing, multi-agent system, mobile information system, life critical applications, self-organizing patient logistics.

1 Requirements for supporting patient logistics using information technology

Hospital scheduling processes impose special demands on information technology support. Various planning goals compete with one another. A minimal throughput time of patients and a maximal allocation of resources cannot be simultaneously optimized [3]. To achieve a working compromise in the light of changing environmental conditions (e.g. number and type of patients to be treated), different scheduling mechanisms today work in parallel. Outpatients are summoned to prefixed appointments; emergency patients always lead to a real-time adaptation of whatever schedule exists at that point in time and inpatients are summoned from the wards in the event of under-allocated resources [9]. All three types have in common that, for treatment, patients need resources in the form of a doctor and diverse medical equipment. In classical information systems, a centralized scheduler using allocation rules creates an optimized appointment plan; however, due to the high dynamics of the hospital environment, the appointments have to be constantly adapted - scheduling becomes a continuous, never-ending process. Especially in life-critical environments such as a hospital, the hold-ups automatically generated by a centralized scheduler can have severe consequences – in contrast to logistics in most other environments.

The fundamental reason for a loss of plannability and thus the need of IT support for patient logistics is the continuous discrepancy between the actual physical state and the logical information available for scheduling [7] [1]. Thus, the goal of IT support is that of increasing the reaction time for adapting the schedule. Other logistical goals like reducing the throughput time are then achievable when realtime information about the current availability of resources exists.

In the EMIKA prototype, the combination of mobile information technology and self-organizing coordination in a multi-agent system achieves the increased reaction time. The technical realization of the information sourcing component does not necessarily depend on the mobility, however it increases the timeliness. The conceptual basis for the implementation divides the application scenario into the *physical* world and its information system model, the *logical* world as seen in figure 1.

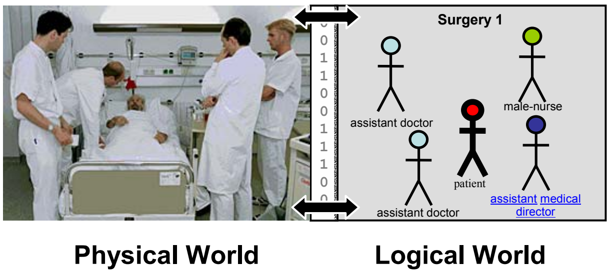

Figure 1: Physical and logical world

The physical world encompasses the concrete, tangible hospital environment, which is occupied by patients, physicians and other hospital staff. Parameters of the physical world, such as the location of a resource, the current task of a physician and the waiting time of a patient are sensed by information technology and modelled using digital data structures of the logical world. The projection of the physical world generates a logical mirror image, which is closer to reality the more often the

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projection is made – preferably in real time. At the same time, the complex real world data is retrieved in simplified, digitalized form - the mirror image is always a simplified model. Increasing the quality of the information feed for the logical world can be achieved either by increasing the frequency of the projection process, or by increasing the number and granularity of data measured.

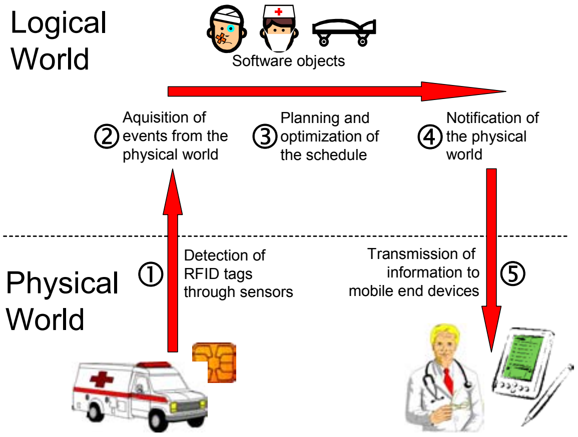


Figure 2: Connection of the physical and logical world

Inside the logical world, states and processes of the physical world can be detected and analyzed. The shadow world of patient logistics detects and replays where queues build up before surgeries, which treatments take longer than expected, and which resources or staff members are currently available or occupied. The procedures which are necessary for continuous planning, making appointments and coordination of processes handle this information. They rectify erroneous allocations and optimize waiting and appointment times [10].

Executing the planning process alone has no effect however, if the results are not communicated back to the physical world. Only the notification of a change in appointments via the mobile phone of a patient, or the transport request via the PDA display of a transport staff employee lead to modifications. This cycle of detection, processing and notification is summarized and displayed in Figure 2.

2 EMIKA – Real-time Coordination of Patient Logistics

The EMIKA project works within the context of the German research focus programme SPP 1083 (Intelligent software agents in business applications) on the realization of a decentralized, self-organizing real-time coordination of hospital logistics using a multi-agent system (MAS). The research method combines simulations, prototypical and empirical methods. The scale model of a hospital department, shown in Figure 3 has been equipped with realistic information technology for the purpose of a technical and functional evaluation. The scale model allows (as an intermediate step on the way to a realistic, fully functional and evaluable prototype) the functional testing of the hospital logistic processes and their coordination without affecting the extremely sensitive hospital procedures.

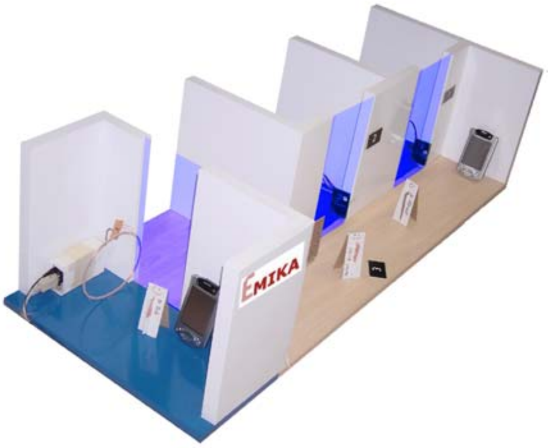


Figure 3: EMIKA scale model

The technical configuration of the model comprises RFID readers on the door frames and RFID-tags on all movable resources, whose change in location can be recorded in the physical sphere and transmitted to the information system. The resources generate a data stream when the doors are passed through, which yields location information through pre-processing in the receiver process and logical interconnection with the previous location.

2.1 The Communication Layer: Acquisition and propagation of real-world-data

Receipt of the RFID signals. The passing of an RFID chip fixed to a mobile object (“tag”) through an RFID-reader produces a “passing” event. The reader sends a signal on a standardized frequency (here 13 MHz) which is received by the passive tag, which has no own power supply. The electrical impulse is sufficient enough to stimulate the tag processor which then sends back an identifying bit string of up to 128-bit. The RFID-reader forwards this identification to an information system for further processing.

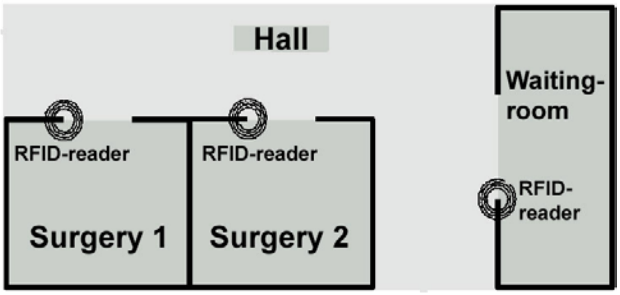


Figure 4: Plan of the scale model

In the EMIKA prototype, these readers are attached to the door frames (see the scale model in Figure 3 and the blueprint in Figure 4). The narrowness of the doorway leads to a relatively short reader distance and thereby only low energy and small antennas are required.

2.2 The Middleware Layer: Processing the location data.

The amount of information generated by the hardware is huge and ambiguous. On the one hand, continuous identification data is transmitted from the RFID-readers, which does not however result in any change in condition in the physical world. Only the first contact between reader and RFID-tag marks the actual incident (entering or leaving a room). The transformation effort of the middleware consists in filtering the continuous data stream and only relaying the events.

Furthermore, since no direction of movement is indicated, the event data can be ambiguously interpreted. The passing of a door frame produces the same RFID event in both directions – a close passing or a turning-around in the doorway is also thereby not recognized as such. To handle this problem the data received from the RFID-reader must be pre-processed with the aid of context knowledge in such a way that a clear as possible determination of location is reached. In the EMIKA prototype three different solutions are implemented and combined to get the best results for location information.

To illustrate the problem, the plan of the scale model is shown in Figure 4. There is an RFID-reader at the door between *surgery 1* and the *hall*. If an individual passing-event is discovered on this door, it is not clear whether the carrier has moved from the *hall* to *surgery 1*, or vice-versa. A history is therefore carried along in the selected realization which is adjusted after each event. For example, if the last position was *surgery 1,* a new reader event at the door would change the location information to *hall*.

This mode of operation seems problem-free as long as all reader events are detected. In a real operating environment, however, it is possible that through concealment, movement beyond the range or the passing of several tags at the same time, reader events are lost. The resulting inconsistency between the last entry in the history of the object and the actual situation increases with each lost event.

In order to solve this problem a graph of the environment is set up, in which the rooms are presented as states and the doors as edges. In the case of lost events, the possible paths between the last reader event and the actual measured event are examined. The approach can be illustrated using figure 5. For example, if a reader event is lost when the object leaves the *hall* towards the *waiting room* the location information becomes inconsistent. If the ensuing reader events were *waiting room/hall* and *hall/surgery 1*, the intersection of both events would be *hall*. From this can be concluded that the object is now, after the last event, in *surgery 1.* Nevertheless, if the error frequency is relatively high and many reader events are omitted, the reliability of the position determination inevitably decreases or becomes impossible at all.

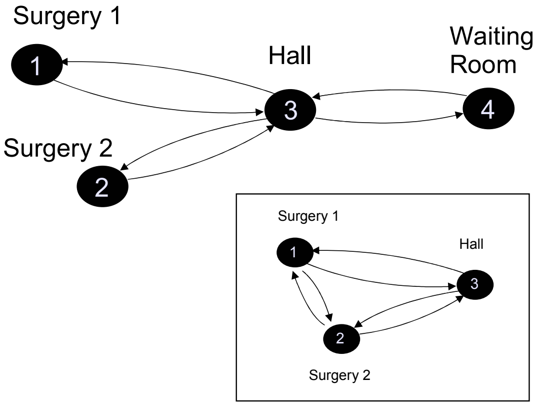


Figure 5: Environment graph with and without cycles

In particular, cycles in the environment graph are a problem (see box in Figure 5). A known position in *surgery 1* and a lacking reader event at the door between *surgery 1* and *surgery 2* leads to a situation in which the next event (door *surgery 2/hall*) cannot be interpreted: there is not enough information to decide, in which direction this door has been passed. A remedy for this problem is the application of two or more RFID-tags equipped to the mobile objects.

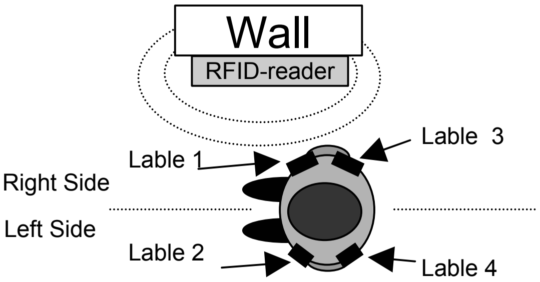


Figure 6: Object fitted with multiple tags

Figure 6 shows a multi-tagged object passing an RFID-reader fitted on the wall. The object is fitted with 4 differently positioned tags. On the assumption that every person enters a room forwards, it is possible to determine the direction of movement of the object on the basis of the chronological order of the contact of two side tags. The reader quality of the tag data can offer further information regarding the movement: a tag, which is held almost parallel to the induction lines of the reader (this is label 1 in the figure) is activated more quickly than the more badly positioned label 2. Only when the carrier moves further forward, the situation changes and the identification of label 2 becomes “visible”.

Such passing and location information can also be gained via other channels. In the EMIKA prototype, additionally infrared data is processed. Infrared (IrDA) beacons are fixed in the rooms in such a way that a certain area is covered (see figure 7). Objects with infrared receivers can receive and send data at any time as long as they are within the range of an IrDA beacon.

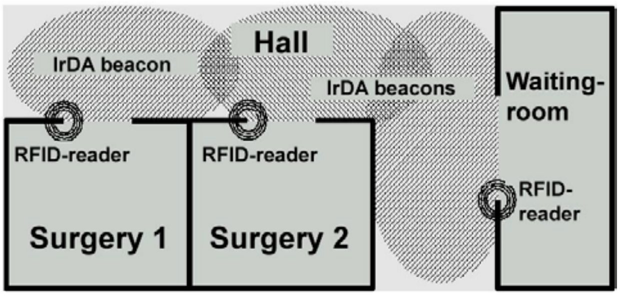


Figure 7: Combination of RFID and IrDA technologies

Alternatives like Radio cell- based location detection methods, e.g. Bluetooth or Wireless LAN, have a too great range for an exact positioning. Mobile telephone technologies like GSM or UMTS have the additional disadvantage that a positioning at altitude is not possible, so that the position data on the ground floor of a hospital would be the same as on the 3rd floor.

Synchronisation and communication. A directory service compares the recorded identification of the hardware with the address of a software object (or a database entry). In the EMIKA prototype, data management is carried out decentralized through the individual agents. The recorded position data is therefore sent directly to the respective agents via message protocols after pre-processing.

2.3 The Application Layer: Data processing in the multi-agent system

On the basis of the additional location data the information system can now *immediately* detect arising problems such as, for instance, long waiting queues or a missing doctor in a surgery. By using information technology the reaction time increases and thus adapting the schedule can be done in real-time. But common scheduling strategies in a centralized model are not capable for a highly dynamic and complex environment like a hospital for three reasons:

1. There are three kinds of patients whose different scheduling strategies are conflicting: Outpatients demand planning reliability to be able to coordinate the appointments with their activities outside the hospital. Their appointments should be conducted in advance through centrally controlled schedules (predictive scheduling). Inpatients are summoned directly in the course of time when the required resources are available (dispatching). Through urgent appointments (emergencies) or cancellations, the already existing and optimized appointment sequences must be additionally amended (reactive scheduling). Through the necessity of reactive rescheduling, the produced schedules are inevitably altered and the stability and robustness of the entire process is disrupted.
2. Optimizing schedule sequences, even when only a limited number of auxiliary conditions are observed, is a NP-hard problem due to the exponential number of alternate solution paths [4]. The non-observance of dependencies on other appointments, the full utilization of the resources and the aims of the actors would create further disruptions in a ‘domino effect’ and thereby lead to a generally less efficient coordination result [6].
3. Because the requirements and general conditions in a hospital are not precisely known in advance, uncertainty is inherent to the system and makes exact planning almost impossible. The duration of the individual examinations strongly differs, there are changes in the diagnoses and emergencies must be treated immediately. Job-shop scheduling using deterministic data cannot be applied, as hospital processes can not assume having a given quantity of orders, production facilities and constant processing time [5].

All in all, a centralized optimization of the schedule is impracticable due to conflicting scheduling strategies, an exponential number of solution paths and uncertainty. Therefore in the EMIKA prototype, a decentralized scheduling process based on a multi-agent-system is implemented to solve the problem of conflicting goals through self-organization [2].

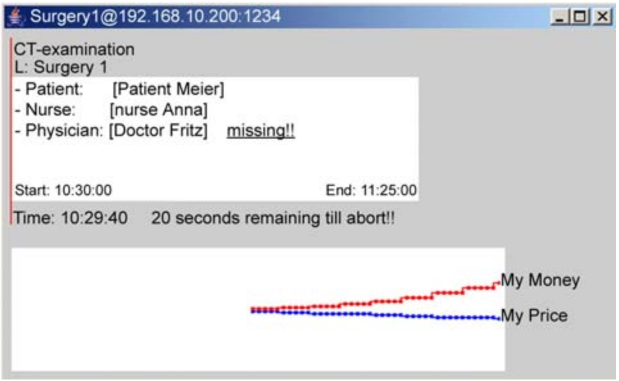
The currently prevailing planning variable for optimizing scheduling and reservations is the *time duration*. The waiting periods of patients in hospital should be minimized; the full utilization of the medical equipment should be maximized. For a negotiation-based scheduling process we need a common “language” with a comparable variable. In the EMIKA project, a virtual monetary substitute in the form of time points is introduced as coordination variable and constitutes the direct connection to the optimizing variable *time*. The time points enable the evaluation of the time required and spent in hospital. The individual scheduling procedures of patients and hospital resources are translated into corresponding negotiation strategies [11].

In the logical model of the hospital environment, each patient and each resource is represented by a software-agent. The coordination of the treatments is achieved through direct negotiation between these software-agents, which announce the desired schedules (goals) on behalf of the actors involved in each case. Using the time-dependent monetary substitute, we create an economic market platform for treatment schedules.

The patients pursue the strategy of completing all treatments in the shortest of time with minimal costs. Through the selection of the most cost-favourable resource at a point in time in each case, overall “costs” are minimized. Compensation for waiting periods spent includes the throughput time into the optimizing strategy in which the patients experience a constantly increasing priority.

All hospital resources try to arrange their appointments as closely together as possible and to treat the highest priority first, calculated in time points gained. This creates a demand and time-dependent price function which signalizes the actual capacity of the resources. With increasing utilization and thereby demand, the price for the remaining capacity increases. A comparison of the prices of two corresponding resources by the patients leads to a relative steering function, which prefers cheaper resources, all other parameters being equal.

Figure 8 shows an excerpt from such a schedule for a surgery where the presence of patient, nurse and doctor is planned. If a resource is lacking in the actual state (e.g. because the doctor is in another surgery due to an emergency), this inconsistency can be recognized and a rescheduling be initiated in the logical world.



Surgery1@192.168.10.200:1234

CT-examination
L: Surgery 1
- Patient: [Patient Meier]
- Nurse: [nurse Anna]
- Physician: [Doctor Fritz] missing!!

Start: 10:30:00
End: 11:25:00

Time: 10:29:40 20 seconds remaining till abort!!

Figure 8: Schedule of a room agent with the list of required resources and development of price and budget

2.4 Notification of the human users

After the rescheduling in the logical world has taken place and a consistent schedule has been restored, it is necessary to communicate the changed data back to the physical world. In general it is not possible to induce the acting parties to behavioural and procedural changes automatically. Normally a user-feedback is necessary, for example a doctor must confirm an appointment change. For this, a device is required which is capable of interaction and it must be in vicinity of the person to notify. The device must be able to present the changed data, provide the possibility to enter a confirmation or rejection of the change through the person and to send back the answer.

Communication with external devices. The first step is the transfer of data out of the information system onto the external units. Basically, two ways of addressing can be aspired, either according to the person or the location. If the hospital staff is equipped with personal, mobile end devices (PDAs, beepers), a direct communication on this end device is the best way. After the planning system has figured out which person has to either actively make or passively confirm an alteration, the end device allocated to this person is addressed. If such a direct allocation is not possible (e.g. in the case of patients), the location at which the person presently finds himself can also be addressed instead of the person itself [13].

A special aspect is the change of plans for devices, which cannot act by themselves in the physical world. A wheelchair or a mobile diagnostic required at another location cannot move itself. In this case, the transport order must be sent to the external device of a transport service assistant, who then performs the necessary change in the physical world.

Data exchange via sockets and network protocols. The external units and internal objects of the information system must be able to communicate with each other via a common interface. In the EMIKA prototype this is realized via Java sockets which transport XML-based messages. Moreover, the addressing of the external units on the systems level takes place via permanently allocated IPv4 addresses. Because of the possibility of making even the smallest objects network-compatible as “smart objects“, IPv6-addresses are assumed for the real application.

Bluetooth/WLAN Connection. The ultimate wireless transfer of information to a PDA or a Tablet-PC also takes place in the hospital via customary radio technologies. In order to guarantee the necessary reachability, RFID cannot currently be implemented, as the point in time of the next connection is uncertain. Technologies with higher reachability and thereby also higher energy expenditure and exposure are Wireless LAN and Bluetooth. The deployment of mobile telephone technologies like GPS/GPRS or UMTS do not offer any guarantee of reachability in closed buildings, such as hospitals, due to their screening effect.

Notification 10:32

EMIKA-Client

Notification

Dr.Albrecht, added schedule: CT-Untersuchung

132.

1

connection established

Figure 9: Notification of the user about a rescheduling.

When the information finally has been received by the persons in the physical world, they can evaluate and confirm the received data (cf. Figure 9), but also alter or ignore them on the basis of their own knowledge. Even ignoring provides the system again with further information (e.g. the notified doctor could have no opportunity to reply due to an emergency) and thereby initiates a feedback to the renewed rescheduling process.

3. Summary and Outlook

This article shows the prototypic realization of a hospital information system which allows the real-time recording and processing of information. Context and location information about the mobile end devices as well as information from the interconnection with other agent systems are thereby collected, processed and compared. The contribution of the described realization for the further development of mobile IT applications is the real-time recording and processing of location information, from which the resource availability can be ascertained, so that their automatic rescheduling can be initiated. The prototypic realization and the tests with the scale model have shown that the desired functionality is achieved by the described approach. Although the EMIKA project primarily focuses on the advancement of agent technology, the conclusions gained are also applicable for normal planning systems and software technologies, which also use location information and mobile end devices for communication and coordination.

The EMIKA project concentrates on logistic services for X-ray diagnostics and is thereby only part of the entire hospital logistic processes. The interaction with other functional areas is achieved in this concrete case by way of the services of the *Agent.Hospital* infrastructure on the basis of the AgentCities EU project [12], which allows access to the services of an information system covering the entire hospital [8]. In a similar way, legacy systems could be linked via HL7 or XML-based interfaces.

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