Design of an Advanced Telemedicine System for Remote Supervision

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Abstract—**The health care systems of industrialized countries around the globe are challenged with several problems caused by the development of the demographic structures. The progress in telematics methods offers new possibilities to deal with this situation. This paper presents a generic and extendable telematics infrastructure offering flexible and mobile telemedicine for patients. More and more sensors and medical actuators are available as commercial "off-the-shelf" (COTS) devices including personal area communication technologies. The presented system integrates these devices into a distributed network to provide medical care at remote locations. The system is designed to support mobile patients in their daily life and to provide real-time access and remote control in critical situations. Therefore, the combination of different communication types is introduced to meet all requirements. As part of the telemedical system, a Tele-Service-Center with an automated data analysis is integrated into the infrastructure to support the treatment of the patients. Altogether, this system offers the opportunity for improving the medical treatment of the patient while simultaneously reducing the costs. The presented system was implemented and tested in a case study with chronic obstructive pulmonary disease patients. All stakeholders of the system were involved in the tests and provided a very positive feedback. Their feedback and suggestions regarding usability or technical functions are already implemented and tested.**

Index Terms—**Medical information systems, networked control systems, telecommunication services, telematics, telemedicine.**

I. Introduction

The ongoing changes in the demographic structure impose significant challenges on the health care sector of industrialized countries. For the year 2050, the expected percentage of people over 65 years within the total population will be about 38% in Japan, 29% in Western Europe, and 22% in the U.S. In comparison, the corresponding numbers were below 10% in 1950 [1]. This development of a rapidly aging society implies increasing health care needs. In addition, the medical coverage of rural areas with a low population density is decreasing due to the growing lack of qualified medical personnel [2]. Due to that, it becomes increasingly difficult to provide a high-quality medical treatment. This situation promotes the introduction of telemedicine to provide fast and high-quality medical consultancy while covering broad areas. The significant increase of capabilities in modern telecommunication and data processing enables advanced solutions to assist medical treatment at remote locations.

II. State-of-the-Art in Telemedical Systems

Due to the recent advances in cellular telecommunication networks, different systems offering telemedicine evolved over the past years [3]. The Trans-European Network-Home-Care Management System (TEN-HMS) study was one of the first international studies pointing out the advantages of using complementary telemedical systems alongside the usual treatment of patients with chronic heart failure [4], [5]. In this study, the patients' weight, blood pressure, heart rate, and heart rhythm were monitored twice a day, resulting in a reduction of hospital readmissions and days spent in hospital. Furthermore, this project showed a reduction of costs, when complementing the normal treatment of patients suffering from chronic heart failure with the telemonitoring of the patients' vital parameters [6].

In the "Telemedical Interventional Monitoring in Heart Failure" study of the project "Partnership for the Heart," a remote telemedical management system was developed to monitor the vital parameters of patients with chronic heart failure and prove the facts provided by the TEN-HMS study [7], [8]. In this study, the patient's weight, blood pressure, oxygen saturation, and electrocardiogram were monitored every morning. This study demonstrated that the use of remote telemedical management can improve the quality of life, especially for unstable patients.

Telemedical projects, like the mentioned ones, always follow a similar structure. The vital parameters of the patients are measured once a day in a predefined setting, collected by a stationary local unit and then transmitted to a central server. These telemedical systems are typically limited to one specific disease and have been designed for specific circumstances. We implemented a telemedical system that offers a generic and flexible infrastructure capable of supporting the treatment of multiple diseases with different requirements in one system. Furthermore, the system is mobile and able to support the patient in their daily life and environment of living while continuously keeping track of the patient's health status. The presented system integrates COTS devices on the patient's side, like medical sensors for vital parameters, medical actuators, and consumer electronics as a system of systems. This generic approach offers the possibility to support any disease treatment

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by using the right combination of COTS devices without an adaption of the system core.

III. Telemedical System

A. Overview

Over the last decades, huge effort has been put into developing medical sensors for many vital parameters. As current trends show, these sensors are increasingly equipped with modern communication interfaces like Bluetooth. By now, several high-quality sensors are available with integrated communication interfaces as COTS devices. In addition to the development of a wide spectrum of medical devices, COTS hardware evolves continuously. Therefore, the usage of these devices offers new possibilities for the field of telemedicine. We present a system that is able to integrate the well-established medical sensors and actuators in combination with modern consumer electronics such as smartphones into a Tele-Service-Infrastructure with the aim to improve medical care for patients while supporting them in their daily live.

Attempting to support the monitoring of multiple diseases in a single system brings up several challenges: every disease is diagnosed with the analysis of a special set of vital parameters. These vital parameters can be measured with a wide set of sensors. In the area of near-field communication, the integration of COTS sensors is still a big problem in terms of usability and robustness due to the heterogeneous communication behavior and protocols. For wide-area connections, different devices have different requirements regarding connection speed, transmission intervals, and whether a bidirectional communication is necessary. The support of mobile patients introduces additional requirements and problems. With the increased mobility of the patient, the surrounding parameters are more and more unstable. Nowadays, projects are often limited to predefined circumstances in which the patient is located at a specific location with known network parameters. The patient measures the parameters only once or twice a day in these settings. We aim to achieve continuous measurements during the whole day without limiting the patient's mobility. This means, for example, that network parameters might change. These requirements all need to be considered. With an adaptable system, we aim to support mobile patients with every needed combination of sensors and actuators.

Fig. 1 shows an overview over the described modular telemedical infrastructure that was implemented in our project. This system is able to meet the requirements for supporting treatments for different diseases. The patient is monitored and assisted by established COTS medical devices. A data acquisition unit, which runs a telemedical application on COTS hardware, is the bridge to the Tele-Service-Infrastructure. It collects all sensor data, stores, and preprocesses it. This hardware might be a COTS smartphone equipped with a high-power CPU, sufficient storage, and several components for wide-area and near-field communication. The central Tele-Service-Infrastructure offers multiple communication services, data storage, security, safety, and central analysis. Through a Web-based application, worldwide access to the data is provided to the doctors and nurses in charge.

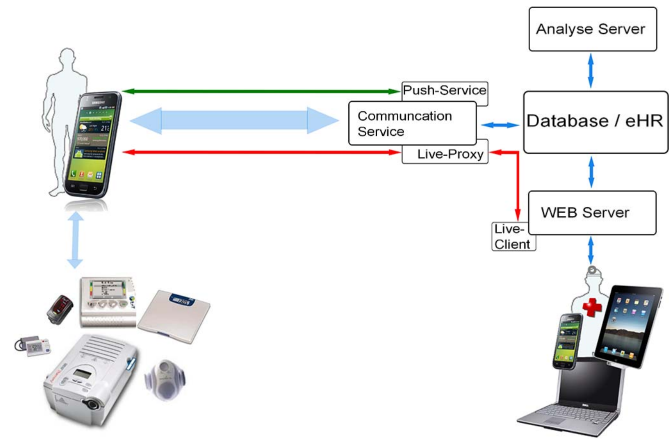

Fig. 1. System overview. The data acquisition unit establishes a connection to multiple COTS sensors and actuators. After a preprocessing, the data are transmitted to the central infrastructure which offers several communication services. All transmitted values and patient information are stored in a central database, and physicians can supervise the patients.

The presented system offers two main advantages: first, supporting the treatment of multiple diseases due to the integration of COTS medical hardware and, second, supporting mobile patients in their daily lives due to the integration of modern consumer electronics. Furthermore, the system enables bidirectional communication of different types, including a live remote supervision, and it offers an on-site preprocessing and backend analysis of data.

B. Main Components

Sensors and Actuators: Since various medical companies put much effort into developing new medical sensors, we propose to use this development for new telemedical applications. Therefore, we suggest to use COTS sensors and actuators that offer communication interfaces. With this approach, a customized set of sensors and actuators can be chosen to monitor the actual health status for each disease and patient. The set of sensors can include standards, such as a weighing scale or a blood pressure monitor, but also more specialized hardware such as an ECG, pulse oximeter, or even a medical ventilator.

Data Acquisition Unit: The data acquisition unit acts as the central patient-side device and also as the bridge to the telemedical infrastructure. This unit collects the data from the local sensors. It stores and preprocesses these data before transmitting it to the central storage and analysis site in the Tele-Service-Infrastructure. To achieve this, we propose to use COTS hardware for the developed telemedical applications. The development of COTS hardware, like smartphones, is driven by consumer electronics and improves very fast in terms of CPU power, battery power, storage, and communication technologies. Therefore, these devices offer a high potential.

The data acquisition unit and the local medical devices need to share a common communication technology. Modern medical devices offer Bluetooth communication which is also very often included in consumer electronics like smartphones. Therefore, this combination is well suited. Upcoming standards

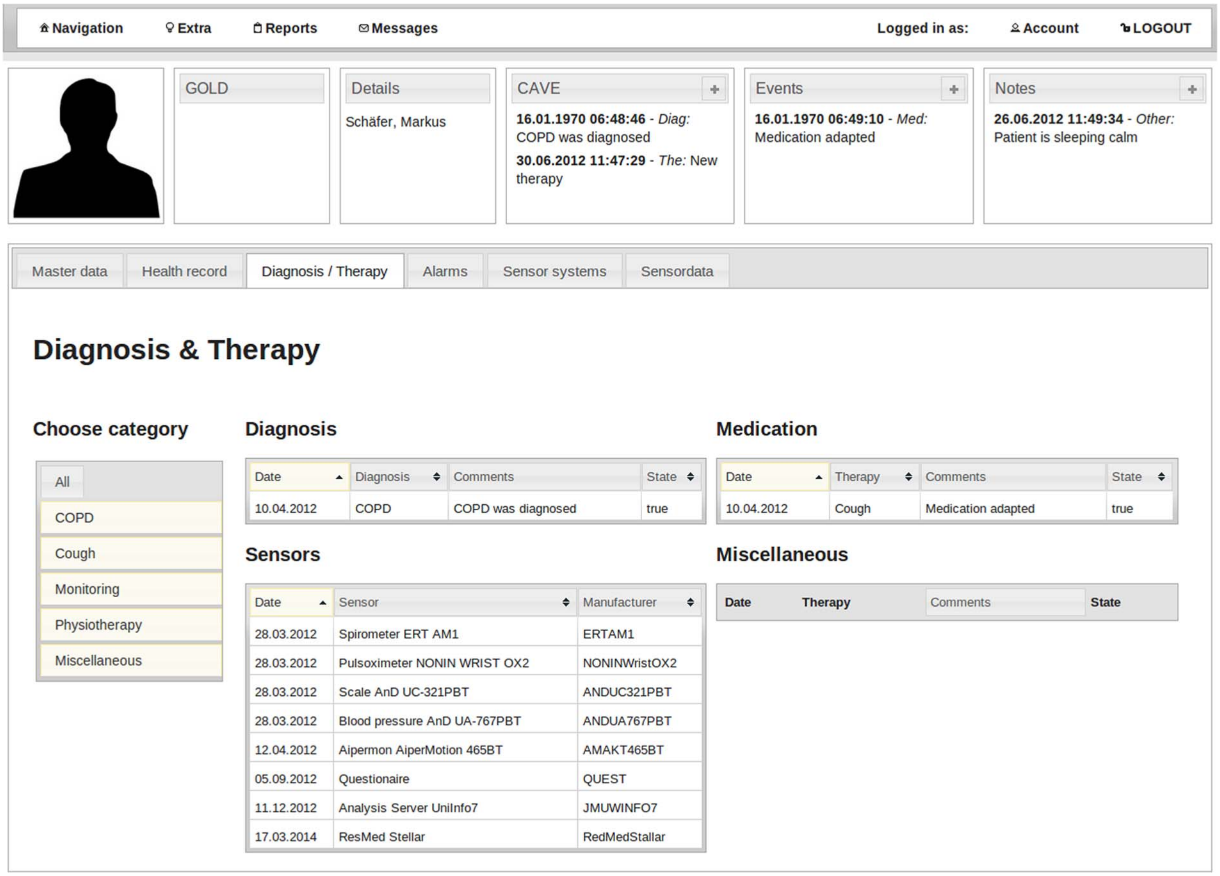

Fig. 2. Telemedical work place showing general information about the patient's diagnosis and treatments. The interface is divided in two main parts, namely, a header with the critical and imported information and the lower part with different tabs for detailed patient reference data, electronic patient records, diagnoses and treatments, alarms, sensor configuration, and measured sensor data.

like Bluetooth HDP and IEEE 11073 increase the interoperability of devices and make the integration of new sensors more feasible [9], [10].

The data acquisition unit was realized with an Android smartphone. This device offers several connectivity standards like BT, BT HDP, WLAN, GPRS, and UMTS. Furthermore, the smartphone has enough computing resources to handle and preprocess the gathered data. The software on the smartphone was implemented with the Android software development kit in Java.

Tele-Service-Infrastructure: The "heart" of the presented telemedical system is the Tele-Service-Infrastructure, with its service-oriented architecture providing different communication services, data storage, and data analysis facilities. To support the treatment of several diseases in one system, a generic and flexible infrastructure was implemented.

The communication module is the bridge to the data acquisition unit on the patient side. Multiple communication types are offered by the module and can be implemented and used from the patient-side device. The communication architecture will be presented in detail later. All patient reference data, sensor setups, and acquired sensor data are stored in the central database. For the representation of the data in the database, all users are assigned to roles like "nurse," "physician," "chronic obstructive pulmonary disease (COPD) patient," "dialysis patient," and so on. For every role, multiple supervisors can be assigned. Therefore, the privacy of a patient can be guaranteed even if he has multiple diseases and wants specific supervisors to only check the data corresponding to one disease. Therefore, the sensor devices of the patients are also assigned to one or more roles of the patients' user. This structure allows us to have a very detailed control of the access to the data and still support different diseases in this flexible and modular system. Another part of the Tele-Service-Infrastructure is the central analysis which will be presented in detail later.

Telemedical Work Place: A special telemedical work place allows physicians to work with the proposed system and supervise patients. This work place provides general information about the patient and the medical status (see Fig. 2) as well as a detailed view on the measured vital parameters (see Fig. 3). Furthermore, alarms generated by the automated analysis of the system are also shown here. With this information, the physicians in the Tele-Service-Center are able to provide optimal care for the patient.

The telemedical work place was developed as a Web-based application since this offers worldwide access to the data without specialized hardware. Through this Web application, different actions on the data acquisition unit can be triggered, like the collection and transmission of sensor data or even a bidirectional real-time data link. To remotely control specialized hardware through this live data link, a live client can be started inside the Web application.

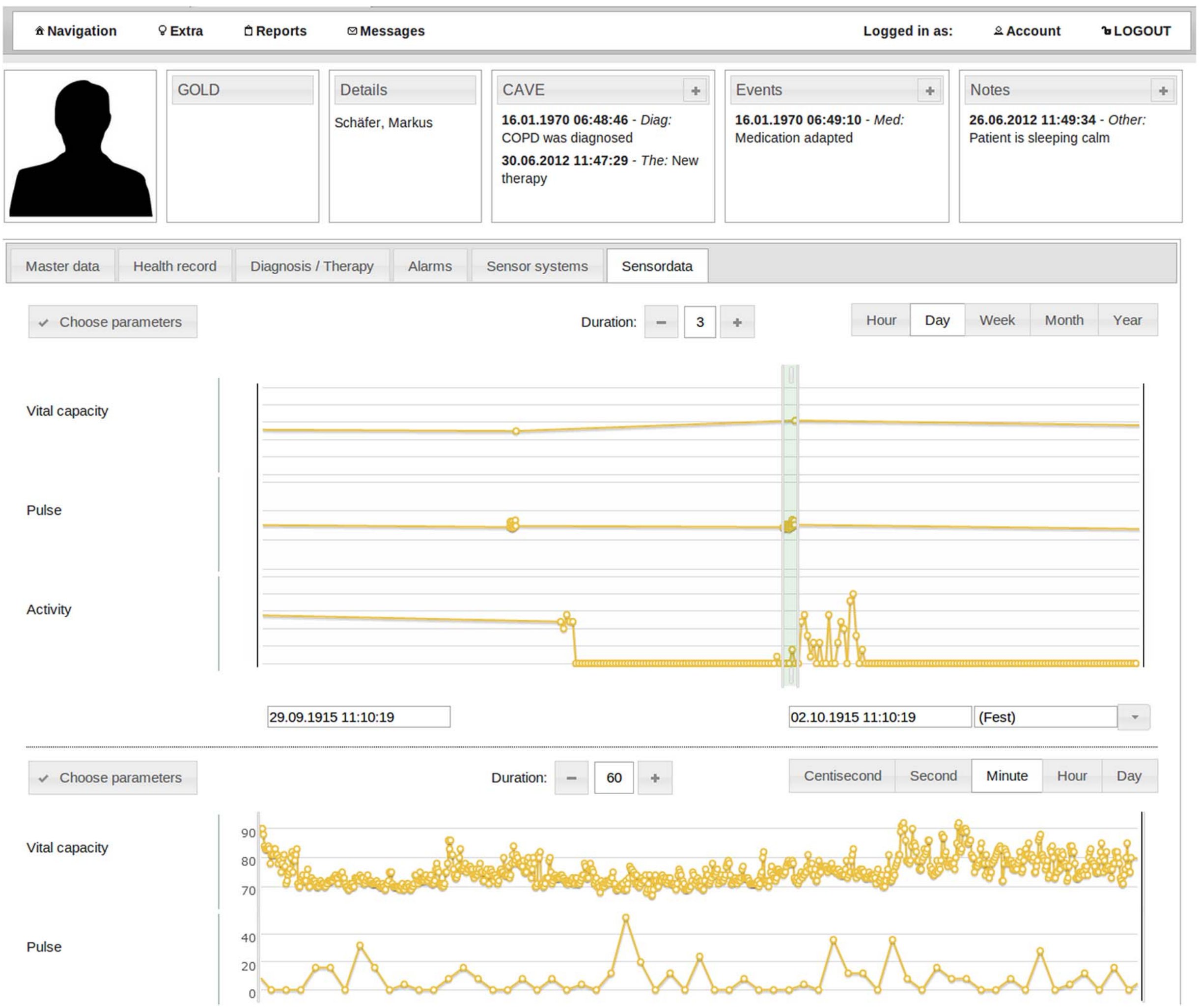

Fig. 3. Lower part of the telemedical work place showing the sensor data tab. The data are presented in a split-view. With the split-view, the physicians can see detailed behavior of vital parameters and the context at once.

C. Communication Infrastructure

The communication architecture is one of the most important parts of the proposed system. Supporting the treatment of different diseases with sensors and actuators in one system imposes a wide spectrum of possible communication needs. To meet these needs, the combination of a basic communication service with a live communication module is used. Like it is suggested in Bluetooth HDP and IEEE 11073 for near-field communication [10], [11], we propose to use the basic communication service for normal and secure data transmission from the data acquisition unit to the central servers. In addition to this, a push module is attached to the communication service in order to provide the possibility for bidirectional communication at all time.

The communication architecture was implemented in Java with the usage of different frameworks like Hibernate for the database connection and Restlet for the Web service connection. The data storage was realized with an Oracle database to provide high flexibility and scalability.

Basic Communication Service: The basic communication service (Fig. 4) provides a robust and secure data transmission service. For this purpose, we propose an HTTPS-based Web service. This type of communication has the advantages of a well-established protocol, a connection-oriented TCP base, a state-of-the-art security through SSL encryption, and its wide distribution. Since the Web service is a very common technique for communication in distributed systems, programming libraries are available for every common programming language [12]. Since HTTP is used all over the Internet, in general, it can be used unrestricted in nearly every network with Internet

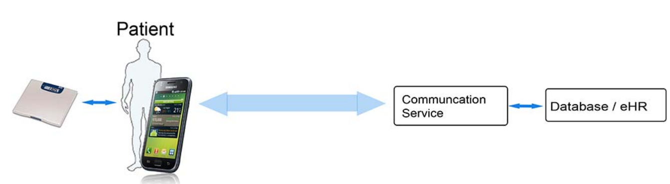

Fig. 4. Basic communication service is providing a solid and secure data transportation between the data acquisition unit at the patient's side and the central infrastructure. The data acquisition unit is collecting the sensor data via local communication. The communication service is connected to the central database for data storage.

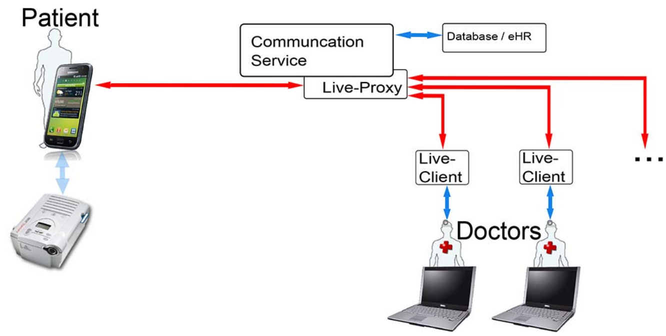

Fig. 5. Live proxy module extends the functionality of the basic communication service. It provides a bidirectional real-time connection between the data acquisition unit, which is connected to sensors or actuators, and multiple physicians.

access like home WiFi with DSL, GPRS, EDGE, UMTS, and HSPA. Other protocols may be restricted by the provider or a firewall. Therefore, an HTTP-based Web service with SSL encryption offers great interoperability and robust communication which can always be used even as a fallback if other communications might fail.

The basic communication service is used for all general communication with the central servers, like authentication, request of up-to-date information of treatment parameters, periodic uploading of sensor data, and so on. The central servers offer these different functions, although an HTTPS server and the clients can use them with the appropriate HTTPS client software. For each function usage, the client initiates a connection to the server. After authentication, the client can send payload data, like sensor data, or request information from the server, like new treatment parameters. This type of communication is optimized for transferring bundled information such as bundled sensor data of the size of several megabytes. Furthermore, the usage of HTTPS-based traffic is a good fallback, since it is accepted in most firewalls while other traffic might be prohibited.

Using the HTTPS protocol imposes protocol overhead, for example, due to handshakes. For bundled transmission, this overhead can be neglected, but for fast repeated transmission like single value every second or even faster, this overhead adds a delay for every transmission and therefore slows down the communication. With the increased round trip times in mobile communication networks, the communication performance of a protocol like HTTPS is not suitable for fast repeated transmissions of single values [13]. For this purpose, the live proxy module extends the functionality of the communication service with another communication protocol.

Live Proxy Module: The live proxy module extends the functionality of the basic communication service. It provides bidirectional stream-based communication (see Fig. 5). The data acquisition unit is connected to a sensor or actuator and initiates a persistent stream connection to the module. Multiple clients can be connected to the proxy module for viewing or controlling the sensor or actuator. The proxy module takes care of forwarding the data coming from the data acquisition unit to the clients and storing the information in the database as well as forwarding the control commands from the clients to the data acquisition unit.

Since the data acquisition unit and also the live clients are often located behind firewalls or Network Address Translation (NAT) routers, the options for a direct connection between these endpoints are often restricted. For both sides, it is possible to establish outgoing connection, but it is often not possible to offer robust services for incoming traffic. Methods like UDP hole pushing offer the possibility to establish a direct connection for data between both sides, if both sides can be instructed via an already established communication [14]. Another possibility is the usage of a central server, which can be addressed from both sides and forward the information to the other side, like a proxy. We propose usage of a live proxy module to establish a fast connection between the patient device and the remote physician. The proxy module opens a server and data acquisition unit, and live clients initiate a connection. The authentication for both sides is facilitated by tokens, which can be requested via the Web service of the basic communication service, where all authentication is handled. The proxy module sorts the corresponding connections into a session and takes care of storing and forwarding the data. This way, a robust end-to-end communication can be established in every situation. Other advantages are that the medical data are automatically stored in the central database and can be used for further analysis. With this proxy module, it is also possible to connect multiple live client to a session because the proxy module takes care of multiplexing the information.

The live client is integrated in the Web interface of the telemedical work place. For remote operation of devices, Java applets which initiate active connections to the proxy module were chosen. This is done because persistent connections offer more performance, then pulling the data via AJAX. Our tests showed the best performance in Java applets for the purpose of a live client operating the remote device. An example can be seen in Fig. 6.

Push Service: For now, every communication between the data acquisition unit on the patient's side and the communication service is initiated by the data acquisition unit. Since we want to achieve a bidirectional communication at all time, we integrated a push module as an extension to the communication service. Different possibilities for pushing alerts to a mobile client are possible [15]–[17]. The usage of SMS or telephone calls is generating additional costs for the system, and in particular, the time of the arrival of an SMS is not deterministic and depends on the usage of the cellular network. With the recent advances in cellular telecommunication networks and wireless home networks, the usage of Internet-based solutions offers the most flexible configuration. Consumer electronic devices are designed to be always online. We propose to use a persistent connection like the IMAP protocol with the IDLE command [18], [19].

For the realization of the push module, a service is offered by the communication server. The mobile data acquisition units can connect to this service and authenticate. The authentication inside the push module is again handled via a token, which can be requested through the basic communication service. When the client is authenticated, it can issue the IDLE command. The

Fig. 6. Lower part of the telemedical work place showing the integration of the Java applet for remote operation of a flow generator.

service will acknowledge the command, and both sides enter the IDLE state. In this state, the connection is continued, while the client can either end the IDLE state or refresh it. The server can only send alerts in this state. The server has a connection timeout of 30 min; if no command has been issued in this time, the server will assume that the connection is lost. To avoid this, the client is supposed to refresh the IDLE state at least every 29 min.

In addition to the persistent connection, we implemented several fallback mechanisms. The device also opens a server, where it can be addressed and triggers can be called. If the persistent connection breaks, this central infrastructure can reconnect to the device if immediate actions are necessary. When the device connects to a network, it checks the status of its global connectivity. If the device has a global IP address, this IP is transferred to the central infrastructure. Normally, the devices will be located behind NAT routers and only have a local IP address which is not reachable for the central infrastructure. If the local network offers UPNP capabilities, a port forwarding on the router is activated, and this information is transferred to the central infrastructure. With this information and the active port forwarding, connections can be established [20]. Furthermore, the integration of IPv6 and the mobility support of IPv6 offers enhanced connectivity, where the mobile device can be reached by the central infrastructure [21]. With this combination of a persistent connection, UPNP, and IPv6 technologies, a redundant bidirectional communication can be established.

This push module can be used to trigger actions on the data acquisition unit at all times and therefore enable bidirectional communication. Common actions that will be triggered are an additional measure of vital parameters, a transmission of data, a change of configuration, or a live data transmission.

D. *Analysis*

The vast amount of data received from the sensors can be used for detailed analysis with the following three goals:

1) to reduce the workload of the physician;
2) to gain new knowledge of the monitored diseases;
3) to support the patient who is using the telemedical system.

Workload Reduction: The physician has to review all of the data collected from the patients in order to evaluate the status of the patient. This produces an enormous workload for the

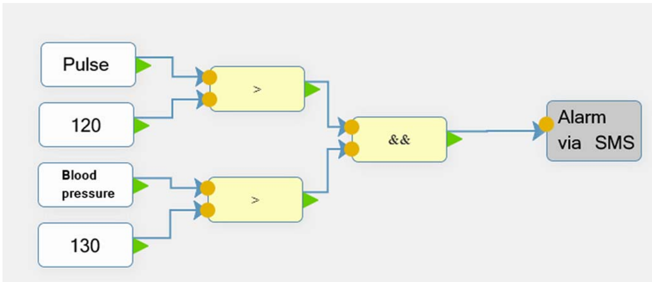

Fig. 7. Example of a rule that alerts the doctor when some parameters reach critical values. Complex rules can be created by a medical personnel with this graphical editor by drag-and-drop.

physician. To reduce this load, the system provides some mechanisms of intelligent filtering and presentation to the physician. The system contains a rule interpretation framework that allows the physician to create rules. These rules are automatically applied to incoming data. When a rule fires, various actions can be performed automatically. This enables the physician to create simple filters, like sorting the data by a specific value or designing a complex behavior that alerts him via email or text message when some critical values in the patient's vital parameters are recorded. Furthermore, algorithms have been integrated to detect a desaturation of a patient's blood oxygen level and generate a warning.

Fig. 7 shows a simple example of a rule that can be created with this framework. The figure shows how the rule is represented in the graphical rule editor for the physician. It takes two measured values (blood pressure and pulse) and compares them to predefined values. These thresholds can be set individually for each rule. When both criteria match, an event is generated. In this fictitious example, the doctor is alerted via text message when the patient's pulse is over 120 while the blood pressure is over 130.

The framework can handle several input sources, like values stored in a database, constant values, or timestamps. It is also able to concatenate rules to form a much more complex behavior. With the implemented set of operators and comparators and the possibility to form concatenated rules, the framework is Turing complete and can therefore do every possible calculation. With each rule, a wide range of events can be triggered. These range from changing values used in other rules over storing information in a database to alerting functions via mail or text message.

Knowledge Acquisition: The system collects lots of data from various patients and stores them in an Oracle database. This leads to a big pool of data that can be used for further analysis. Some diseases are well investigated, and others have unknown progressions. Analyzing the data of many patients suffering from the same disease can provide new insights. Therefore, an interface for cross-patient analysis has been implemented. This allows the implementation of algorithms and statistical evaluations which access a large amount of samples. The results give new knowledge of the disease progression or unknown correlations between parameters. Due to privacy issues and restrictions by law, the data are used only in anonymized form and with permission from the patients. The production system will use only data from patients who gave permission for cross-patient analysis.

Supporting the Patient: The rule interpretation framework mentioned previously can be used to create rules for preprocessing of the sensor values directly on the patient's device. Therefore, the physician creates the rules and has the possibility to transmit them to the patient's device via the communication link used for data transmission. The patient's device is then able to preprocess the data and react to critical situations even if the communication link is not available. The computation on the mobile client can also be used to provide feedback to the patient how effective the treatment is.

IV. Remote Supervision of COPD Patients

In a research project, the proposed system was implemented for remote support of COPD patients. COPD is a progressive disease of the lung and a growing problem [22]. The Global Burden of Disease identified COPD as the fourth leading cause of death worldwide in 2004. COPD is projected to be the third leading cause of death worldwide in 2030 [23]. In the project, patients were equipped with a set of sensors consisting of a pulse oximeter, a blood pressure monitor, a scale, an activity monitor, and a peak flow meter. In addition to these sensors, the integration of an actuator was tested with a medical ventilator. All devices are available as COTS standalone systems with integrated communication interfaces. A commercial smartphone was used as the data acquisition unit. Additionally, the smartphone provided a questionnaire for quality of life questions.

For several weeks, patients measured their vital parameters with the provided sensors, while the smartphone collected all of the data. Activity and oxygen saturation were measured continuously for long time periods. Other parameters like blood pressure and weight were measured once a day. The collected data were automatically transmitted to the server of the telemedical center whenever new data and a communication link were available. First analysis functions were implemented and tested in the central analysis server to gather additional information like the number of desaturations at night. Alarms could be generated for specified conditions. Via the telemedical work place, a nurse supervised the patients and provided medical support when needed.

For the described project, a wide set of sensors was integrated. During the test phase, we were able to show that the proposed system is capable of supervising COPD patients during their daily life. We hope to reduce the set of sensors during a larger and longer test or clinical trial in the future with a detailed analysis of the data. The goal is to find the best prediction for the patient's health status with as few sensors as possible.

The user interface design and handling were optimized for the target group of patients. These are often elderly patients with physical restrictions. Therefore, the handling of the android smartphone was adapted with a special launcher and a single main application. With the restricted access to system components, the patients were not afraid to "do something wrong." This provided a feeling of safety. After starting the main application, all communication to the sensors was handled autonomously. The patients just used the sensors as usual. Via a visual feedback, the patients easily recognized which sensors were used and which are next. After finishing the daily routine, the patients got feedback over upcoming events, e.g., the next measurement or an appointment with the physician, and could leave the application. With this one-click design, a very high acceptance and compliance was established, and the patients got the feeling of being well supervised.

On the clinical side, a nurse was using the telemedical work place to view the patient's data. The data were viewed and checked for abnormalities by the nurse. The telemedical center had several time slots where patients could contact the center for discussing technical difficulties or abnormalities in the data. The personnel at the telemedical center also tested the usability and the technical functions of the telemedical work place and gave continuous feedback to the developers.

V. Conclusion

The presented system offers a highly flexible and mobile telemedical support for patients. This provides a new quality for the treatment of patients at home and improves their quality of life while allowing reduction of costs. Therefore, the presented system shows a way to deal with the demographic challenges of our modern societies. The proposed system was implemented and tested successfully with patients. The achieved results were very promising. Due to the usage of COTS hardware and a straight focus on usability, the system was highly accepted on both sides, doctors and patients. Patients reported a feeling of being well supervised even if there was no regular contact to the supervising doctors. Also, a higher self-awareness of the treatment effects on the disease progression was recognized by the patients. Due to continuous measurements at home and the possibility to interact with the patient while seeing the live sensor data, the physicians could keep closer contact with the patient, and it was easier to evaluate the patient's status.

The system has to be tested with a larger number of patients, physicians, and nurses to prove its scalability and give detailed results of the performance of individual modules. Implementing connectors for more sensors can increase the number of possible supervised diseases. The extension of the analysis framework with new algorithms provides more and more knowledge about the diseases and their treatments.

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