A New Telesupervision System Integrated in an Intelligent Networked Operating Room

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***Abstract*—In this article, a telesupervision system for the anesthesiologist is presented. It makes use of a manufacturer independent standard for a networked operating room, which is currently under development in a research project called smartOR. The telesupervision system itself is part of the smartOR network and consists of a workstation at the anesthesiologist's workplace and a remote tablet PC, a supervisor can use. Besides a short description of the smartOR network, this work shows the technical principles of the anesthesiology workstation and telesupervision system called SomnuCare. Furthermore, some exemplary opportunities a networked operating room can offer are presented, based on a data acquisition during surgery in the University Hospital Aachen.**

***Keywords*-telesupervision; anesthesiology; smart operating room; network**

I. Introduction

Currently, most of the devices in an operating room are stand alone, each having its own display and control panel for human interaction. In Figure 1 such a scenario from the anesthesiologists view can be seen. It is obviously challanging to observe all these displays, operate the devices and locate possible acoustic alarms, especially in critical situations. A further issue is the communication between the anesthesiologistical and the surgical team. Due to hygienic reasons there is often a barrier between the patients head, respectively the anesthesiologist's workplace, and the surgical team, which complicates the communication between the anesthesiologist and the surgical team.

Networking all devices in the operating room can improve the efficiency of the operating room staff and therefore improve the patients safety [2]. It can help breaking the barrier between the surgeon and the anesthesiologist using central displays, which shows individually optimized information for every side of the barrier. For several special procedures like cardiac surgery, shared, central monitors for vital data are already common. Telesupervision systems [3] would even benefit from such a network. They can easily acquire information from the whole network without effort and are able to support the patients treatment in critical situations by an experienced supervisor. Furthermore, intelligent patient alarms can be generated and displayed using all information available in the network.

Figure 1. Operating room scenario [1]

A. State of the art

As above mentioned, most of the devices are stand alone. The patient monitor and the anesthetic machine are linked in most cases, via proprietary or semi proprietary protocols like Draeger Medibus [4]. In the meantime, first approaches to an integrated networked operating room were made for example by Olympus [5] or Brainlab [6]. A further restriction is that only manufacturers which are able to implement the proprietary standard are able to integrate their own devices. This certification process is expensive and time consuming, so new innovations can enter slowly into the operating room. As telesupervision systems for the operating room, especially for anesthesia purposes, only prototypes like [3] exist. One is the previous version of the SomnuCare system, which was mentioned before. Patient alarms are, in most cases, generated by each device on its own. They are primarily triggered by exceeding pre-defined limits. There are other concepts like the medical device plug and play [7]. But, there are currently no systems which are able to generate alarms

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regarding the anesthesiology with an integrated supervision system.

B. The vision

Assuming that all devices in an operating room are networked and able to exchange information, it is possible to build a central display for both sides of the barrier, optimized for their special requirements. The display on the surgical side for example could show only the relevant vital data for the surgeons. On the anesthesia side, the monitor shows vital signs, ventilator settings, respiration parameters. All of these displays can be further optimized to adapt displayed information to the current workflow. For example alarm limits can be adopted or the anesthesiologist can be warned if the depth of the anesthesia is not adequate, depending on the current state of the surgical intervention. Additionally, the anesthesiologist can consult a colleague in critical situations using the integrated telesupervision system. Smart alarms could support the anesthesiologist and the supervisor to get a quick overview of the current patient's situation.

II. Materials and Methods

A. The smartOR network standard

The smartOR network [8] standard is still in development, hence the current state is described. As a physical communication layer, Ethernet will be used, as it is a commonly used standard and it is already used and approved in many medical applications like MDPNP [7] or Draeger Infinity network [9]. To solve problems with the Ethernet CSMA/CD protocol in time critical networks each operating room has its own network and is connected to the hospital IT via a special gateway. This reduces network load, because the gateway filters irrelevant traffic from other networks. As upper layer IP with UDP or TCP will be used, with a SOAP protocol as a web service architecture [10]. The complete context of the smartOR network and the developed anesthesia system is described in Figure 2. The gateway only exchanges relevant data between the networks. For example vital signs from the smartOR network are not transmitted to the clinic IT. Otherwise DICOM images can be send to the smartOR network for analysis during the surgery, whereas other information from the clinic network is filtered out.

B. Network structure

As shown in Figure 2, the smartOR network is the central component. All devices supporting the smartOR protocol in the operating room are connected via Ethernet. For the connection to the clinic IT a gateway is used, as described in Section II-A. This ensures an isolation of the smartOR network of each operating room and the clinic network. The anesthesia workstation is connected to the smartOR network, too. As central processing and viewing component of the anesthesiologist's workplace, it has much more features. It

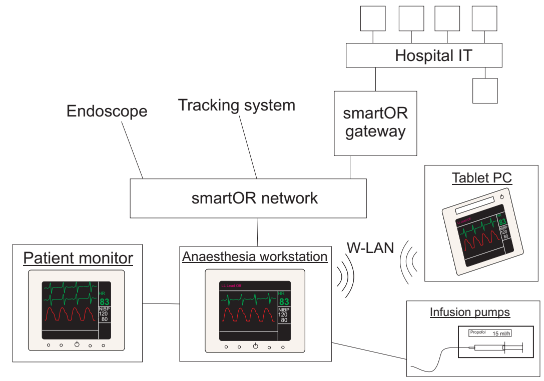

Figure 2. Network structure

integrates devices of the anesthesiologist's workplace and therefore all of the devices are directly connected to the workstation. Necessary data of the anesthesiologist's devices can be converted to the smartOR protocol and be provided to other smartOR devices. Ideally, all devices should be connected to the smartOR network, but especially the anesthesiologist's devices like patient monitor, respirator and perfusion pumps are critical. The necessary modifications of such devices could not be made during the research project. Due to high requirements in data processing for vital signs, it is necessary to process the data stream without any interruption at data rates of up to 200 Hz with up to 50 channels. Furthermore, a continuously transmission must be ensured without interruptions. Hence, the remote tablet PC for the supervisor is directly connected to the anesthesia workstation and not to the smartOR network. Additionally the direct connection allows the workstation a pre-processing of vital signs and enables it to send these directly to the tablet pc without diversion over the smartOR network. The anesthesiologist's workstation and telesupervision system is described in the following part.

C. The anaesthesia workstation

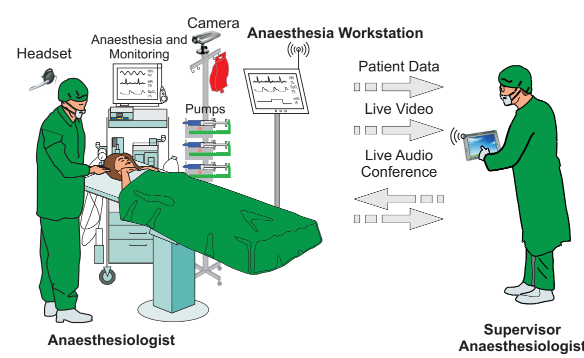

Figure 3. Telesupervision system. Modified after [3]

The essential parts of the anesthesiologist's workplace are shown in Figure 3. The workstation supplies the smartOR components with the necessary physiologic vital signs and retrieves the relevant data from the smartOR network. This can be events like start of the surgical intervention or other critical procedures. All of the data processed by the workstation can be transmitted to the supervisor via wireless LAN. Additionally to the vital signs, events and alarms, a live video stream from the operating room and a live audio conference can be transmitted.

D. Description of the SomnuCare software

An overview of the important elements of the SomnuCare software can be seen in Figure 4. The central element is the memory mapped file engine. It stores and caches all data from the interfaces, where each memory mapped file represents one vital sign. Data acquisition is done by the interfaces described in Section II-D1. All interfaces in SomnuCare have a specific API, which is equal to all interfaces. This concept enables the programmer to add further interfaces for data acquisition without change of other parts of SomnuCare. Furthermore, the telesupervision server emulates an interface for the supervisors tablet PC and mirrors all data stored in the memory mapped files to a special interface on the tablet PC.

1) SCInterface: All interfaces in SomnuCare have a specific API. This makes it easy to implement and integrate new devices into the workstation. The complete communication and handling with the connected device is done by the interface, so independently from the physical connection each device can be integrated in SomnuCare. The interface only has to implement functions like configuration, starting, stopping and resetting the interface. Every interface holds an internal state machine, which is controlled by these functions. This enables SomnuCare to automatically handle different types of connected devices the same way. Received data are directly written by the interface to the memory mapped file engine. For each data stream or vital sign one file is used.

2) Memory Mapped File engine: The memory mapped file engine makes use of the operating system's memory mapped file API and supports reading and writing data to a segmented memory mapped file. So, writing and reading data is cached via operating system functions on the one hand. On the other hand, the memory mapped file is a complete log file of all inserted data. The engine supports only one writer which can append data to the memory mapped file. This is sufficient because the interfaces are the only writers to the memory mapped file and they only need to append data, because the vital signs are time continuous. As it can be seen in Figure 5, more readers are allowed. This is necessary because the data from the interfaces are needed in parts of the software. The GUI as viewing element needs access to the last appended piece of data, the telesupervision server must send the last inserted piece of data to the client and the smartOR interface needs to send data on request. To save memory not the whole file is mapped into

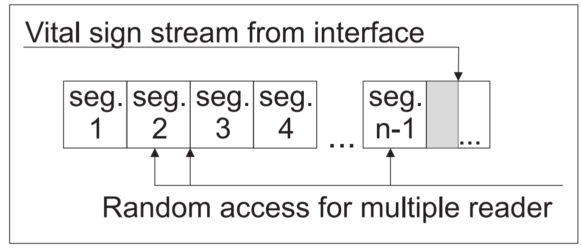

Figure 5. Memory Mapped File

memory. For writing, only the last segment is allocated. If the last segment is full, the file will be expanded with the segments size and this new segment will be allocated. The reading function is able to randomly access segments. To improve the performance of multiple readers, appended data are tagged as new, so with a special read function only new recently appended data can be retrieved. The control of the memory mapped file is done via a special control segment. This is held in a separate memory mapped file, the control file. It stores information for the segment handler and tagging new data. Furthermore individual information about the data held in the memory mapped file can be stored in the control segment.

3) Telesupervision server: The telesupervision server mirrors all data in all memory mapped files over the wireless network to a client. It makes use of the memory mapped file engine and sends all new data over the network. On the client side the receiver is implemented as a regular interface (IfNetwork) so there is no modification needed for the clients except activating the IfNetwork interface and setting the IP address of the server. It acts as a normal interface, but additionally renames the vital signs and therefore emulates the interfaces from the server. Like all other interfaces the IfNetwork interface must implement the state machine for the interface state. This enables the network interface to automatically reconnect after a WLAN disconnect or any other failure. After such a disconnect the IfNetwork tries, as fast as possible, to reconnect and load missing data and then continuous with normal operation. The vital signs are automatically cached by the memory mapped file engine described in Section II-D2. Due to automatic caching and the consistency of the memory mapped files, no data will be lost, so a resynchronization is not necessary.

4) Graphical user interface: The graphical user interface is implemented as a QT grid [11] layout. It can be customized via a configuration stored in a SQLite database, but the standard view is similar to the one of a patient monitor.

5) Simulation interface: The simulation interface is used to evaluating the new alarming concepts. It is able to load saved memory mapped files and CDF data. These data are send to SomnuCare in defined time steps to simulate a conventional interface. This enables the user to replay a

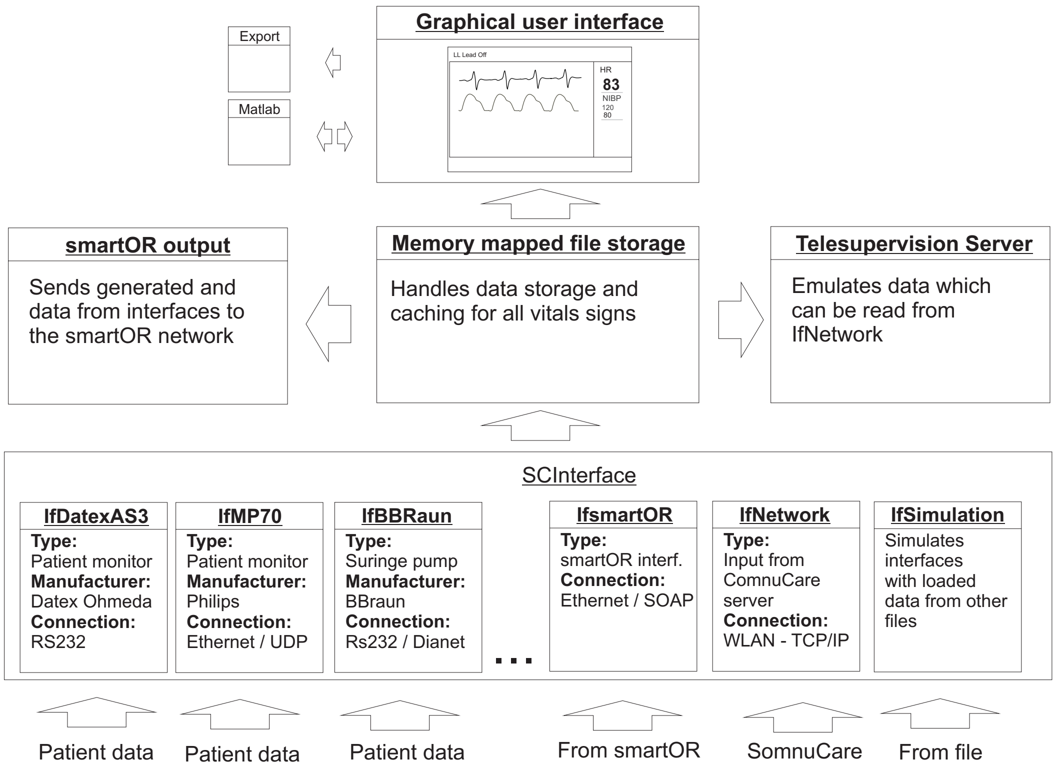

Figure 4. Functional diagramm of SomnuCare

scenario faster than normal time for studies evaluating the new smart alarms.

E. Data acquisition during surgery

The described data acquisition during surgery is the foundation of the alarm system integrated in SomnuCare. First the realization of this data acquisition is described. After that the first approach to the smart alarms is described in Section II-E2.

1) Realization of the data acquisition: In order to improve comparability of the collected data, similar surgical interventions, most of them laparoscopic, were selected for recording. Anonymous data acquisition took place at the University Hospital Aachen (UKA) after approval by the local ethics committee within a time period of three weeks. Generally, the most important steps were pointed out as milestones:

- Start of the presence of the anesthesiologist
- Start of anesthetization
- Approval for surgery
- Start of the surgical preparation
- Start of the surgical intervention
- End of the surgical intervention
- End of the surgical wrap-up
- End of anesthesia
- End of presence of the anesthesiologist

Furthermore the following events were recorded:

- Anesthetic events, like intubation or inserting of a stomach tube
- Surgical events like skin incision, intra-operative relocation
- Intravenous drug injection

All vital signs and information from the following devices were recorded:

- Datex Ohmeda AS/3 patient monitor
- Draeger Cicero and Cato anesthetic machine connected over Datex monitor
- Up to four BBraun perfusor infusion pumps

This represents the standard setup in the UKA for these surgical interventions and resulted in the following recorded vital signs:

- Heart rate, non-invasive and/or invasive blood pressure, oxygen saturation
- Respiratory rate, tidal volumes, pressures, fractions of end-tidal CO2, O2 and anesthetic gases
- Anesthesia agents via perfusion pumps or and/or anesthetic gas concentration via the anesthetic machine

For recording all the vital signs and events, a special software has been developed. This software is a prerelease of SomnuCare and is able to capture the data from Datex and BBraun serial interfaces and store them as comma separated text files. The events and milestones were recorded using the software as well, so all timestamps have the same time basis. Furthermore the patients sex, weight, age and size were recorded.

In total, data from 17 surgical interventions were recorded. (8 female, 9 male patients) A balanced anesthesia using anesthetic gases was carried out in 8 cases, the remaining 9 received a total intravenous anesthesia using propofol and remifentanil.

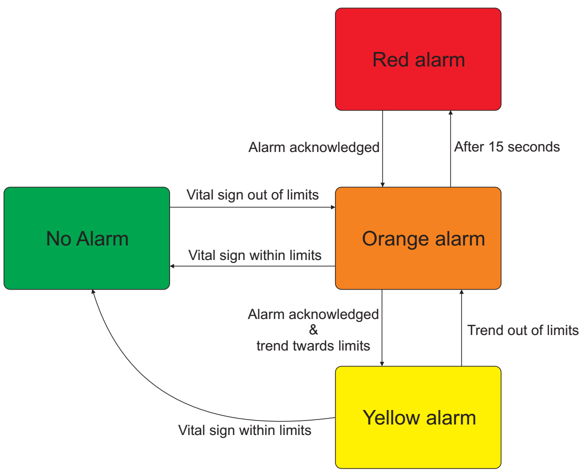

Figure 6. Stateflow

2) *First approach to smart alarms:* As a first approach to intelligent alarms, the following state machine was implemented for every important vital sign, for example like heard rate, non-invasive blood pressure and oxygen saturation. Compared to conventional alarms, which are triggered by exceeding pre-configured but fixed limits, the state machine considers the change of the vital sign after exceeding the limits. So, the concept of classical limits is kept, but supplemented with the state machine after the alarm rises. The alarm is rated into four conditions, similar to a traffic light.

- RED for a serious danger for the patient
- ORANGE for a situation with a potential danger for the patient
- YELLOW for the phase after a RED or ORANGE alarm is cleared
- GREEN for no alarm

The resulting state machine and flow diagram can be seen in Figure 6. For evaluation the state machine was implemented in Matlab/Simulink/Stateflow [12]. The results are presented in Section III-B.

III. Results

Some parts described in this paper like the smartOR protocol and the integration of the anesthesia workstation into the smartOR network are work in progress. Therefore, the authors cannot present any results regarding these parts.

A. SomnuCare software

The SomnuCare software is, except the smartOR part, fully functional. It will be improved continuously as well as its design.

1) *Memory mapped file:* The memory mapped file engine has been tested and verified by regular software operation. By only allocating needed segments, we have a much better memory efficient use. As tested under Microsoft Windows 7 the allocation granularity of the segments is 64 KB. So only 128 KB are reserved for one reading and one writing segment for each memory mapped file. Compared to a 12 channel ECG signal sampled with 100 Hz over one hour and each value stored as double with 8 Byte timestamp which needs 66 MB this signal stored under the same condition with the memory mapped file. Regarding a surgical intervention lasting 5 hours with multiple other vital signs recorded, the benefit is obvious. Because of the pointer exchange function the MS Windows API offers there is nearly no overhead due to the allocation algorithm.

2) *Wireless LAN connection to the client:* The WLAN connection is currently in implementation. First tests showed a good performance. Disconnects are handled directly by the interface manager, which reconnects the interface as soon as possible with the device, in this case with the server. It should be noted that for the network interface a faster handling should be implemented by the manager. For short disconnects, which can depend on the network architecture, it is not sufficient to wait 2 seconds for the reconnect. Exact timing measurements have not yet be done, but will follow.

B. Data acquisition during surgery

The benefit of this concept can be demonstrated by the following example in Figure 7: The patient shows a strong reaction to the anesthesia agents. The blood pressure and heart rate decreases. As reaction to this, the anesthesiologist decreases the anesthesia depth. Once the skin incision occurs the patient reacts heavily to this pain stimulus. The heart rate and blood pressure increase rapidly and on the O2 curve spontaneous breathing can be seen, due to an inadequate depth of analgesia. The above described state machine is currently not able to prevent the situation, but can relieve the anesthesiologist from unnecessary raised alarms. Possibly advising the physician of a trend (like an increasing blood pressure), at an early stage, would result in a more appropriate behavior of the anesthesiologist. Compared with the state diagram in Figure 6, the blood pressure alarm will raise directly after the skin incision, because the alarm limits are exceeded. For the first 15 seconds it will turn to an orange alarm. If nobody acknowledges the alarm it will turn into a red one. If the alarm is acknowledged, it will turn into an orange one and as long as the blood pressure shows a falling trend it will turn into a yellow alarm with no acoustic warnings. If the vital sign is back in normal range, the alarm is switched off and reaches the green state. Compared to

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conventional alarms, the alarms rises every 2 minutes with an acoustic sound.

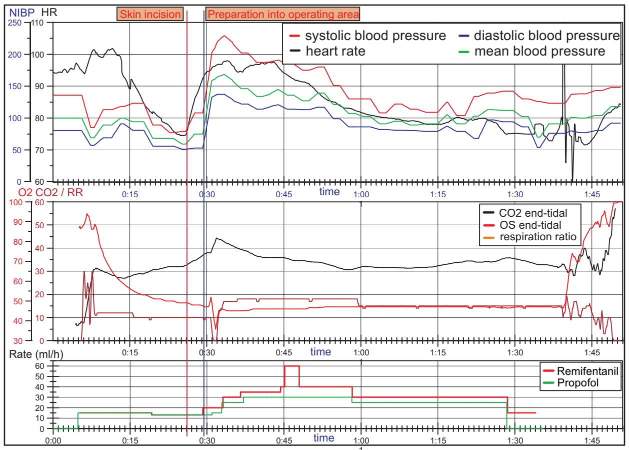

Figure 7. Recorded data of a patient during a surgery

So, at this point the alarm state machine is based only on the information of one vital sign, as described in Section II-E2. This reduces the number of unnecessary alarms essentially and helps the anesthesiologist to keep an overview in critical situations. For example a conventional alarm which is generated by exceeded limits can only be switched off for 2 minutes and then raises again. The described concept is only a basic example and it is still in development.

IV. Discussion and Outlook

A. Multi operating room ability

As described in Section II-A, the smartOR network is an isolated network for each operating room, which is only connected to the hospital IT via a special gateway, due to security reasons. Hence exchanging data between different operating rooms is difficult, but usually not necessary, the telesupervision system can only be connected to one operating room. However in reality the supervisor must be able to supervise more than one operating room. One possible realization could be a network between the gateways of each operating room connected to a central Wireless LAN access point, which is accessed by the supervisors tablet PC. This is more efficient than realizing a Wireless LAN for every operating room and switching between them, because the tablet PC is only able to login to one WLAN at the same time.

B. Data acquisition during surgery

With the basic concept described above it is only possible to reduce the number of unnecessary acoustic alarms. As mentioned in Section II-E2 the system cannot prevent the above described situation, because the actual context of the surgical intervention is not considered and the state machine analyses only one vital sign. Furthermore the state machine should consider multiple vital signs for a smart alarm.

In the future the state machine will be developed further to analyze heart rate, blood pressure, CO2/O2 concentration and depleted anesthesia agents at the same time. Furthermore the state of the surgical intervention will be considered. This will enable the system to recognize the trend in future and support the anesthesiologist during the anesthesia.

Acknowledgment

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