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Non-invasive online PSi signal acquisition from a patient monitor for depth-of-anesthesia assessment

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Abstract

A proper introduction and dosing of anesthetic agents is essential when performing a diagnostic procedure or surgery in general anesthesia. In modern clinical practice, the depth of anesthesia (DoA) is determined by assessing the relevant clinical signs (iris, sweating, movements), by interpreting hemodynamic measurements and by estimating it from EEG signals. The latter is made possible by several established measurement systems, e.g. Patient State Index (PSi), bispectral (BIS) index, Narcotrend, Scale Entropy and Response Entropy. DoA supervision and control seems a suitable problem to tackle using a closed-loop control approach. In order to implement a closed-loop control system for DoA, one must be able to acquire the relevant signals online and in real-time. However, due to safety reasons, the patient monitors are purposely unable to connect to an external (possibly medically unapproved) device, such as a laptop computer, during the procedure. The paper introduces a non-invasive image-based system for signal acquisition from a patient monitor for online depth-of-anesthesia assessment. The signal acquisition system operates in Matlab-Simulink environment, which can be conveniently used for DoA modelling, simulation and control.

Keywords: Depth of anesthesia; Patient State Index (PSi); signal acquisition; modelling; control

1. Introduction

When performing general anesthesia (GA), it is necessary to use substances, which enable deep unconsciousness, analgesia, amnesia and muscle relaxation. A proper introduction of anesthetic agents is essential when performing a diagnostic procedure or surgery. GA and the related activities in the human body are dynamically very complex processes. The processes involve various pharmacokinetic and pharmacodynamic mechanisms, which have not been fully studied yet. During the GA, the anesthesiologist needs to monitor the patient's vital functions and maintain the functions of vital organs. To achieve adequate GA, substances are introduced in different manners into the patient's body.

In clinical practice, the most commonly used methods are the intravenous induction of an anesthetic agent, i.e., injection of the anesthetic into a vein, and inhalation induction of anesthesia, whereby the patient inhales the substance from the breathing mixture. The anesthesiologic technique, where substances are injected intravenously, is known as total intravenous anesthesia (TIVA).

The goal of the anesthesiologist is to maintain the appropriate depth of anesthesia (DoA) by adjusting the dosage of anesthetic. The pharmacokinetics and pharmacodynamics of the anesthetic agent and the type of procedure must be taken into account. Too deep anesthesia is manifested with a drop in blood pressure level and heart rate frequency as well as a slow post-operative awakening of the patient from GA. On the other hand, inadequate depth of anesthesia results in the activation of sympathetic nerves, or in the most unlikely event with the patient awakening, which must be avoided at all costs.

DoA supervision and control seems a suitable problem to tackle using a closed-loop control approach (see Dumnot (2012)). This would benefit the anesthesiologist by relieving the tedious task of constantly adjusting the inflow of the anesthetic agent.

In order to implement a closed-loop control system for DoA, one must be able to acquire the relevant signals online and in real-time. However, due to safety reasons, the patient monitors are purposely unable to connect to an external device, such as a laptop computer, during the procedure.

The paper presents a solution to the aforementioned problem, namely, a non-invasive image-based system for signal acquisition from a patient monitor for online depth-of-anesthesia assessment. The signal acquisition system operates in Matlab-Simulink environment, which can be conveniently used for DoA modelling, simulation and control.

2. State of the art

In modern clinical practice, the DoA is determined by assessing the relevant clinical signs (iris, sweating, movements), by interpreting hemodynamic measurements (see Potočnik et al. (2011)) and by estimating the DoA from EEG signals. The latter is made possible by several established measurement systems, e.g. BIS index, PSi, Narcotrend, Scale Entropy and Response Entropy.

2.1. EEG-based DoA assessment

BIS index is a non-invasive measurement method. A BIS monitor is connected to electrodes on the patients head and the bispectral index is calculated from the measured EEG signals. The value represents the DoA. The BIS monitor provides a single dimensionless number, which ranges from 0 (equivalent to EEG silence) to 100. A BIS value between 40 and 60 indicates an appropriate level for GA, whereas a value below 40 is appropriate for long-term sedation due to head injuries. The reference can thus be set to the applicable value; the manner and speed of approaching the reference value depend on the specific characteristics of the procedure and the pharmacokinetics and pharmacodynamics of the substance in the patient's body. Due to its non-invasive nature and simple implementation, BIS index has been extensively used in clinical practice.

Another very promising DoA measuring method based on EEG signals is the Masimo proprietary Patient State Index (PSi) (see Drover and Ortega (2006), Lobo and Schraag (2011)). Masimo's Next Generation SedLine features an enhanced signal-processing engine, which provides an enhanced PSi calculation. This represents a processed EEG parameter related to the effect of the anesthetic agents. The forehead sensor collects the patient's EEG data from the frontal lobe on both sides of the brain.

2.2. Modelling the effect of propofol

There are various approaches to modelling the effect of propofol described in the literature. For these purposes, several pharmacokinetic and pharmacodynamic models have been developed, e.g. Marsh et al. (1991), Schnider et al. (1998, 1999), Kataria et al. (1994), Scüttler and Ihmsen (2000), Kenny and White (1990) etc. The models of propofol effect typically define the basic structure of the dynamic system, whereas the parameters depend on the individual patient's characteristics, such as weight, height, age, gender etc., as well as the patient's individual sensitivity to propofol and his ability to excrete propofol.

Certain infusion pumps enable target-controlled infusion (TCI), where the pump sets the proper flow of the medication with regard to the model. Various pharmacokinetic models can be employed for this purpose. However, the models often do not react the real dynamics, which also depends on individual sensitivity of the patients to the substance, which is typically not considered. Since TCI procedures are based on open-loop induction, they often can not ensure optimal performance, especially when dealing with a particular patient's considerable discrepancy from the mean-population models.

2.3. DoA control concept

DoA supervision and control seems a suitable problem to tackle using a closed-loop control approach (see Dumnot (2012)). In such a manner, DoA is actively adjusted by changing the propofol inflow and accordingly reducing or increasing the DoA.

It is essential that an anesthesiologist must always be present to supervise and assess the patient's needs. EEG signals and thereof calculated indices (BIS, PSi) are definitely related to the effect of the anesthetic agents, e.g., propofol. However, these indices strictly speaking do not represent DoA in an absolute manner. That said, they are nevertheless a good indicator of DoA and can be effectively used as a controlled variable in a DoA closed-loop control system.

2.4. Real-time signal acquisition

As mentioned, in order to implement a closed-loop control system for DoA, one must be able to acquire the relevant signals online and in real-time, so that the appropriate inflow of the anesthetic agent can be calculated and applied.

Figure 1 shows a screenshot of the Masimo Root with SedLine patient-monitor display with PSi signal.

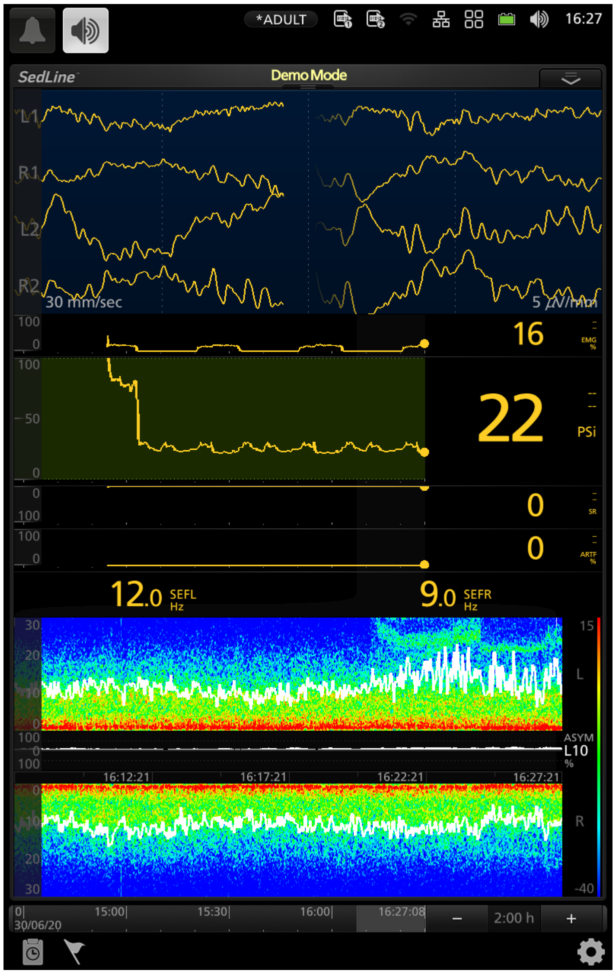

Figure 1. A screenshot of the Masimo Root with SedLine patient-monitor display. The actual PSi signal value is 22 and is shown with a larger number at the right side of the display.

However, the problem with acquiring the relevant signals for DoA assessment has not been satisfactorily solved yet. First, to the best of the author's knowledge, there are currently no medically approved DoA monitors capable of online feeding out a usable signal for further processing in an external computer. On the other hand, many patient monitors provide an option to record the relevant signals during operation. These recordings can later be acquired by connecting the monitor to an external device (computer or data-storage device) and downloading the data. However, there is no option to acquire these signals online, which is a prerequisite for closed-loop control.

The patient monitors are purposely unable to connect to an external (possibly medically unapproved) device, such as a laptop computer. This is primarily due to safety reasons as any interference could compromise the safe operation of the patient monitor and thus also the patient's safety.

Therefore, we need to develop a non-invasive system for signal acquisition from a patient monitor for online depth-of-anesthesia assessment. The system should work non-invasively so that it does not interfere with the medical devices that are routinely used during a diagnostic or surgical procedure. This is an important requirement that must be strictly satisfied so as to enable the use of the developed system in clinical practice without prior approval, which is necessary for medical equipment.

3. Materials and methods

3.1. Signal value acquisition

The developed non-invasive system for signal acquisition from a patient monitor is based on repeated photo acquisition. A camera grabs a photo of the patient-monitor display and analyses it in order to extract the relevant information, namely the treated signal value.

The system operates in Matlab-Simulink environment, which can be conveniently used for DoA modelling, simulation and control.

The basic idea of the system is as follows:

- use a simple USB camera for a regular online acquisition of the image of the patient monitor's display,
- apply optical character recognition for extracting the signal value and
- repeat that task periodically every sample time.

In such a manner, it is possible to acquire online signals in real-time (or with a minimal delay) and therefore use the acquired data in a closed-loop DoA control algorithm or in a real-time DoA simulation.

3.2. Hardware aspects

The signal acquisition system uses a simple webcam to snap images of the patient-monitor display that include the relevant signal value number. The camera is connected to a PC through a USB port. The camera itself does not represent a very critical aspect for the system operation, thus it is not required to use a very sophisticated one. However, the following features are convenient for the practical implementation of the whole system:

- The camera resolution should be high enough so as not to hinder or even prevent optical character recognition. Optical zooming capability can also help in this regard.
- The camera should have the possibility to manually set its aperture, shutter speed and sensor gain. These parameters can be software-adjustable and are important to ensure proper exposure of the images.
- The camera should have the possibility to manually set the focus, either via software or by using a dedicated lens ring. Although autofocusing usually works adequately, it can be problematic as

the patient-monitor (glossy) display can reflect the surroundings. The camera then focuses on the reflected image instead of on the display.
- The camera should have some mounting option such as a standard tripod thread.

The aforementioned features are by no means necessary for the system to work if proper care is taken. However, as the clinical environment can get quite frenzy, it is convenient to use a camera that enables a robust solution so that the resulting system is less prone to errors.

We have implemented several USB cameras, which were available for testing during the development of the signal-acquisition system:

- Logitech HD Webcam C270,
- Logitech HD Pro Webcam C910 and
- Logitech HD Pro Webcam C920.

Due to the reasons mentioned above, we found that the last one (Logitech HD Pro Webcam C920) is the most suitable option. That said, all of the mentioned cameras have been tested and can be successfully implemented in the system. Surely, most of the USB cameras available on the market today should be suitable for implementation.

In a clinical setting, the patient monitor is mostly stationed for the whole duration of the procedure. Therefore, the camera can be mounted on the monitor stand using some sort of arm with a threaded end for mounting the camera. On the other hand, it is also possible to use a simple photographic tripod or another stand, to which the camera can be mounted.

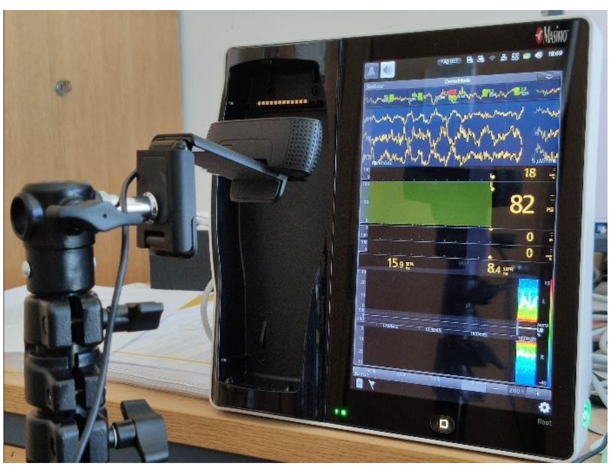

Figure 2. The system in operation.

Figure 2 shows the system with the Logitech HD Pro Webcam C920 mounted on a tripod in operation.

3.3. Software operation

The signal-acquisition system is developed in Matlab-Simulink programming and simulation environment. Therefore, it represents a convenient first step for further developing DoA modelling, simulation and control.

Figure 3 shows the basic Simulink scheme. The S-function block returns the actual PSi signal value and the reading confidence. Both signals can be simply fed into other Simulink blocks if needed.

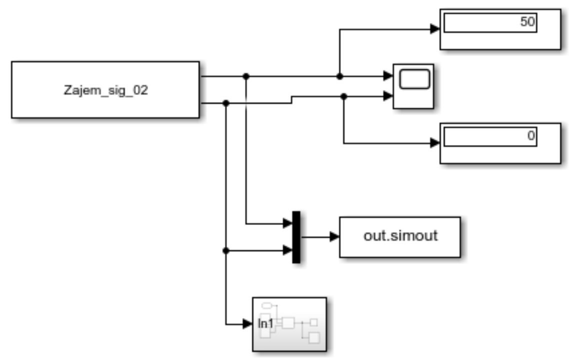

Figure 3. The basic Simulink scheme. The upper line is the acquired signal value, the lower line is the reading confidence. The signals are fed to a Scope block, to two Display blocks and to a ToWorkspace block. The subsystem at the bottom is used for triggering the red warning light.

3.3.1. *Initialization*

The user must first initialize the camera. According to the type of the detected USB camera, the initialization procedure first selects the native camera resolution. Next, the most appropriate aperture, shutter speed and sensor gain for image acquisition depending on the camera model are set.

If the camera has not been positioned properly yet, a preview video can be used in order to facilitate suitable positioning of the camera. Once set, the system should be left in a stationary position.

If possible (camera-model depending), after achieving autofocus, the focusing mode is switched from automatic to manual. During the initialization, the user can further adjust the camera focus if needed.

Next, the user has to select the frame containing the relevant signal-value number. This is a very simple task as the user only needs to indicate the approximate position of the vertices of the rectangular frame containing the signal value, as shown in Figure 4. This is done by clicking four times on a grabbed image. The image is displayed in negative colors to make it easier to see where the user is aiming, as well as to differentiate the image used for a frame-position indication from the regularly grabbed ones.

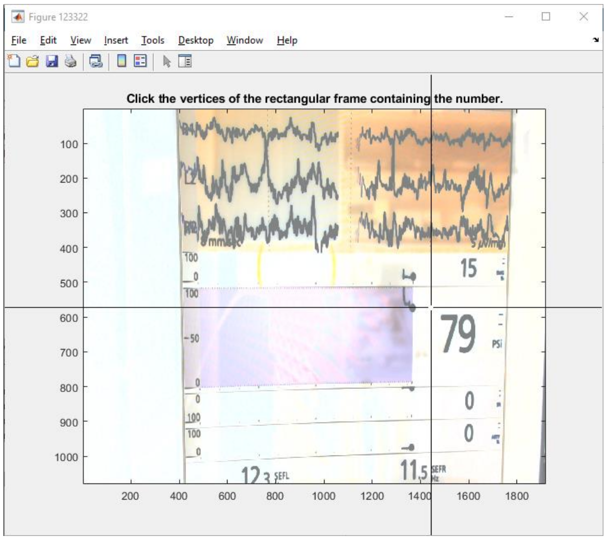

Figure 4. Clicking the vertices of the rectangular frame containing the number.

In case any component is accidentally or purposely displaced during operation, the user must check if a reinitialization is needed. Most often, the camera only needs to be simply repositioned.

3.3.2. *Signal-acquisition system in operation*

Now the system is properly initialized and can be used for signal acquisition. The user can start the process by running the Simulink model.

Every sampling instant the camera grabs an image and an optical character recognition algorithm (see Smith (2007)) is carried out over the predefined-frame-constrained part of the grabbed image.

The optical character recognition result is checked against several criteria. If it fails to meet any of the criteria, the system returns the last correctly recognized signal value instead. Besides, an audio beep is played, a red-light warning lights up and a warning message is displayed. The criteria are the following:

- The reading result is exactly one word. If not, the confidence value is set to 0. A warning message is displayed: »No reading: returning the previous value!«.
- The reading result is a number. If not, the confidence value is set to 0. A warning message is displayed: »Reading = NaN: returning the previous value!«.
- The reading result is a real number. If not, the confidence value is set to 0. A warning message is displayed: »Reading = complex: returning the previous value!«.
- The reading result is a value in the range between 0 and 100. If not, the confidence value is set to 0. A warning message is displayed: »Reading out of range [0,100]: returning the previous value!«.
- The reading confidence is at least 0.7 (70 %). If not, the confidence value is set to the actual reading confidence. A warning message is displayed: »conf < 0.7: returning the previous value!«.

In case the optical character recognition result meets all of the aforementioned criteria, the system returns the actual signal value along with the reading confidence in every sample. The procedure is repeated periodically with the time step specified by the user.

The Simulink scheme includes a convenient dashboard with useful graphical trends, gauges and digital displays for showing the acquired signals. Furthermore, there are also buttons for readjusting focus and resetting the image area during the procedure.

4. Results and discussion

We tested the signal-acquisition system using a patient monitor Masimo Root with SedLine. The goal was to acquire the PSi signal from a simulated patient undergoing a surgical procedure. Therefore, a special demonstration SedLine module was implemented.

As the patient monitor Masimo Root with SedLine refreshes its signal every 1.2 s, the sampling time in our case was set to 1 s. In such a manner, we made sure that none of the displayed values would be skipped.

The PSi signal was faithfully acquired. All the values displayed during the procedure have been accurately recognized and saved by the system. In the case where the camera view was obstructed, e.g., by putting a hand between the camera and the display, the system returned the last correctly recognized signal value, played an audio beep, displayed a red-light warning and the corresponding warning message. If the signal was to be used in a closed-loop control algorithm, such error handling would be the most appropriate solution.

5. Conclusions

The paper presents the development and operation of a non-invasive image-based system for PSi signal acquisition from a patient monitor for online DoA assessment. The system operation has been verified in a simulated setting using a patient monitor with artificially generated EEG signals. The first practically applicable results have been shown.

The presented signal-acquisition system is image-based and therefore manufacturer-independent. It can be used to acquire various signals that are displayed with numerical values on different patient monitors.

Besides, the developed system does not interfere with the medical devices that are routinely used during a diagnostic or surgical procedure. Thus, it does not require prior approval that is otherwise necessary for medical equipment. Therefore, it is ready to be evaluated in an operating theatre so as to prove its usefulness in clinical practice. That said, there is still a long way to go before a proper closed-loop control system for DoA is developed and put into routine clinical operation.

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