Environmental Monitoring System in a Cruise Ship Cabin

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Abstract. Data collected in a cruise ship cabin from a monitoring system can be used for various scenarios, such as the energy waste reduction and the passenger wellness & comfort. Although the reference scenarios are out of the scope of this paper, we concentrate on presenting an effective and efficient monitoring system. In this context, we describe an environmental monitoring system for a closed environment, based on heterogeneous sensor networks, and a minimal invasiveness approach for a robust monitoring of sleep quality, which integrates signals from different types of sensors to estimate physiological parameters.

Keywords. cruise ship cabin, monitoring system, sleep quality, air quality

1. Introduction

In the world of cruises, there are different factors that influence the choice of the ship on which to embark, such as the costs, the luxury of the environments, and the quality of the on-board services. These last factors are directly related to the perception of the overall level of comfort expected from the experience. Comfort is a subjective feeling, perceived by the user in a certain environment and indicates the level of perceived well-being in a given situation, given a set of factors that could influence it. Among all these factors, the most important ones surely concern vibrations and noise, which are always taken into consideration in the design phases of the ship. Other factors are considered critical to ensure the comfort of the passenger, such as the thermo-hygrometric comfort, the quality of the lighting and of the air, and the quality of the sleeping phase, while other aspects are of interest for the owner of a cruise ship, such as the reduction in energy waste. A non-invasive monitoring system in the cabin can help both in improving the passenger comfort feeling and satisfying the ship owner requirements. A monitoring system is the set of technologies that deal with automation, integration of electronic devices, and communication & control systems [1]. The data collected can be used to:

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- Increase in passenger comfort level: applications can make the living space more welcoming, making easier and automatic to manage it;
- Monitor the passenger wellness: if the passenger agrees by wearing some very simple tools;
- Achieve an adequate level of safety: the systems developed must guarantee the safety of the user when facing emergency situations (for example, anti-intrusion techniques, detection of fires, gas leaks, etc.);
- Achieve energy savings: a more accurate and efficient management of the energy consumption is achievable. This aspect is certainly of interest for the ship owner as it allows reducing the energy waste.

This paper presents the monitoring system designed for a cruise ship cabin, based on heterogeneous sensors capable to monitor different quantities related to sleep assessment, quality of the air, environmental noise level, temperature, humidity, light intensity, and energy consumption. The paper is not aimed at presenting the possible scenarios where the collected data can be used to improve the passenger comfort, or the passenger wellness or the energy waste reduction, but it only presents the monitoring system by itself. At the current time the system performance evaluation is ongoing, with a series of tests in the test-cabin installed at the University of Trieste.

2. The Environmental Monitoring System

The environmental monitoring system (EMS) is constituted by a platform that integrates sensors and technologies of different nature. EMS uses different wireless communication systems, such as: a) ZigBee, which is a communication protocol largely used in industrial environment as it supports several network topologies; b) Z-wave, the emerging technology for the domotic environments as it is poorly affected by propagation interference; c) 6LowPAN, the emerging standard for the internet of things (IoT). The three technologies are then integrated by means of a middleware application. The sensors are composed by noise, presence, humidity, temperature, energy consumption and light intensity transducers, actuators, magnetic sensors, air quality, and sleep quality assessment, which communicate their data to the monitoring server.

2.1. The sleep quality monitoring system

We use a minimal invasiveness approach, which integrates signals from different types of sensors to estimate physiological parameters correlated to the sleep stages (light sleep, deep sleep, REM sleep and wakefulness). The proposed system (Figure 1) is made of a strip force sensor put under the bed sheets (Beddit [2]), two ballistocardiographic sensors (Murata SCA11H [3]) put on one side of the mattress and on the bed frame, respectively, and a wrist smartwatch (Samsung GearFit2 Pro [4]). We do not use the processed information on sleep given by the devices, but

[2] http://www.beddit.com/
[3] https://www.murata.com/products/sensor/accel/sca10h_11h/sca11h
[4] http://www.samsung.com/it/wearables/gear-fit-2-pro-r365-small

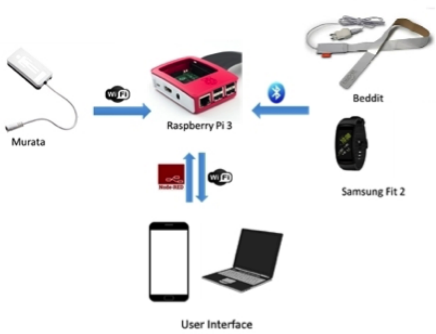

Figure 1. Architecture of the sleep monitoring system

their raw data only; in particular, the accelerometer data are streamed over WiFi by Murata, the photoplethysmographic signal from GearFit2 and the force signal from Beddit are both streamed over Bluetooth Low Energy (BLE). The data collector for acquisition and processing is a Raspberry Pi3, which manages Wi-Fi and BLE connections with other devices. In order to protect data privacy and security, connections are all locally managed and data are encrypted according to AES CBC 256 bit standard [5]. The sleep quality assessment is performed in two phases; first, physiological parameters showing good correlation with the different phases of sleep [2] are estimated from the raw signals provided by the sensors; these parameters are heart rate (HR), heart rate variability (HRV), respiration rate (RR), respiratory rate variability (RRV), respiratory depth (RDepth), and amount of movements (MQ). In the second phase, the levels of the time-varying parameters have been categorized by experimentally defined thresholds, from the lowest to the highest (low, decreased, medium, increased, and high) and associated to the corresponding sleep phases (light sleep, deep sleep, REM sleep and wakefulness), as shown in Table 1. The parameter thresholds and the correlation of the categorized values with the sleep stages have been estimated in a lab environment by means of an experimental campaign based on standard polysomnographic recordings, where sleeping subjects were assessed at the same time by the monitoring system and by expert personnel (details in [3]). The classification of the sleep periods into sleep phases allows to build a simplified hypnogram [4], which is then used to evaluate the sleep quality by the standard parameters of polysomnography: the initial latency to sleep, the number of awakenings, the total duration of sleep and the efficiency of sleep (relationship between duration of sleep over time spent in bed). The variations in these parameters with respect to the subject-specific standard values are indicative of the user sleep quality and stress.

2.2. The air quality monitoring system

The air-quality sensor platform consists of a microcontroller that acquires and processes the signals of two sensors, which measure temperature, humidity, and

[5] https://tools.ietf.org/html/rfc3394

Table 1. Correlation between physiological parameters and sleep phases

	Light sleep	Deep sleep	REM sleep	Wakefulness
HR	decreased	decreased	increased	increased
HRV	medium	decreased	increased	high
RR	medium	medium	increased	increased
RRV	medium	low	increased	high
RDepth	medium	decreased	decreased	increased
MQ	medium	medium	decreased	high

VOCs (volatile organic compounds) concentration in the cabin air. The microcontroller is the STM32LO73RZ [6] produced by STMicroelectronics for ultra-low power applications. The microcontroller includes the Arm©Cortex©-M0+ 32-bit RISC core operating at a 32 MHz frequency, high-speed embedded memories (192 Kbytes of Flash program memory, 6 Kbytes of data EEPROM and 20 Kbytes of RAM) and an extensive range of enhanced I/Os and peripherals. The STM32LO73RZ also integrates standard and advanced communication interfaces: three I2Cs, two SPIs, one I2S, four USARTs, a low-power UART (LPUART), and a crystal-less USB. The temperature and relative humidity are measured by the ENS210 [7] sensor produced by the AMS. The device integrates one high-accuracy temperature sensor and one relative humidity sensor, and it includes an I^2C slave interface for communication with a master processor. The VOCs concentration is measured by the iAQ-Core sensor module [8] produced by the AMS. The device provides the prediction of the relative equivalents of CO2 and Total VOCs (TVOC) via the I^2C bus. The device can be used in continuous mode and in pulsed mode. In the continuous mode, with a measurement interval of 1 s, the device has a power consumption of 66 mW that decreases to only 9 mW in pulsed mode, with a measurement interval of 11 s.

2.3. The environmental noise monitoring and spectral characterization

The proposed system aims at monitoring the ambient noise level in the passenger cabin 24 hours a day and characterizing its spectral content to detect which frequency bands have the maximum impact during the day. The system also compares the measured level of the noise with ISO (International Standard Organization) Noise Rating curves [9] to determine the equivalent level of noisiness. The system comprises a small-sized omni-directional condenser microphone with high sensitivity to low level sounds, a dedicated and low input noise A/D sound card to perform analog-to-digital conversion (16 bit, 44100 Hz sampling rate, $20--20000$ Hz bandwidth) of the analog sound signal acquired by the microphone, and a dedicated microprocessor to process the digitalized version of the sound, analyze its spectral content, calculate the noisiness level, store and transmit the calculated

[6] Technical Brochure of the STM32LO73RZ microcontroller, www.st.com

[7] Technical Brochure of the ENS210 Relative Humidity and Temperature Sensor, www.ams.com

[8] Technical Brochure of the iAQ-core C Indoor air quality module, www.ams.com

[9] ISO 1996-1:2016. Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures

data to a central data repository. The spectral content of the ambient noise measured by the system is obtained in nine acoustic octave bands, from 31.5 to 8000 Hz. The ambient sound is acquired each minute in time frames of 30 s, during the 24 hours of a day. For each acquisition frame, the system calculates $NRcalc_{max}$, i.e., the equivalent noise rating level of the measured sound and determines the first three octave bands $NRcalc_i (i = 1, , 3)$ with the highest noisiness. Finally, for each acquisition frame, the system calculates the equivalent level of noise LAeq using a digital A-weighting filter [10].

2.4. Other sensors, virtual sensors and actuators

Sensors and actuators are deployed over the network and communicate with the infrastructure through the sensor gateway, which sends messages to the monitoring infrastructure through an MQTT Broker (Mosquitto), using a predefined event type. The sensor nodes considered in the proposed infrastructure are based on the module Core2530, produced by WaveShare Electronics[11]. They are connected to a ZigBee [12] node, which is able to: i) evaluate the real power consumption of the target environment; ii) identify all the indoor user movements through PIR-based motion sensors; iii) detect environmental noise; iv) measure temperature and relative humidity. Each node is configured as a ZigBee router to exploit multihop functionality and, periodically, it sends the measured data to the ZigBee coordinator. The ZigBee network ensures reliable communications in indoor environment, which, contrarily to the outdoor environment, is affected by multipath effects [5]. We exploit the Z-wave technology in order to monitor presence, luminance, and temperature inside the cabin, and magnetic contact sensors have been installed on the two cabin doors in order to monitor their status. Finally, a smart switch has been installed, which allows control over whatever is plugged into it and reports the power consumption. All the values measured in a specific cabin help in deciding whether or not someone is in, in order to apply, for instance, specific decisions on the energy saving functions and settings. With the term occupancy, we refer to the possibility of determining whether or not a person along with a time interval occupies a cabin. We determine the occupancy by means of a fusion strategy inspired by the stigmergy concept [6]. This approach compares the value sampled by a sensor to the intensity of a pheromone; similarly to the decay of an ant pheromone released when it finds some food, the value of a sensor changes along the time and it decays as the time progresses. The room occupancy is determined by observing the output of the motion, noise, and power supply sensors [7]. Finally, some actuators have been installed to control the status of certain devices. In particular, a smart switch, which allows controlling whatever is plugged into it, has been installed, together with the Philips hue lighting system.

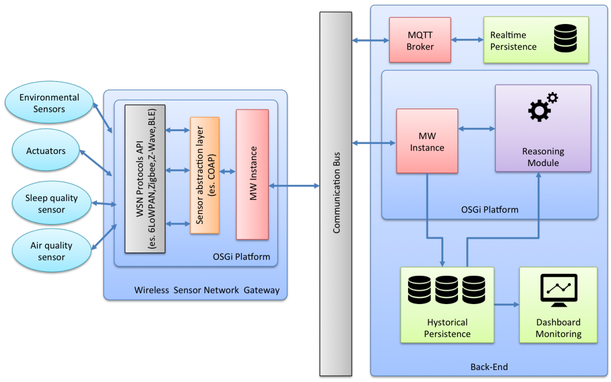

Figure 2. The middleware architecture.

3. Communication platform

The main goal of the middleware is to provide a secure communication platform for exchanging sensing information in a distributed sensor network environment [6]. It also provides tools and applications that enable long-term sensor monitoring and allows an automatic control over the actuators deployed in the WSN. The middleware uses ZB4O [13] to interact with sensors and actuators deployed in the ZigBee network and integrates the Z-wave technologies in order to work regardless of the underlaying different kinds of technologies. The gateway node provides access to the sensors discovered through an IP network and a communication platform. In order to separate the middleware communication concerns, we designed several communication buses (Figure 2), having each bus a specific managing role: (i) a Service Bus for service life-cycle events; (ii) a Context Bus for sensor measurement updates; (iii) a Control Bus for invocations of actuators. We implemented this communication platform on top of the OSGi platform and we use the MQTT messaging service [7].

4. Preliminary Laboratory results

Preliminary experimental tests were performed in a lab environment simulating a real dimension passenger cabin equipped with real furniture (bed, wardrobe, writing desk, curtains, etc) with the goal of verifying each single device performance before integrating all devices into the final prototype.

4.1. Sleep quality monitoring results

The experiments on the feasibility of our on-board sleep quality monitoring have been undertaken with awake subjects because we did not yet have the ethics com-

[10] IEC 61672-1:2002 Electroacoustics Sound level meters: Part 1: Specifications
[11] http://www.wvshare.com/
[12] http://www.zigbee.org/
[13] http://zb4osgi.aaloa.org/

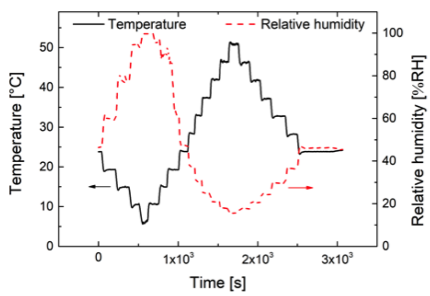

Figure 3. Preliminary test of the ENS210 device placed over a temperature controlled plate.

mittee approval for testing on sleeping persons. The goal was to establish if the monitoring system performance suffers from the vibrating environment. In order to simulate real navigation conditions, the system was assembled on a bed lying on a floor platform mounted on a mechanical shaker and shaken in a frequency bandwidth within the 2-100Hz range, at an amplitude level comparable to that of a real cabin environment. We note that the vibrations are almost imperceptible to the subject but they have an impact on the monitoring system. While in *shaker-off* state the system performance correctly identifies physiological parameters and subject wakefulness, in *shaker-on* state the assessment of physiological parameters and sleep status was quite inaccurate, mainly due to the high sensitivity to vibration of the Murata devices. The Beddit device and the smartwatch did not suffer too much from the vibrations. Based on this preliminary experiment, some indications can be given: accelerometer devices should be avoided, or used to measure vibrations and to compensate for them; a cabin bed should be designed to reduce vibration transmission, not only to make the monitoring system more robust but also to increase the passenger comfort.

4.2. Air quality monitoring results

The ENS210 device has been tested placing it on a copper plate thermally coupled to a Peltier cell driven by an electronic controller; two temperature cycles have been applied to the copper plate. In the first cycle, the plate temperature has been decreased from the room value to 5 °C and, successively, it has been increased to return to the initial conditions. In the second cycle, the plate temperature has been increased from the room value to 50 °C and then it has been decreased to return to the initial conditions. The temperature and relative humidity values measured by the ENS210 have been acquired with a sampling interval of 1 s. It can be observed that both sensors are capable of detecting variations in the environmental conditions with an accuracy suitable for the intended application (Fig. 3).

4.3. Ambient noise results

Ambient noise measurements were performed at two acquisition points: one corresponding to the position of the bed, to capture the ambient sound perceived by a passenger lying down into the bed, the other at the reading-corner of the cabin, to measure the noise level perceived by the passenger when sitting at the reading-desk. For both acquisition points, the test consisted first in the characterization of the system response to pure tones within the octave band ranging from 1000 to 8000 Hz and then the acquisition and measurement of the ambient noises, such as those produced by air conditioning appliance, vibrations generated by the boat engines and machinery during navigation, and leisure activities performed inside or outside the cabin. Pre-recorded noise samples were played into the cabin by using a pair of sound woofers positioned at the two corners of the wall in front of the bed. The system acquired the played noise samples in a reliable manner, with less distortion. The spectral characteristics of the noise measured at the two acquisition positions were almost identical, while a change of nearly 10 dB was observed in the LAeq level (with the acquisition point at the bed, being the louder between the two).

5. Conclusions and future work

This paper presented a complex and heterogeneous environmental monitoring system designed for a cruise ship cabin, which allows an estimation of the physiological parameters correlated to the sleep stages (light sleep, deep sleep, REM sleep and wakefulness), the incidence of the ambient noise on the quality of sleep, the air quality, the energy consumption in the cabin, as well as temperature, humidity and light intensity. Tests on the comfort perceived by a group of persons are in progress and will be finished within October 2018.

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