Project Abstract:

All recent reviews of the epidemiology of sleep-disordered breathing have shown that obstructive sleep apnea syndrome is a common condition affecting (by conservative estimates) about 2% of the female adult population and 4% of the adult male population. At present to diagnose the patient's sleeping apnea, he should go to hospital or rent an expensive complicated device. The examination is carried out while patient sleeping, and to get real result is required that patient must feel free and relaxed. But the most of devices doesn't give that possibility, and that examination are uncomfortable. The technologies that were used to conduct such measurements evolve from year to year, as a result there are produce better and better systems that give us unprecedented until today opportunities.

This project that used newest technologies, will be the most patient-friendly and also provide a comprehensive set of sensors that may be use to diagnose the patient in many ways.
1. INTRODUCTION

- **Obstructive Sleep Apnea Syndrome (OSAS)**
  OSAS is a disease in which during sleep occur, which are called apneas. During apnea there is a lack of air flow through the respiratory tract. Direct cause of interruption in breathing is the collapse of the soft parts within the throat, above all, the collapse of the soft palate and tongue withdrawal into the throat. This leads to a complete airway obstruction.

  The causes of such disorders can be:
  - anatomical abnormalities of the throat and/or nose, such as curvature of the nasal septum, enlarged tonsils and tongue. An important factor is obesity, as a result, the fat is deposited around the throat and neck
  - disorders of the nervous regulation of muscle forming the throat. Nerve malfunction leads to reduce muscle tension of tongue, soft palate and throat.

  Effects of sleep apnea:
  Sleep apnea causes disorder of the respiratory system through lack of air exchange in the lungs. Due to the lack of breath, oxygenation of the blood significantly decreases, which in turn causes hypoxia of all bodies, including the most sensitive to lack of oxygen - brain, heart or kidneys. In addition to reducing the level of oxygenation break respiratory cause blood pressure rising (systolic blood pressure may be up to 200mmHg), this leads to cardiac arrhythmias. Apnea ends awake for a few seconds. muscle tone during waking increases, the airways open up, the patient takes a few breaths and go to sleep again, and have another sleep apnea. Awakenings have a defensive function against suffocation, but they also cause disturbance of sleep, which does not allow adequate rest.

- **Holter Examination**
  Holter examination is used to probe many biomedical human signals for long time. So we create low power consumption device allowing 5 days of data collection from patient. Other features of our sleep apnea monitor are small size and portability. Despite of that it can receive as much data as stationary device.

- **Distributed Embedded Architecture:**
  There are two possible ways to implement multitask embedded system: use large fast central unit that have software implemented multitasking system, or hardware solution - split system into smaller independent parts. We always prefer hardware solution so we adhibit distributed architecture. This way have a lot of advantages like a higher reliability cause of modules independence, faster processing, and possibly wide area to implement advanced power saving management. Distributed architecture consisted of connection each analog track to ultra low power microcontroller MSP430G2553 which task is smart initial signal processing and if necessary such operations like adjustment of signal gain, AGC, prediction based on analog signal (event happen or not). By this actions main processor receives
digital signals, that can be further digitally processed and/or saved in external memory (in our device we use SD Card). Doing so saved the effective CPU time and create possibility for better DSP or longer power saving mode.

By the architecture we create two independent layers: intelligent - collecting data, and data processing/saving. The layers can communicate with each other by Philips synchronous two wire I2C interface. Due that this device can be easy extended by creation new modules that can have a high level of complexity and connection it to main data bus.

![Figure 1: Architecture block diagram](image)

2. MOTIVATION FOR PROJECT

We are students of Faculty of Mechatronics Warsaw University of Technology. We are specialized in biomedical engineering. Our diploma projects are related to the ECG, pulse oximetry and breath control. Combination of our knowledge and interests in analog electronics and embedded systems, we decided to create a device that can help diagnose sleep apnea. We are all interested in digital signal processing, connecting our passion with the knowledge and skills earned in college. The main reason for building a holter is that nowadays the role of portable medical devices is increasing.

3. THEORETICAL BACKGROUND

- **ECG** is used to measure electrical activity of heart during some period of time. The measurement of time intervals and signal amplitude allows detection of heart diseases and abnormalities. In our case we can observe heart reactions to apnea, course of heartbeats by all night and heart respond for long respiratory arrest. We use 4 electrodes (RA, LA, LL, RL - driver) to receive 3 Einthoven’s leads. Electrodes are placed on chest, RA at right collarbone, LA at opposite position, LL electrode at middle of chest, moved few centimeters to left body side and RL – driver electrode is placed near right hip.

- **Pulse oximetry** determines changes in blood oxygen levels that often occur with sleep apnea and other respiratory problems. Pulse Oximeter is an electronic device used for non-invasive measurement of blood oxygen.
saturation. It measures radiation absorption of two different wavelengths (red and infrared light) by red blood cells in the capillaries. For measuring we use sensor built of two LEDs, using wavelengths of 660nm (R) and 940nm (IR), and a photodiode. The sensor is placed on the earlobe. Based on measurements we calculate the degree of hemoglobin oxygen saturation (SpO2). The correct level of oxygen saturation ranges from 95 to 99%. Saturation during sleep apnea is reduced by around 40-50%.

- **Breath control** is very important in the diagnosis of sleep apnea. Episodes of not breathing may occur as rare as 5 times an hour up to more than 50 times an hour, depending on the severity of apnea. Every episode takes at least 10 seconds. Sleep apnea is connected with loud snoring. Almost all people who have sleep apnea snore. But not all people who snore have sleep apnea. To record the episodes of apnea we may study the temperature in the vicinity of the nose and mouth and airflow pressure. The detection is based on the difference in temperature between exhausted and inhaled air. The difference between temperature values ranges from 10 degrees to higher. To note that the patient is not breathing, we can also observe his chest by using the belt with strain gauge.

4. IMPLEMENTATION

- **Mother board architecture**

![Figure 2: Schematics of the mother board](image-url)
The Mother Board consists of a several parts with different functions. The central unit is the low power consumption processor STM32L151C8 based on ARM Cortex-M3 architecture. We were trying to use DSP Piccolo TMS320F2802 processor but because of practical (low chip and development tools availability in Poland) and financial reasons, we were unable to use it, and finally we decided to use low power consumption ARM that are very common in Poland - STM32L1xx. As a result we obtained very energy-efficient system. Keeping in mind patient safety (we excluded possibility to connect device to external power source) the IO interfaces for data is SD Card at which results of medical examination are saved in *.edf data format (European Data Format). On-board external flash memory enables processor to boot/read external program or release more space for digital signal processing.

Next functional block on the mother board is power management which main functional part is synchronous boost converter TPS61025. This component has great potential and it seems to be one of the most advanced solutions on the market. The only drawback for hobbyists is relatively difficult soldering on which depends efficiency of entire system. TPS61025 also enables programming of output voltage and threshold voltage. When input voltage falls below programmed value, chip indicates this event by setting low state on LBI line, thus central unit is informed in case of low battery. It is additional benefit because reliefs the designer from the obligation to create extra systems to control the battery condition. In case of unexpected battery discharge, additional battery is installed on board. It can be used to maintain processor memory and register activity until system saves all data and can be safely turned off.

- **ECG board**

To get ECG signal we used 3-lead Einthoven method. The intensity of the signal from cardiac muscles ranges from 1mV to 10mV (QRS wide). It is necessary to amplify this signal in the analog front-end. At each electrode are transient-voltage-suppression (TVS) diodes to protect from ESD and 100k resistor to protect against over-current. Signals after passing first amplifier are double multiplexed to differential amplifier INA333. There are settings on MUX – for I, II, III lead. Right leg driver goes out from INA, compensates cables shield noise and is connected to electrode RL on
patient body. Differential signal from INA333 is filtered by high pass 0.5Hz, again amplified and next filtered by low pass 40Hz active filter. The last step of analog signal is regulated gain amplifier (AGC) with digital potentiometer. Then signal is converted to digital by MSP430G2553 hardware ADC.

- **Pulse oximetry board**

After passing NOR gates modulated PWM signal causes switching IR and R LEDs. It triggers change in intensity of light passing through earlobe and shedding light on PIN photodiode. Conducted current on photodiode is converted into voltage by transimpedance amplifier OPA380. Next signal is separated (sample and hold amp LF398) to probe each part – from R and IR led – apart. Both channels have low pass active 6Hz filter implemented. In next section, capacitor cuts off DC part of signal. Last element of circuit is AGC. Strength of IR and Red light is regulated by added DAC (TLV5625).

![Figure 4: Schematics of the pulse oximetry board](image)

- **Air flow board**

**Temperature sensor**

To measure the temperature we use three thermistors with short time of reaction (less than 1s). The thermistors are type of NTC. They have 100 kΩ resistance in 25°C. The thermistors are placed on the nasal cannula near the nostrils and mouth. The parallel connection between thermo-active elements is applied to read the average temperature from nose and mouth.

INA330 is a precision amplifier designed for thermistor based temperature controllers. On the output we provide the passive low-pass filter with the frequency limit of \( f_g = 8 \) Hz. The data is stored by microprocessor with frequency 20Hz. Having
the supply voltage on the level of 3.6V and the $V_{\text{adj}} = 1.8V$ we get the 300mV peak to peak value of studied signal. The signal to noise ratio is about 30dB. The curves are obtained with very high accuracy to determine the various stages of breath.

**Pressure sensor**

The sensor for pressure detection was produced by Honeywell. It is a differential pressure detection circuit based on Wheatstone bridge. It runs from -1 psi to 1 psi. Pressure curve of the voltage is linear. It works with 13 mV/V resolution. For processing the output data from the sensor we use the ADS1232. It is a precision 24-bit analog-to-digital converter providing a complete front-end solution for bridge sensors. It supports the low-noise programmable gain amplifier, delta-sigma ADC and internal oscillator. The programming gain is set to 128 and the sampling speed to 10SPS. The system works on internal oscillator and communicates with microcontroller by SPI.

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**Breath board**

**Snoring Sensor**

To detect snoring we use electret microphone. We chose this type of microphone because of its small size and because it provides the best measurement results. For processing of the output data from the sensor we use low voltage microphone preamplifier SSM2167. It contains automatic gain control. Data output from amplifier are filtered and transmitted to ADC of the microcontroller.

**Chest movement sensor**

We can collect data of the breath, watching the movements of the chest. For this examination our team have designed a special belt with strain gauge beam. Inhalation results in stretching the belt which leads to changes in the dimensions of strain gauge. We create a graph of breath from the obtained data. We again use the ADS1232 to process the data. The sampling speed is set to 10SPS and the programming is 128. To communicate with MSP430 we use SPI.
We chose ADS1232 as an analog-to-digital converters because they are the best converters for bridge sensors on the market. They give the best results and their parameters are best suited for our application.

**Power management**

As previously described, main silicon chip which provides power supply is TPS61025, it was adjusted to provide 3.6V on output. Reference 1.8V voltage, additionally placed on board, is necessary because most of analog amplifier circuit have symmetrical supply. I2C bus speed is 100kb/s and data size from sensors is about 50kb/s, thus central unit has a time reserve (not including benefits like DMA channels) to go in low power mode, that really reduces the amount of consumed energy. The same is in case of MSP430G2553 processors. Depending on the sensor type, microcontroller is periodically woken up from LPM by interruptions from the ADC to prepare the measurement and send resulting data to motherboard by I2C.

We have made power consumption tests for whole device in the following configuration: main processor in normal mode (clock: 4MHz and PLL x4), MSP430 in active mode - and total energy consumption by device was about 12mA. Using the battery cell of Nokia BP-4L (1500mA/h) results in more than 100h of work. Additionally tests were conducted with all processors in low power mode (MSP430 - 0.5uA/MHz, STM32 - 4.4uA/MHz) and turned off ICs that have disable option, the result were about 3mA. That effect is caused by ECG and pulse oximetry modules (they have large analog circuits) we estimate that over 99% of this energy were consumed by these modules.

![Schematics of the breath board](image)
• Sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG electrodes</td>
<td>detection of the small electrical changes on the skin that are caused by heart muscle depolarization, we use disposable electrodes</td>
</tr>
<tr>
<td>Photodiode PIN</td>
<td>range of light length detection: 400 nm to 1100 nm, the diode conducts current proportional to light intensity and length (in our device 660nm red light, and 940nm IR values)</td>
</tr>
<tr>
<td>Thermistors</td>
<td>very fast reaction for exhaled air temperature change, variable resistance value is compare with constant $R_{\text{set}}$ resistance, rated output: $1.0 \pm 0.15\text{mV/V}$</td>
</tr>
<tr>
<td>Strain gauge bridge</td>
<td>proportional to chest moves area of the gauge narrows (tension) - resistance increases or thickens (compression) – resistance decreases</td>
</tr>
<tr>
<td>Electret microphone</td>
<td>provides high precision of human snore record; supply 3.6V; two leads</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>the sensor measures difference between atmospheric pressure and pressure of exhaled air; extremely low power consumption pressure sensor (NSC series) from Honeywell</td>
</tr>
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</table>

5. EXPERIMENTAL RESULTS

Image 2: Patient during medical examination

Figure 7: Examination results
On the figure 7 are shown the four most important signals from apnea detection: ECG, oxygen saturation, chest movement and temperature changes. Shapes of received biomedical signal plots are in accordance with expectations. Analog circuit fulfills its function. Visible noises are negligible.

Our tests showed that automatic gain control gives better results in hardware implementation than in software calculations.

6. CONCLUSION & SUMMARY

We successfully built ultra low power consumption medical device, which correctly records biomedical signals. We can use whole system not only to detect sleep apnea but also as a separate holters that can be adjusted to patients needs. In our configuration temperature and pressure signals carry similar information, therefore one of them is not necessary - using both parameters increases reliability of device.

Image 3: All works!

All filters and amplifiers in analog circuits were designed and calculate manually. We did not make computer simulations. We have tested each configuration on many real circuits and in this way we chose the best silicon in an accessible price range for us.

Analog Design Contest was a great opportunity for us to test our knowledge and develop practical skills. Everyone had a chance to work on his favorite field of electronics: analog processing, DSP, microcontroller programming, design electronic devices. We worked in young and dynamic team which has taught us teamwork and responsibility for the whole project.

7. FUTURE PLANS

In the next revision of our devices we plan to add:
- the small LCD screen to check the accuracy of the collected data;
- accelerometer sensors on legs to detect restless legs syndrome;
- RF communication rather than I2C and cables (our architecture allows such a solution, MSP430 will work on a separate battery and transmit data wireless)

The next step that we need to do is to conduct research on a broader group of patients who are diagnosed with sleep apnea or who are suspected of the disease. So far we did tests on ourselves and we didn’t detect sleep apnea symptoms. We are in contact with the Medical University of Warsaw negotiating permission to test on bigger group of patients.