Monitoring Vital Signs of buried avalanche victims

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***Abstract* – Ski touring and backcountry skiing are trending sports and become more and more popular every year with a major consequence for the mountain rescue teams. The motivation for this topic is to make ski touring safer and to provide the rescue chain with information about the condition of buried victims. This paper reviews consideration of vital signs acquired by wearable health devices: first a discussion about the data mining and the parameter and diseases is presented and then existing approaches for wearable health monitoring systems are discussed. The developed system of this study consists of heartbeat module, a CO_2 module, a digital pressure sensor and an MPU-6050 module connected to an NodeMCU ESP8266 microcontroller. The system gives information of heart rate, altitude, air pressure, temperature, CO_2 content and the angular velocity. The potential integration into the rescue chain in case of an avalanche accident and the resulting benefits are presented. The influencing factors for avalanche rescues and an implementation in the avalanche management algorithm is proposed.**

Keywords - winter sports, safety equipment, wearable health devices, vital signs, avalanche backpacks

I. Introduction

Ski touring in open terrain has been experiencing a noticeable boom in the last decade. The first turns in the untracked slope, peaks with endless views, gathering impressions in the lonely nature or the sporting challenge. Some of the countless reasons that bring people to this sport. Hardly any other sport in Austria has had such a positive upward trend in recent years and established itself as such a popular sport. The more versatile can also be the sports equipment. This includes tours with touring skis, split board, snowshoes or telemark skis. With the performance of the sport in the alpine terrain, potentially life-threatening situation may be faced. The most severe risks include avalanches, crevasse falls, snow cornice breaks, danger of falling on hard icy snow surfaces and sudden weather changes. The biggest hazards in ski touring are avalanches. Although the changes of surviving an avalanche were increased in the last decades by protective gear such as avalanche airbags, suffocation is apart from trauma still the major reason for death. In the winter season 2020/21, 14 people died in avalanche accidents in Austria. During the same period, 199 avalanche accidents (fatalities, injuries, uninjured) occurred in Austria.[1] This shows the dangers of the trend sport and the associated consequences for the mountain rescue teams. The motivation for this topic is to make ski touring safer and increase the chances of surviving in an avalanche. There's still some protection gear at the market, like the AvaLung or avalanche backpacks, but these systems require that the skier actively uses them. This paper deals with the topic of measuring and monitoring vital signs of buried avalanche victims. A system for recording and monitoring vital signs should be developed in this approach. The possibilities of vital signs monitoring and the methods and systems of existing approaches are presented. The Methods chapter contains the performed steps, system tests and measurements of the prototype system. The discussion evaluates how such a system can potentially be integrated with existing gear such as avalanche airbags or other avalanche safety equipment and how the system data can potentially used from rescue forces.

II. Wearable Health devices

A. Data Mining

Wearable health devices (WHD) are part of personal health systems and can be used during daily life (sport activities, at work, etc.) or in clinical environments without interference with normal human activities. These devices should raise people interest about their health status, improving the quality of care and making use of new technology capabilities.[2] In the study by Banaee et al. [3], they described three predominant types of data mining tasks. The prediction, anomaly detection which may include the subtask of raising alarms and diagnosis. In the study by Dias et al. [2] they additionally added the category activity to the data mining tasks. In the active area all WHD from the main area activity monitoring where fitness and non-medical applications, self-monitoring and rehabilitation procedures are included. The second main area of WHD is the medical area and can be divides into the three main subcategories prediction, anomaly detection and diagnosis support.[2], [3]

B. Parameters and Diseases

Figure 1 lists an excerpt of the vital signs that can be monitored by WHD. The figure is divided into the vital functions, the corresponding type of sensor and the source from which the signal can be tapped on the human body.

Type of vital signals	Type of sensor	Signal source
Electromyogram (EMG)	Skin electrodes	Electrical activity of a muscle
Electroencephalogram (EEG)	Scalp-placed electrodes	Electrical activity of brain, Brain potentials
Activity, mobility, fall	Accelerometer	Gesture posture/limb movements
Respiration rate	Piezoelectric/ piezoresistive sensor	Inspiration and expiration per unit time
Heart sounds	Phonograph	Record of heart sounds, with a microphone
Blood glucose	Glucose meter	Assessment of the amount of glucose in blood
Oxygen saturation	Pulse oximeter	Oxy-hemoglobin in blood
Body or skin temperature	Temperature probe or skin patch	Body or skin
Galvanic skin response	Woven metal electrodes	Skin electrical conductivity

Figure 1 List of vital parameters assessed using WHD.[4]

It can be seen how many different parameters the WHD can be used for and how many application areas result from this. The wide range of applications also opens up a number of diseases, handicaps and disabilities that can be monitored by WHD. By analysing changes in ECG pattern, the cardiovascular diseases can be diagnosed. Patients suffering respiratory diseases like dyspnea, chronic obstructive pulmonary disease or asthma can be monitored for an early detection of symptoms.[4] The method of capnography can be used to make an early diagnosis of sleep apnea syndrome.[2] Patients suffering from diabetes can benefit from the WHD through continuous monitoring of their blood glucose concentration to maintain the right quantity of insulin to prevent the complication of hypoglycaemia.[4] Ambulatory blood pressure monitoring can obtain blood pressure readings several times a day, which is ideal for monitoring hypertension and improving cardiovascular diseases prediction.[2] In addition to the numerous other applications in the medical field, WHD can also be used in sports sciences. By evaluating physiological signs and body kinematics during training performance, conclusions can be made about an athlete's training and progress.

C. *Existing approaches*

The Electrocardiogram (ECG) waveform provides information about the cardiac electrical cycle of the heart and is the most commonly used biosignal and effective diagnostic tool that helps physicians identify heart-related problems. The conventional clinical ECG systems are composed of 12 or 15 electrodes, which are attached to specific parts of the chest, arms, hands and legs.[5] The wearable cardiovascular monitoring systems require a wearable and portable system that monitor the patient's data without affecting the daily activities. Andreoni et al. [6] designed and build a custom t-shirt and textile belt, the SMARTA wearable system, with embedded textile electrodes for monitoring ECG, HR and R-R interval. The three electrodes used are made of silver-based conductive yarns and embedded in the t-shirt. Conductive paste is not needed when using the SMARTA system compared to clinical use. The wearing time of the t-shirt helps to improve the signal quality. This is because sweat helps to moisten the sensor, which further improves electrical conductivity and also reduces motion artifacts. The SMARTA system also included a SpO2 sensor and a three-axis accelerometer for fall detection and it could transmit the data over low-power Bluetooth 4.0.[6] Tseng et al. [7] introduces a fabric elastic ECG vest that consists of three electrodes and a data acquisition module, and also provides robust contact of the electrodes with the skin. The electrodes used in this system were fabricated from NI/Cu coated compressed urethane polymer foam that was enclosed by an Au-coated conductive taffeta fabric. Even measurements on real subjects were not shown, the ECG measured with the system exhibited high correlation with the simulated signal. The electrode motion noise was also reduced due to the conductive and flexible nature of the substrate, which kept the impedance of the skin electrode low and stable over a longer period of time.[8] A mobile phone is used as the system platform for monitoring the ECG signal. The MIDlet program for ECG monitoring on the mobile phone platform was developed using Borland JBuilder2005 in conjunction with the Wireless Development Kit 2.2.[7] Piezoelectric pressure sensors can also be used to measure heart rate. Here, the heart rate is sampled by the arterial pulse wave generated by the periodic contraction and relaxation of the heart. The following HR monitoring device, developed by Park et al. [9], could estimate HR from the pressure variation in the ears canal surface using a piezoelectric film pressure to sense the in-ear pulse wave and convert it to an electric current. The digital circuit comprises a micro-controller unit and a wireless communication module with an antenna. A software program embedded in the micro-controller unit detects pulse peaks in real time, and then the HR value is periodically transmitted to the host via a wireless communication module.[9] Body movements affect the pressure variance and the peak height of the pressure waves and introduce errors in the HR estimation. In addition, long-term use of an ear-mounted system results in an uncomfortable wearing experience.[8] Another cardiovascular monitoring systems example, here, flexible capacitive electrodes are used to reduce motion artifacts in a portable electrocardiogram system. In the system of Lee et al. [10], the capacitive electrodes are with a conductive foam on their surface, a shield, an optimal input bias resistor and a protective feedback. The entire system, is integrated into a chest strap and the acquired signals are transmitted wirelessly to the ambulatory heart rate monitor. A reduction in electrode motion artifacts was achieved due to the high bias resistance at the input of the preamplifier. They also used a noise reduction and peak detection algorithm run on the raw ECG data to detect the QRS complex and heart rate. The accuracy of the system was up to 91,32% QRS detection at 7km/h walking speed.[8], [10] The temperature of the body represents the balance between heat produced and heat lost and can be influenced by underlying pathophysiology, skin exposure or age. With the core body temperature and the surface body temperature it's one of the vital signs that reflect health conditions. Oguz et al. [11] developed a portable device with wireless computer connectivity that provides non-invasive dual channel digital body temperature measurements. The system can measure temperature with an accuracy of ±0,1ºC within the range 16-42ºC and transmit the data over a Bluetooth communication platform. The device has two temperature probes with a digital temperature sensor each, that measure temperature from two ear canals simultaneously from which the mean temperature is calculated.[8], [11] Like the system of Park et al. [9] in the previous chapter, this may also not be feasible for long-term monitoring because of uncomfortable wearing experience due to the ear-canal probes. With the design and the built of a non-invasive wearable wireless monitoring system for accurate body temperature measurements and real time feedback to the medic, Boano et al. [12] have created a system that can be worn by an individual for a long period of time. Via two sensor units attached to the skin, the measured data are sent to a more powerful central unit worn on the body. The overall system forms a star-type body sensor network. The recorded data is sent via the central unit to a computer that communicates with healthcare facilities via the Internet. With this prototype the authors achieved an accuracy of 0,02ºC over a temperature range of 16-42ºC and a long battery lifetime of uninterrupted operations for several weeks.[8], [12] The next temperature monitoring system of Mansor et al. [13], use commercial sensors measuring and transmitting the data to a microcontroller. They used an Arduino Ethernet shield for developing the prototype. The microcontroller sends the collected data to a remote server over a wireless local area network. Data communication unit was developed by using MySQL that serve as a database to store the entire patient's information. With a web application, the clinician is able to access the patient's record as well as all measurements taken remotely.[13] Similar to this system, the developed system by Asaduzzaman et al. [14] consists of an Arduino UNO microcontroller system, a transmission system and an Android based application. The system gives information of heart rate and body temperature simultaneously acquired on the portable device in real time and shows it through the connected Android application instantly.

III. Method

A. System Overview

For the implementation of the prototype, a NodeMCU V2 by Joy-IT, an ESP8266-based development kit for programming WLAN-controlled projects with an open-source firmware, is used for this IoT project.[15] This model works with a clock frequency of 80-160 MHz and has a data storage of 96kB and a RAM of 64kB. It has a wireless standard of 802.11 b/g/n at a frequency of 2.4 GHz. With the operating temperature from -40ºC to 125ºC, it offers a wide range of application for the IoT project. Figure 2 shows the working diagram of the system with the functional blocks. It can be seen, that the system for measuring vital data consists of three units.

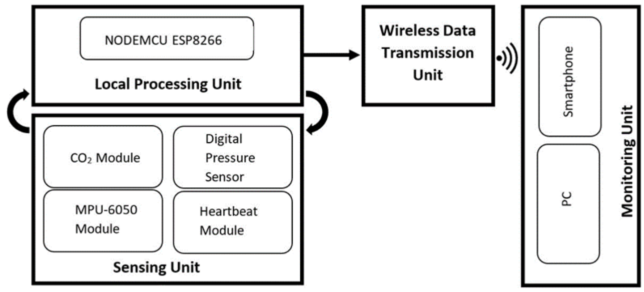

Figure 2 System diagram of the proposed system.

The local processing unit is controlled by the microcontroller Node MCU ESP8266, which is to be programmed via the program Arduino IDE. This can be connected to the PC via micro-USB interface and save the program for later use. The sensing unit is the next part of the system. Here, through the connection and exchange with the Local Processing Unit, the data is collected and then processed in the microcontroller. Through test measurements and test applications in the work process of the thesis, the basic functions and data acquisition of the different sensors were tested. The CO_2 module, the digital pressure sensor, the MPU-6050 module and the heartbeat module should be integrated into the prototype system. The focus will be on the acquisition of the core data of the sensors. This includes recording the CO_2 content of the air, the current temperature, the air pressure and the associated altitude, the angular velocity via the gyroscope of the MPU-6050 module and the heart rate. In this prototype state an implementation is designed for a bread board. The circuit diagram of the project can be found in the appendix under Figure 7. The heartbeat sensor is connected via the analog input, all other sensors provide their data via the digital pins. The power supply of the system in test mode runs via the micro-USB port, but the circuit diagram and structure of the system is designed for operation with a rechargeable battery. The query of the values from the CO_2 sensor occurs via the PWM port, the MPU-6050 sensor is connected as in the test example. The programming part of the microcontroller is done with the software Arduino IDE.[16] Figure 3 shows the system flow chart.

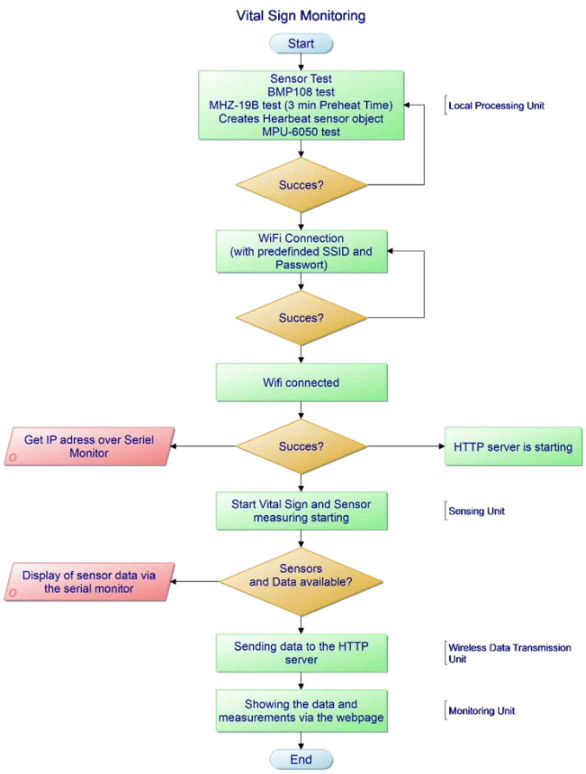

Figure 3 Algorithm for measuring the vital signs and sensor data of the system.

The program sequence is, at first the system checks the sensors in the local processing unit. If the connection with the sensors is ok and the preheating time for the CO_2 sensor has expired, the connection with the network is established. When a connection to the network is established, the IP address from the serial monitor is displayed and the HTTP server is activated. Now the actual process of data acquisition with the sensors via the Sensing Unit starts. The process can be controlled through the serial monitor all the time. Via the wireless data transmission unit of the microcontroller the data is provided via the HTTP server. The previously defined IP address can now be used to access the data and the monitor.

B. *Performance Measurement*

Figure 8 shows the bread board implementation of the vital function unit. The user of the system only has to provide a power supply after implementation and setting of the correct network data, the rest of the process is regulated by the system itself. When testing the system, the serial monitor enables the control of the data acquisition and programming. Through the serial Port, as stored in the program, the measured values of the sensors but also the IP address to open the website as well as the information about the connection to the network are displayed. Starting the system, a sensor test is performed first, as defined in the program. After that, the CO_2 sensor waits for the preheating time, which is 3 minutes, as stated in the specification.[17] After this time the connection to the MPU-6050 module is checked. If this is present, the microcontroller starts the recording of the data via the sensors and establishes the connection to the network. The output IP address can now entered via a terminal device and the programmed website with the data of the sensors is opened and can be accessed. Refreshing the website, retrieves the new server data again and displays it.

C. *Monitoring Unit*

The data can be retrieved via the web page. An example of this is shown in the Figure below. The main vital sign dashboard of the prototype system can be seen.

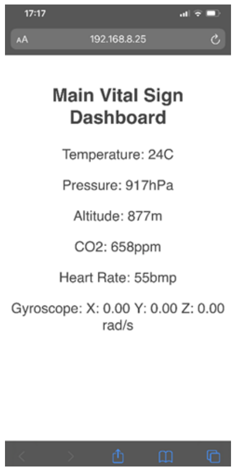

Figure 4 Dashboard view with the smartphone.

Here, the web page was opened with the smartphone by retrieving the IP address in the network and the data is visualized. Regardless of which device it is accessed from or in what amount, the website is displayed via the IP address.

D. *Power Supply Unit*

The operating voltage required by all electronic components of the device can be supplied via the micro-USB port or via a rechargeable battery. In the prototype stage, the battery, a schematic of the developed device with the connections of the electronic components is shown in Figure 7, can be integrated via the ports 3V3 and GND on the bread board.

E. *Significance of the system*

With this system, low-cost electronics monitoring system for vital signs and environmental parameters has been implemented for use in avalanche backpacks. The system was implemented in a web-based platform and can communicate wirelessly with end devices such as smartphone or PC in the same network. The device is portable and lightweight, so it can be easily taken anywhere. It has been designed in such a way that it can be powered by a rechargeable battery. The parameters measured include temperature in Celsius, air pressure in hPa, altitude in meters, CO_2 content in ppm, heart rate in bpm and gyroscope in rad/sec, which are acquired from the sensors connected to the system: CO_2 module, digital pressure sensor, MPU-6050 module and the heartbeat module. For recreational athletes and users of avalanche backpacks, where these parameters need to be monitored continuously, the system can be used.

IV. DISCUSSION

A. Integration into the rescue chain

The main research question is how to improve existing avalanche protection gear such as avalanche backpacks or avalanche beacons, which require an active interaction, by using a system that requires no or minimum user interaction. A prototype system for recording vital signs and environmental parameters is being developed, which can be potentially used during skiing and provides the data for monitoring. This chapter conducts an evaluation of the potential implementation of this system with existing safety equipment. The benefits arising and a possible integration into existing avalanche safety equipment and the limitations are discussed. For a prospective integration of such a prototype for vital sign acquisition into an avalanche backpack, the process chain of the entire safety process must be considered. Considering the case of an avalanche accident, this can be directly classified as an emergency situation. Regardless of how the avalanche occurred and due to which mistakes in the terrain, five factors now influence this situation. These are time, hazard, life or death, multi-victim avalanches and the degree of burial, shown in Figure 5.

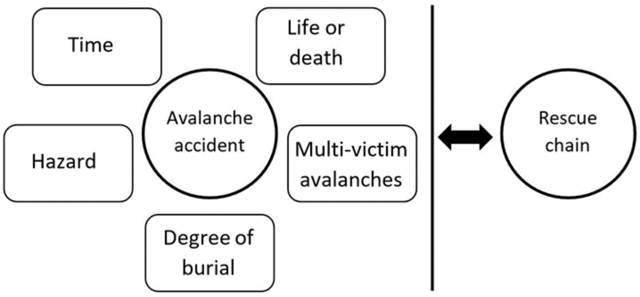

Figure 5 Influencing factors after an avalanche accident.

The time factor in terms of the survival curve of avalanche victims plays a major role, once buried, the race against time starts. In the survival phase up to 18 minutes, the avalanche victims have a survival chance of over 90%, after the 18 minutes this decreases drastically and 60% die in the asphyxiation phase between 18 and 35 minutes, as there is no possibility of breathing.[18] Depending on the group size and the terrain in which the avalanche accident occurred in the backcountry, it is important to consider that there continues a high risk due to external influences. These can be rapid changes in weather, obstructions of visibility or even possible secondary avalanches. An example of a secondary avalanche occurred in the Obertauern ski area during the winter of 2021. Here, first a skier was buried off-piste by an avalanche and then a second avalanche caught three mountain rescuers, who arrived at the scene of the accident in just a few minutes by helicopter.[19] The degree of burial significantly affects the avalanche accident. Only in case of a complete burial of the victim, the mentioned survival curve comes into effect, in which asphyxiation is the main cause of death. However, there is still the cause of death due to trauma with 32% and that of succumbing to the 3-H syndrome with 2%.[18], [20] These two factors can be directly related to the degree of burial. An avalanche accident with multiple buried victims is more fatal on the one hand, since a more complex search operation is required here, but on the other hand, with small group sizes, it must be decided which buried victim is to be rescued first. This also brings the life-or-death factor into the discussion. If we assume, for example, that in a group of 3 ski tourers, two are buried by an avalanche, then only one person can still search for the two people until the arrival of the rescue chain. In this stressful situation, the people involved usually act intuitively and rationally, which reinforces the point of practicing these scenarios.[21] As shown in the Figure 5, the rescue chain, this can be the mountain rescue, piste rescue, first responders on site or the emergency physician, is also included in the consideration, because they have a direct influence on the outcome of an avalanche accident. It should be mentioned that an avalanche emergency is a special case in alpine emergency medicine, as the prognosis of buried victims depends on the severity of the asphyxia and the traumatic injuries.[22] In addition, there is a correlation with above-mentioned factors, as rescue workers are also exposed to the hazards, high psychical and physical stress, and resulting high operational risk. Including a system in the discussion that can record the vital functions of potential avalanche victims and transmit them to the emergency services raises the question of benefit. In the example, let assume if the emergency services arrive at the accident site and one person of the group is already searching in vain for the two buried victims, would a system that transmits the victim's vital signs now be used. It's not appropriate to use this system at this point in the process. The life-or-death factor would reappear and the ethical question of a selection principle for multi-victim burials would arise. A detailed analysis of the data of the avalanche accidents researched by Haegeli et al. [20] shows, that with a burial duration of less than 10 minutes, the survival rate of the accidents researched in Canada is 89.5% and in Switzerland 93.6%. This proves that no time shall be wasted to check the vital functions with the system first, because the probability of survival decreases drastically to 36.2% in Canada and to 71.1% in Switzerland after 10 minutes of burial. A system for monitoring vital signs can be used when an avalanche victim is successfully rescued. Here, it can be an important support for the rescuers and save valuable and life-saving time. For a better understanding, the International Commission for Mountain Emergency Medicine, ICAR MEDCON, developed an algorithm for the management of buried avalanche victims, seen in Figure 6. There are also other measures to improve the prognosis after a successful rescue of avalanche victims. For this, ICAR MEDCON [23] has also developed an Avalanche Victim Resuscitation Checklist, in order to improve resuscitation care, prescribes the further course of action after the essential basic parameters such as vital signs, burial duration, core body temperature and airway have been recorded via the form of a flow chart.[22] It is shown that on the one hand the duration of the burial plays an important role and on the other hand the monitoring of vital signs is the first step in avalanche management.

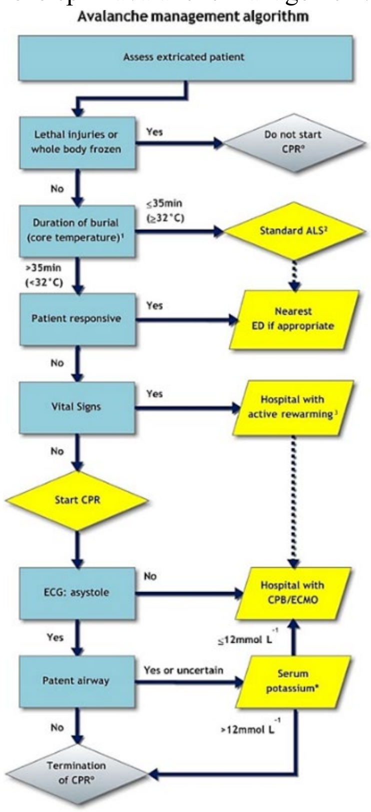

Figure 6 Algorithm for the management of buried avalanche victims.[59]

The duration of the burial plays an important role in the further treatment, as it is usually related to the core body temperature. The measurement of parameters is primarily related to spontaneous respiration and pulse. In addition to these clinical parameters, core body temperature is a critical parameter for monitoring of hypothermic avalanche victims.[22] The implementation of a system that records the clinical parameters pulse and core body temperature, as well as the burial time, is beneficial, because this saves a lot of time for the emergency services, and the further treatment can also proceed quicker in accordance with the avalanche checklist. In terms of Figure 6, this would optimize and shorten the steps for evaluating the duration of burial with the core temperature, the patient responsiveness, and taking vital signs. In addition, the onsite management is improved, leading to an improved triage and can improve relative survival of avalanche victims. This is shown by the study of Strapazzon et al. [24], in which 46% possible survivors were declared dead while CPR would have been indicated. In such cases, new technology and systems can be considered for better decision making by emergency physicians, and there is always the need for practice and training for such an emergency for the rescue forces to achieve maximum results.

B. *Limitations of the prototype*

The prototype developed in this work described in Methods, has some limitations regarding performance and applicability, which are outlined here. Through the prototype system, the data of altitude, barometric pressure, temperature, CO_2 content and gyroscope are recorded. The first factor limiting the system concerns the sensors. Here, the CO_2 sensor has significant limitations in the detection range, which is between 0 ppm and 5000 ppm. According to the study by Lahrz et al. [25], the CO_2 concentration in investigated German classrooms can exceed this mark up to a maximum value of 6000 ppm. This shows that this sensor, assuming the test example of use in an air cavity of the avalanche, will exceed the limit of its detection range. Due to the requirements to implement a cost-effective system, this is reflected in such limitations. The digital pressure module offers the inputs with the three parameters altitude, pressure and temperature. The altitude related to the rescue, which avoids a long search when this is accurately transmitted, it is an important parameter. There is an importance for core body temperature measurements for the rescue process, but the sensor cannot represent more than the environmental temperature as no required measurement for this can be performed with this sensor. This can only be done medically by temperature probes measuring in the middle to lower third of the esophagus.[22] The implementation of the heartbeat module could be done through the helmet of the skier and the MPU-6050 module can be fixed in a defined position in the backpack. With this module, the parameter of the position of the victim could be integrated by measuring and calculating the angles of the individual axes. The second factor limiting the system concerns the microcontroller. The NodeMCU ESP8266 controller features Wifi capability. In this specific application, the SSID and the password of the respective network must be defined in the program code beforehand, which limits the range and the applicability significantly. In the current constellation of hardware and software elements of the prototype, it is not possible to save the collected data, except via the connection to the serial port of the PC. If a solution for saving the data via the monitoring website can be created, this will enhance the application possibilities.

V. Conclusion

A wireless prototype system for collecting vital signs of buried avalanche victims has been developed using small mounted sensors. The system has a short-range wireless communication capability to transfer altitude, air pressure, temperature, CO_2 content and gyroscope to a webpage. The insight into wearable health devices demonstrates the development in recording medical parameters, application areas and examples of parameters with the respective signal source and sensor types. Several approaches were presented, how such a system can be potentially integrated into existing equipment, such as avalanche airbags or other avalanche safety equipment, and how the system data can be used by rescuers several. This classification in the avalanche management algorithm considers all influencing factors after an avalanche accident.

Appendix

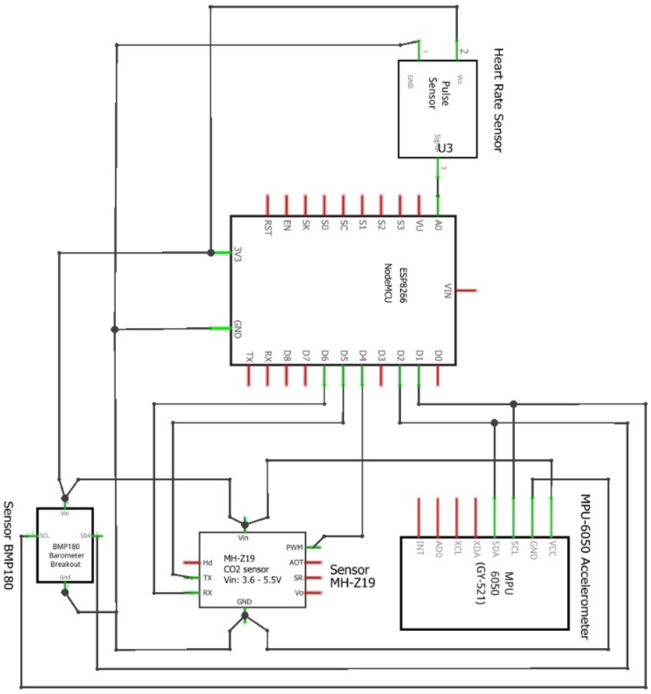

Figure 7 Circuit diagram of the device prototype.

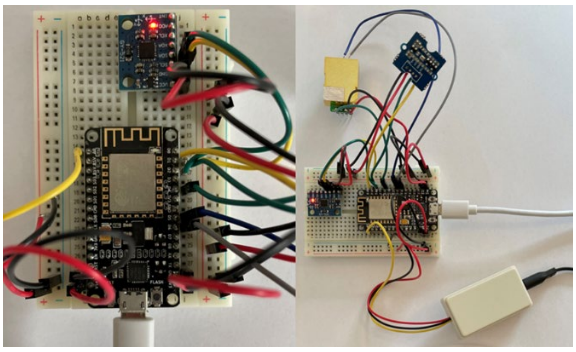

Figure 8 Device prototype bread board implementation.

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