A Smart Helmet for Air Quality and Hazardous Event Detection for the Mining Industry

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***Abstract*— A smart helmet has been developed that is able to detect of hazardous events in the mines industry. In the development of helmet, we have considered the three main types of hazard such as air quality, helmet removal, and collision (miners are struck by an object). The first is the concentration level of the hazardous gases such as CO, SO_2, NO_2, and particulate matter. The second hazardous event was classified as a miner removing the mining helmet off their head. An IR sensor was developed unsuccessfully but an off-the shelf IR sensor was then used to successfully determine when the helmet is on the miner's head. The third hazardous event is defined as an event where miners are struck by an object against the head with a force exceeding a value of 1000 on the HIC (Head Injury Criteria). An accelerometer was used to measure the acceleration of the head and the HIC was calculated in software. The layout of the visualisation software was completed, however the implementation was unsuccessful. Tests were successfully done to calibrate the accelerometer. PCB's that were designed and made included a breakout board and a prototype board. A whole software implementation was done based on Contiki operating system in order to do the control of the measuring of sensors and of calculations done with the measured values. This paper presents the undertaken design detailing solutions to issues raised in previous research.**

Keywords*— *air quality; mining; safety; wireless sensor networks; ZigBee.

I. INTRODUCTION

South Africa is known for its extensive and diverse mineral resources and large mining industry [1]. Supervisors are held responsible for all injuries sustained under their supervision, and should therefore be aware of potentially risky situations [1]. The problem addressed in this paper was the improvement of a mining helmet in order to ensure more safety awareness between miners. When working with noisy equipment, being aware of one's surroundings can sometimes be challenging [2]. In the mining industry miners tend to remove some of their safety gear because the gear is too heavy, warm or uncomfortable to work with. However, miners generally do not remove their helmets. Presently mining safety helmets only have the purpose of protecting the miner's head against potential hazardous bumps. The safety helmets do not have any technology added to it to let miners know when a fellow miner has encountered a hazardous event. Therefore the purpose of the project described in this paper was to modify an existing mining safety helmet to make the helmet even safer by adding a wireless sensor node network. The task was extended to designing the system small enough to fit into the safety helmet and last long enough while running on battery power. A further challenge was to modify the helmet without changing its physical structure. The added weight had to be kept to a minimum.

A mining helmet needs to be modified to improve miner safety by adding intelligence to the helmet. When a miner removes his helmet he needs to be warned. If an object falls on a miner even when wearing his helmet he can become unconscious or immobile. The system must determine whether or not a miner has sustained a life-threatening injury. These two events are defined as hazardous events. Thirdly, dangerous gases need to be detected and announced.

In the area of mining technology, real-time monitor and control of mine hazard are more complex. Mine safety modules are configured to communicate to ground control or a central station. A real critical issue in mines is hazardous gases. Systems used in a mine can create intense vibrations and increase the level of hazardous gases such as CO, SO_2, NO_2 and particulate matter. The working conditions can be very noisy and miners don't watch each other constantly. Miners tend to stay in groups and will be no more than 5 meters (m) from each other. A warning system needs to be incorporated that will warn miners within a 5 m radius that a miner is experiencing a hazardous event. This system needs to process and transmit the event within 1 second (s). These systems measure the environment around the miner with gas sensors and are then used to implement evacuations. These do not alert the miner at all or only alert the miner in an audible way. These systems warn miners, but when a miner is obstructed or injured, an external input is required from ground control [3]-[5]. In recent years, harvesting technology has played an important role in the area of mine applications. The literature on mines technology is available but very limited. Nutter, et al. proposed a methodology for identifying safety hazards inherent in underground monitoring and control. They also designed potential safety hazard equipment. They developed methodologies based on analytical electronics and computer-based hardware/software systems [6]-[8]. Kock, et al. developed the technology in terms of health, safety, and productivity for the South African coal mining industry. They also investigating the coal interface detection (CID), productivity, communication channels (infrared, power line, optical fibers, and radio) [9]. Misra et al. presents a case study for mines. They reviewed on communication techniques such as through the wire (TTW), through the air (TTA), and through the earth (TTE) [10]. Forooshani, et al. presents a compressive

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survey of wireless propagation in tunnels and underground mines with a focus on current wireless channel modeling, technologies, and applications [11]. The Internet-of-Things, where all devices are smart and interconnected, are increasingly being used in more industrial applications [12], [15], and it is therefore also a principle that can make a difference in mining safety with smarter equipment. The literature also shows that despite some attractive solutions; very few have been implemented and tested in the real-world, identifying the existence of a gap between theory and real world application at scientifically accepted level. In this paper smart helmet in compliance with IEEE 21451 standards is presented. It has various advanced features such as fast response time low, portability, and low cost with precisely acceptable accuracy.

II. SYSTEM OVERVIEW

Solving the problem of miners removing their safety equipment was a challenge, taken that any new safety equipment that is not lightweight and non-distracting, will just be removed, like all the other safety equipment. As the helmet is the only safety gear miners tend to keep on, this is where the new safety equipment was added on to. Three sensors were used, an accelerometer, air quality and an Infra-red (IR) sensor. These were used either to detect if a miner has experienced a bump to the head or removed his helmet and surrounding air quality. The three sensors were connected to a ZigBee module. This module does all the processing and also controls the wireless communication between separate helmets through the Contiki operating system (OS). The whole system was analyzed throughout the design process in order to keep the power consumption to a minimum as the system is running on battery power. Different sensors were considered for each separate component in order to keep the power level as low as possible. In order to explain the entire system and the alternatives of each component, the system will be explained component by component. The system consists of six components, helmet remove sensor, collision sensor, air quality sensor, data processing unit, wireless transmission and alerting unit. Figure 1 represents the block diagram of the smart helmet for mining safety. The developed prototype mining safety model is shown in Figure 2. The development of the prototype complies with the IEEE 21451 standard [12].

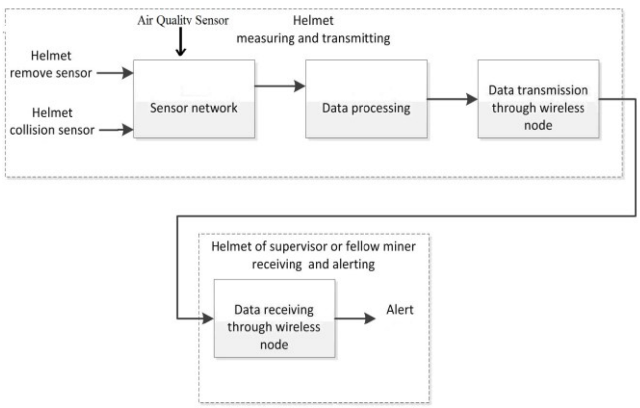

Fig. 1. Functional Block diagram of Smart Helmet.

A. Air Quality Sensor

Air pollution from coal mines is mainly due to emissions of particulate matter and gases include methane (CH_4), sulphur dioxide (SO_2), and oxides of nitrogen (NO_2), as well as carbon monoxide (CO). From different studies, it is well known that when human being comes in contact these chemicals/ pollutants it could have adverse effect on their health. These unbalanced ratios of air pollution gases, such as suspended particulate matter, increase respiratory diseases such as asthma, chronic bronchitis, and cardiovascular problems [13]. In this article we have measured the CO, SO_2, and NO_2. Per the literature we have chosen the electrochemical gas sensor because of its accuracy and low power consumption in the development of air quality detectors. These sensors are also very selective to the target gas. The characteristics of the sensors used are summarized in Table 1. Fig. 3, represents the block diagram of the air quality monitoring and alerting of the critical level of hazardous gases.

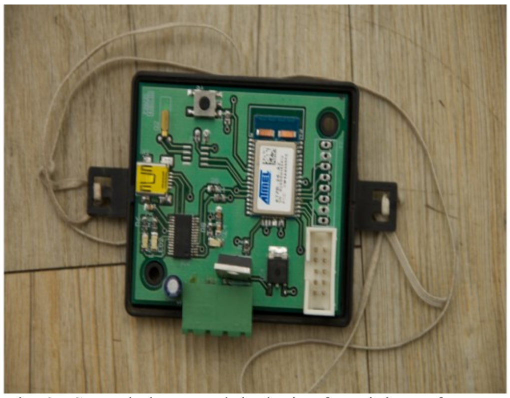

Fig. 2. Smart helmet module device for mining safety.

Table 1
Sensor used in the development of hazardous environmental gases

Sensor	Target Gas	Range (ppm)	Resolution (ppm)	Response Time (seconds)
EC4-500-CO	CO	0-500	1	<30
EC4-20-SO_2	SO_2	0-20	0.1	<35
EC4-20-NO_2	NO_2	0-20	0.1	<35

We have used electrochemical sensors for CO, SO_2, and NO_2 from SGX Sensor Tech. The electrochemical sensor's advantages, disadvantages, typical signal conditioning circuit, mathematical formulation (output sensor signal conversion to gas concentration) was reported in [13]. Regarding the concentration of CO: healthy people can tolerate a CO level of up to 6 ppm without serious health effects, but it should always be kept below 4 ppm [13]. The upper level of CO, SO_2, and NO_2 gas concentrations were fixed at 4 ppm, 0.2 ppm, and 0.10 ppm respectively, for the developed system. If increases in the concentration level of air quality parameters are observed, then a signal is transmitted through a ZigBee transmitter module to the alerting unit of the helmet.

B. Helmet Removal Sensor

For detecting the removal of the helmet a few different approaches were considered. The comparison, advantage, and disadvantage of the proposed approaches in the literature was reported in [1]-[11]. For this study, the IR beam based helmet remove sensor technique was considered better among other available techniques such as a switch, analogue distance sensor, and digital distance sensor. The IR beam can be designed to use low amounts of power. An off-the-shelf IR distance detector was used for this application. The IR sensor was designed to send a constant signal from the one side of the helmet to the other side with the circuit in Fig. 4.

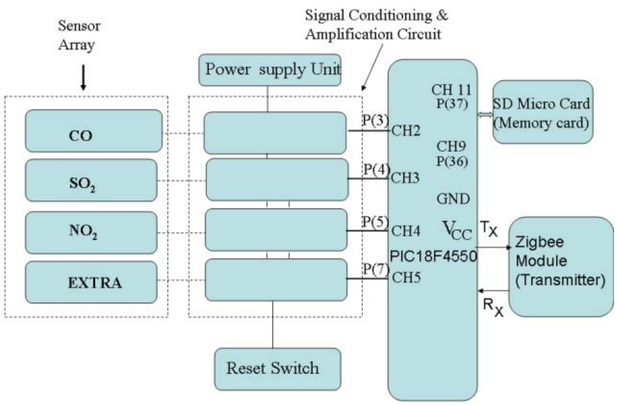

Fig. 3. Block diagram of the device for air quality monitoring and alerting of the critical level of hazardous gas.

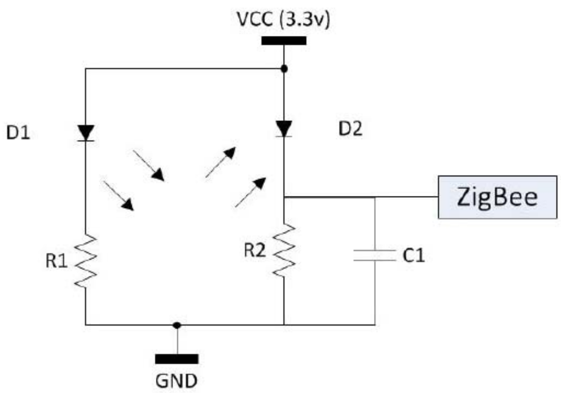

Fig. 4. Circuit diagram of IR circuit designed based on IEEE21451 standards.

C. Collision Sensor

In order to conclude that a bump is actually dangerous, the bump needs to exceed a certain threshold for a certain amount of time. According to the Federal Motor Vehicle Safety Standard 208 (FMVSS 208) a Head Injury Criteria (HIC) should not exceed a value of more than 1000.

$$HIC = \left[(t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right]_{max} \quad (1)$$

The variable t_1 is starting time, t_2 is the end time, a(t) is the acceleration over time. An accelerometer was needed to measure the acceleration of the system. The accelerometer needed to be able to measure at least 70 g in 3 axes. The ADXL377 accelerometer satisfied the specifications. There are a few limitations when using the HIC equation. The time interval t_2-t_1 should be limited to a maximum of only 36 milliseconds (ms). The time limitation is to limit the equation to impacts and not sustained accelerations. It is also mentioned that the accelerometers can give inaccurate measurements due to scull deformation. To compensate and to over design, the accelerometer is placed on the helmet itself and not on the plastic harness holding the head. This will allow the accelerometer to reach acceleration experienced by the helmet that will be greater than the actual acceleration experienced by the miner's head.

D. Wireless Transmission

Wireless transmission between the different nodes was required. Bluetooth, Wi-Fi and ZigBee are the three types of wireless systems that are practical for the system specifications. ZigBee was created to be a low power, low-data rate and a low-cost device. ZigBee has all the same benefits as a Wi-Fi system. ZigBee is based on the IEEE 802.15.4 standard [13], [16]. A ZigBee module is also more useful for creating larger mesh networks than Bluetooth and is therefore the better option when routers and access points cannot be implemented. In [3] all the components are attached to the safety helmet with Velcro. Some of the components are placed inside the helmet, while this helps to protect the components from bumps and gasses, this can result in electronics being embedded into the head of a miner if a seriously hard bump is experienced. In [4] ZigBee modules are the chosen wireless chip because its signals are able to penetrate walls and work very well in mines. Wireless or more specifically Wi-Fi, is sometimes used in mines, but it needs cabling throughout the mine to the routers, that can be damaged [13]. A study was done to determine the best frequency to be used in mines as the attenuation of signals over a distance determines how far the signal will travel. It was found that the best frequency was 2.4 Gigahertz (GHz). The transmission was found to be effective up to 15 m from where the signal was transmitted. [14]-[20]. ZigBee systems can be set up to work in a few different network structures such as star, light mesh, mesh and cluster tree, are four of the most commonly used structures. Mesh structures are used when one node needs to communicate information to all the other nodes, but is in reach only of a number of nodes. Mesh network configuration is also good as it makes multiple pathways to each node. The advantage and disadvantage of the ZigBee communication was reported in [13]-[22].

E. Data Processing Uni

The original thought process was to use a Raspberry Pi as the main processor in conjunction with a ZigBee module as the wireless communication terminal, keeping with an open hardware design [23]. The sensors and the ZigBee module would be connected to the Raspberry Pi. The Raspberry Pi would measure the sensors and control the ZigBee module. The Raspberry Pi would then be used to create the user interface for the user to examine the data that has been logged. Two problems turned up: the first being power consumption and the second interfacing with the Raspberry Pi. The power consumption was a problem as the system would be running off a battery, even though the Raspberry Pi uses very little power it is much more than what is used by the ZigBee module. The interfacing problem was caused by the difficulty of connecting to the Raspberry Pi, because it would not have a built-in display as this would dramatically reduce the durability of the product. The only other option is to connect to the Raspberry Pi through a network cable. The user interface would only then be accessible. This network configuration would be a complex and impractical process for the mining environment. After further examination it was decided to choose the ZigBee module ATZB-24-A2 wireless chip. It has an adequate amount of processing power and a built-in electrically erasable programmable read-only memory (EEPROM). Any other additional processing units would use more space and consume additional power as well.

F. Alerting Unit

Alerting miners in a mine can be a difficult process bearing in mind the everyday working conditions that are encountered in a mine. Underground mines are very dark places and therefore the miners use safety helmets with built-in or attachable mining lights. The equipment used in underground mines can create a lot of noise and vibrations, which are compounded by the cramped conditions in the underground tunnels. The problem associated with the noise is that warning a miner with a speaker or an alarm system when a fellow miner is experiencing a hazardous event would most probably be in vain as the miner would not hear the alarm. A second option was considered with the use of a vibrating unit within the mining helmet. Warning a miner with a vibrating helmet would work. However when a miner is working with one or close to equipment that creates a lot of vibration, the miner most probably would feel or misinterpret the vibration as part of the vibration created by the equipment. This will allow the system to only work in specific conditions. The aim would be for the system to work under all conditions. Using light-emitting diodes (LED's) placed on the cap of the mining helmet was also considered as it would be a visual way of alerting the miner. It was then decided that adding LED's to a mining helmet that is already equipped with a big light connected to the helmet would mean not using the available resources. It was therefore decided to implement a system that will warn the miner by flashing the mining light a few times. Using this warning method has the added benefit of using the mining helmet light of the miner who is experiencing the hazardous event. Flashing the light constantly simultaneously show who is experiencing the problem as well as indicate the location of the miner.

III. EXPERIMENTAL WORK

A. Air Quality Test

In the air quality testing process, we have used the known gas concentration cylinder and follow the static chamber method for the development of the AQ sensor. An incubator is used for testing of the developed system. The incubator is simply a rectangular plastic box with a hole on the side to fit a pipe that is used to pump in gas. The sensor node is powered on and placed inside the incubator that is then closed. Gas cylinders were used to pump the gas into the incubator. The sensor node then takes measurements of the gas concentration. Off-the-shelf air quality monitoring devices are very expensive and thus there was nothing to compare the measurements to, however the concentration levels were estimated and the accuracy of the system was determined.

B. Helmet Removal Test

The purpose of this test is to show that the system will detect when the helmet is completely removed from the dummy head. For the system to pass the test it needs to detect the removal of the helmet with an accuracy of above 90%. The helmet was connected to the computer through the USB port. The helmet was placed on the dummy head. The node was configured to transmit the data through the USB port, which would have been sent through the wireless network. The computer displayed the serial data constantly. The helmet was then removed slowly until the IR sensor triggered the serial port to display that the helmet was removed. The distance was measured from the top of the dummy up to the inside of the helmet. The test was repeated ten times.

C. Impact Test

In this section, we have tested to the impact reading that the accelerometer gives when in two situations. The first is a hazardous force like a hammer, showing that it would trigger a hazardous event. The second is a bumped with a non-hazardous force like a human hand hitting the helmet, showing that would not trigger a hazardous event. The test with the hammer was changed a few times as discoveries were made through the results. The final test with the hammer was dropping the hammer for ten repetitive tests from a height of 1 m above the helmet. The accelerometer was placed on the inside of the safety helmet with a wooden bowl used as the dummy head with a sampling rate set to 250 Hz. The data was sent through the USB to the computer and then imported into Matlab to give the graphs shown in Fig. 5. The test with the hand was done with two impacts. The first impacts are simulating a fellow miner making a joke and hitting the miner lightly on the helmet. The second impact are simulating a harder blow but still with a non-hazardous force. The results are shown in Fig. 6.

D. Wireless Transmission Test

The purpose of this test was to determine whether or not the wireless transmission between the nodes meets the minimal requirement of transmitting data more than 5 m and how successful the data transmission. Placing the one node at distance 0 m (stationary point) configured to transmit every second continuously. The second node was placed at distances varying from 1 m to 13 m, 8 m further than specified. The second node was configured to receive and transmit the data through the USART. Connecting a computer and storing the first hundred seconds, of the system clock, that was received. The data of each distance was stored and analyzed. The test was done in an environment with people moving through the line of sight and the presence of a Wi-Fi network with the router situated in the middle of the transmission.

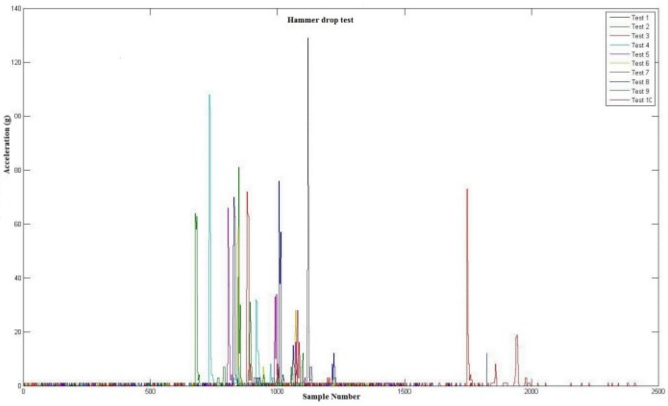

Fig. 5. Accelerometer measurements from impact test on helmet with hammer dropped.

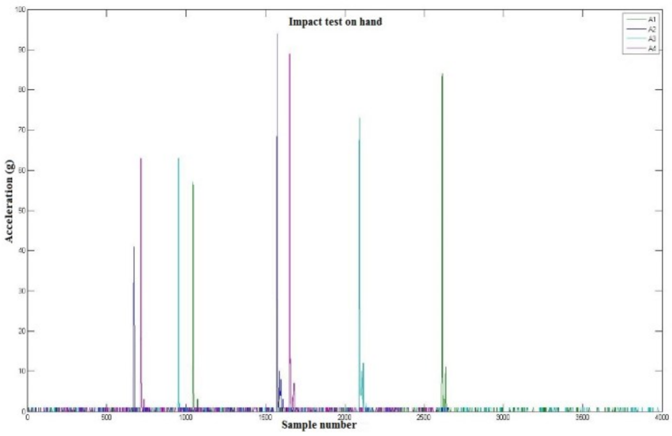

Fig. 6. Accelerometer measurements from impact test on helmet with hand.

The results showed the data received and the corresponding system time. It was then determined which of the hundred transmitted signals were received successfully, which were skipped and which ones were received more than once. The data of the thirteen distances were then imported into Matlab. These results were then plotted onto the graph in Fig. 7. The top blue line shows the amount of numbers that were received more than once, the green peaks show the amount of transmissions that were not received.

IV. Result and Discussion

The critical levels of the hazardous gases such as CO, SO_2, and NO_2 in the mines industry has been indicated through alerting unit. The helmet removal test was done successfully with an off the-shelf IR distance sensor. The IR sensor designed from first principles was working device. It was discovered, after the system was integrated, that the transmitted IR signals reflects off the dummy head and kept reflecting off the helmet's surface until it reached the receiver. The signal at the receiver side was close to the same amplitude as the signal received when the helmet was removed from the head. The system can therefore not distinguish between whether the helmet is removed or not. The test results for this test were not added as the system constantly triggered the alert signal.

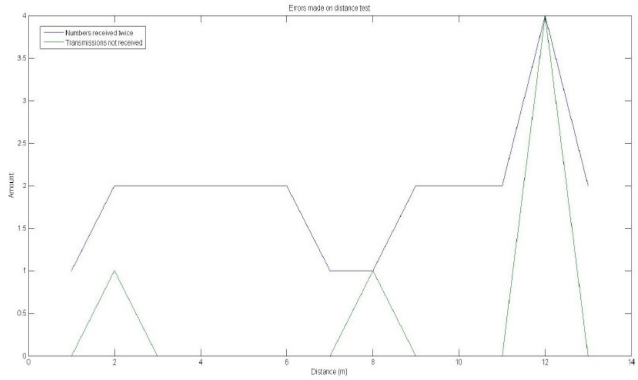

Fig. 7. Distance test error, showing a transmission that was not received and transmission received more than ones.

The test was then done using an off-the-shelf IR sensor. It gave the results that were expected and needed for the test to be successful. The system successfully detected when the helmet is removed 10 cm off the dummy head with an average deviation of 0.3% too far. The effect of these results is that any miner will trigger the alert signal when removing the helmet completely off their head as it was specified. Fig. 5 showed the consistent values between 81 g and 64 g with an average of 71 g. The results Fig. 6 show the first impact at an average of 56 g and the second more severe impact with an average of 85 g. The result showed that the output of the accelerometer was scaled inaccurately and that the accelerometer needed to be calibrated more accurately. The test could not be repeated with the correct accelerometer calibration being 80% g of the values as seen above. The test also indicated that the sampling interval of the accelerometer was not sufficient enough. The system measured the different axes of the accelerometer one after the other, as the ZigBee module only contains one ADC with different ports connected to the ADC through port switching. The Contiki OS works by repeating procedures on the interval of eTimers. eTimers however can only be configured for a 8 MHz chip to repeat every 4 ms. This means that a single axis of the accelerometer can only be measured every 12 ms. With the use eq^n. 1, the maximum acceleration that can be measured safely for non-hazardous events, can be calculated 92.967 g. For taking safety factors into consideration the value was used as 90 g. The transmission was successful at distances more than double than were specified.

V. Conclusion and Future Scope

A smart mining helmet was developed that is able to detect three types of hazardous events such as danger level of hazardous gases, miner helmet removing, and collision or impact (miners are struck by an object). The hazardous events were classified as a miner removing the mining helmet off their head. An off-the-shelf IR sensor was then used to successfully determine when the helmet is on the miner's head. Another hazardous event is defined as an event where miners are struck by an object against the head with a force exceeding a value of 1000 on the HIC (Head Injury Criteria). An accelerometer was used to measure the acceleration of the head and the HIC was calculated in software. The layout of the visualisation software was completed. Tests were successfully done to calibrate the accelerometer. PCB's that were designed and made included a breakout board and a prototype board. A whole software implementation was done based on Contiki OS in order to do the control of the measuring of sensors and of calculations done with the measured values. The system was extensively tested in order to determine whether or not the system works to the requirements. It was observed that the accelerometer should be placed on the inside of the helmet and not on the plastic harness inside the helmet to compensate for the weight difference. The accelerometer calibration was then modified to correctly calibrate the accelerometer. A few aspects of the system can be improved. Adding an external antenna would extend the range or improve the signal strength in order to allow for more human interference. The distance might still want to be limited as it would be impractical to warn miners that are too far away to find the miner who is experiencing a hazardous event. The processing speed of the system can be improved to allow for more accurate accelerometer measurement. The IR sensor can be improved to work within the helmet by not triggering because of reflections. Node hopping can be implemented to allow transmissions to the supervisor or even a central control station. This can be done by adding stationary nodes that are programmed to only bounce any signal that is received. The system can be improved by adding more measuring devices to check the miner's blood pressure and heart rate. Gas concentrations can be measured as well. In future, it could also be considered if such modules can also be used for secondary services, such as localization of workers relative to each other [24].

REFERENCES

[1] M. A. Hermanus, "Occupational health and safety in mining—status, new developments, and concerns," *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 107, pp. 531-538, Aug. 2007.

[2] A.P. Squelch, "Virtual reality for mine safety training in South Africa," *The Journal of The South African Institute of Mining and Metallurgy*, pp. 209-216, July 2001.

[3] C. Qiang, S. Ji-ping, Z. Zhe and Z. Fan, "ZigBee Based Intelligent Helmet for Coal Miners," *IEEE World Congress on Computer Science and Information Engineering (WRI 2009),* 31 Mar. -2 April 2009, vol. 3, pp. 433–435, 2009.

[4] H. Hongjiang and W. Shuangyou, "The application of ARM and ZigBee technology wireless networks in monitoring mine safety system," *IEEE International Colloquium on Computing, Communication, Control, and Management (ISECS 2008)*, 3-4 Aug. 2008, Guangzhou, pp. 430–433, 2008.

[5] X. Liu, J. S. Huang and Z. Chen, "The research of ranging with timing over packet network for the mine safety application," *Journal of Networks,* vol. 7, no. 7, pp. 1054–1062, Jul. 2012.

[6] R. S. Nutter, "Hazard evaluation methodology for computer-controlled mine monitoring/control systems," *IEEE Trans. on Industry Applications*, vol. IA-19, no. 3, pp. 445-449, May/June 1983.

[7] R. S. Nutter, "A distributed microprocessor monitoring and control system for coal mines," *in Proc. 4th WVU Conf. on Coal Mine Electrotechnology*, Aug. 2-4, 1978.

[8] R. S. Nutter and M. D. Aldridge, "Status of mine monitoring and communications," *IEEE Trans. on Industry Applications*, vol. 24, no. 5, pp. 820-826, Sep./Oct. 1998.

[9] A. D. Kock and J. W. Oberholzer, "The development and application of electronic technology to increase health, safety, and productivity in the South African coal mining industry," *IEEE Trans. on Industry Applications*, vol. 33, no. 1, pp. 100-105, Jan/Feb. 1997.

[10] P. Misra, S. Kanhere, D. Ostry and S. Jha, "Safety assurance and rescue communication systems in high-stress environments: a mining case study," *IEEE Communications Magazine*, vol. 48, no. 4, pp. 66-73, April 2010.

[11] A. E. Forooshani, S. Bashir, D. G. Michelson and S. Noghanian, "A survey of wireless communications and propagation modelling in underground mines," IEEE Communications Surveys and Tutorials, vol. 15, no. 4, pp. 1524-1545, Nov. 2013.

[12] C. P. Kruger and G. P. Hancke, "Implementing the Internet of Things vision in industrial wireless sensor networks," *IEEE Int. Conf. on Industrial Informatics*, pp. 627-632, July 2014.

[13] A. Kumar and G. P. Hancke, "Energy efficient environment monitoring system based on the IEEE 802.15.4 standard for low cost requirements", *IEEE Sensors Journal,* vol. 14, no. 8, pp. 2557-2566, Aug. 2014.

[14] D. M. Han and J. H. Lim, "Smart home energy management system using IEEE 802.15.4 and ZigBee," *IEEE Trans. on Consumer Electronics*, vol. 56, no. 3, pp. 1403-1410, Aug. 2010.

[15] C. P. Kruger and G. P. Hancke, "Benchmarking Internet Of Things devices," *IEEE Int. Conf. on Industrial Informatics*, pp. 611-616, July 2014.

[16] K. Gill, S. H. Yang, F. Yao and X. Lu, "A ZigBee-based home automation system," *IEEE Trans. on Consumer Electronics*, vol. 55, no. 2, pp. 422-430, May 2009.

[17] J. Byun and S. Park, "Development of a self-adapting intelligent system for building energy-saving and context-aware smart services," *IEEE Trans. on Consumer Electronics*, vol. 57, no. 1, pp. 90-98, 2011.

[18] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, pp. 393-422, 2002.

[19] V. C. Gungor and G. P. Hancke, *Industrial Wireless Sensor Networks: Applications, Protocols, and Standards*, Published by CRC Press, 2013.

[20] ZigBee Alliance, "Zigbee wireless standards". www.didgi.com/ technology/rf-articles/wireless-zigbee

[21] Contiki os. Available: http://www.contiki-os.org/.

[22] B. Silva, A. Kumar and G. P. Hancke, "Experimental Link Quality Characterization of Wireless Sensor Networks for Underground Monitoring," *IEEE Trans. on Industrial Informatics*, vol. 11, no. 5, pp. 1099-1110, Oct. 2015.

[23] R. Fisher, L. Ledwaba, G. P. Hancke and C. Kruger. "Open Hardware: A Role to Play in Wireless Sensor Networks?," *Sensors,* vol.15, no. 3, pp. 6818-6844, 2015.

[24] AM Abu-Mahfouz and GP Hancke. "An efficient distributed localisation algorithm for wireless sensor networks: based on smart reference-selection method", *International Journal of Sensor Networks,* vol. 13, no. 2, pp. 94-111, May 2013