HeadgearX: a Connected Smart Helmet for Construction Sites

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Figure 1: Use case examples: a.b. front and back obstacle warning via directional red LED and scalp haptic feedback. c. automatic flashlight under in dark ambience (the obstacle warning also functions in darkness)

ABSTRACT

This work demonstrates a connected smart helmet platform, HeadgearX, aimed at improving personnel safety and real-time monitoring of construction sites. The smart helmet hardware design is driven by flexible and expandable sensing and actuating capabilities to adapt to various workplace requirements and functionalities. In our demonstrator, the system consists of ten different sensors, visual and haptic feedback mechanism, and Bluetooth connectivity. A companion Android application is also developed to add further functionalities including those configurable over-the-air. The construction project supervisors can monitor all on-site personnel's real-time statuses from a central web server which communicates to individual HeadgearX helmets via the companion app. Several use case scenarios are demonstrated as examples, while further specific functionalities can be added into HeadgearX by either software reconfigurations with the existing system or hardware modifications.

CCS CONCEPTS

• **Computer systems organization → Embedded systems**.

KEYWORDS

sensors and actuators, smart construction, user experience

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1 INTRODUCTION

Construction site personnel encounter various hazardous elements and events on a daily basis. The construction sites are also ever changing with the projects' progress. There have been studies trying to leverage the Internet-of-Things and embedded wearable systems to help better understand the construction personnel's collaboration and personal safety [3, 5].

We introduce HeadgearX, a connected safety helmet augmented with various sensors and actuators that constantly monitors the construction personnel's activities and surrounding. The helmet provides timely feedback via haptic and visual cues. HeadgearX is tethered via Bluetooth with the worker's smartphone, which then communicates with the rest of the on-site personnel as well as a web server (which the project management may access) via its wireless network. Our HeadgearX solution provides real-time transmission and notification.

2 FUNCTIONALITY-DRIVEN HARDWARE

The HeadgearX hardware architecture is designed with functional versatility and expansion in mind. We envision that the *functionality* (e.g. wearer detection, element exposure, alarm, etc.) is a software-configurable layer. The *functionality* layer is built on top of the hardware *capability* layer (e.g. proximity sensor, atmosphere sensor, haptic motor, etc.). To achieve this goal, the system needs to

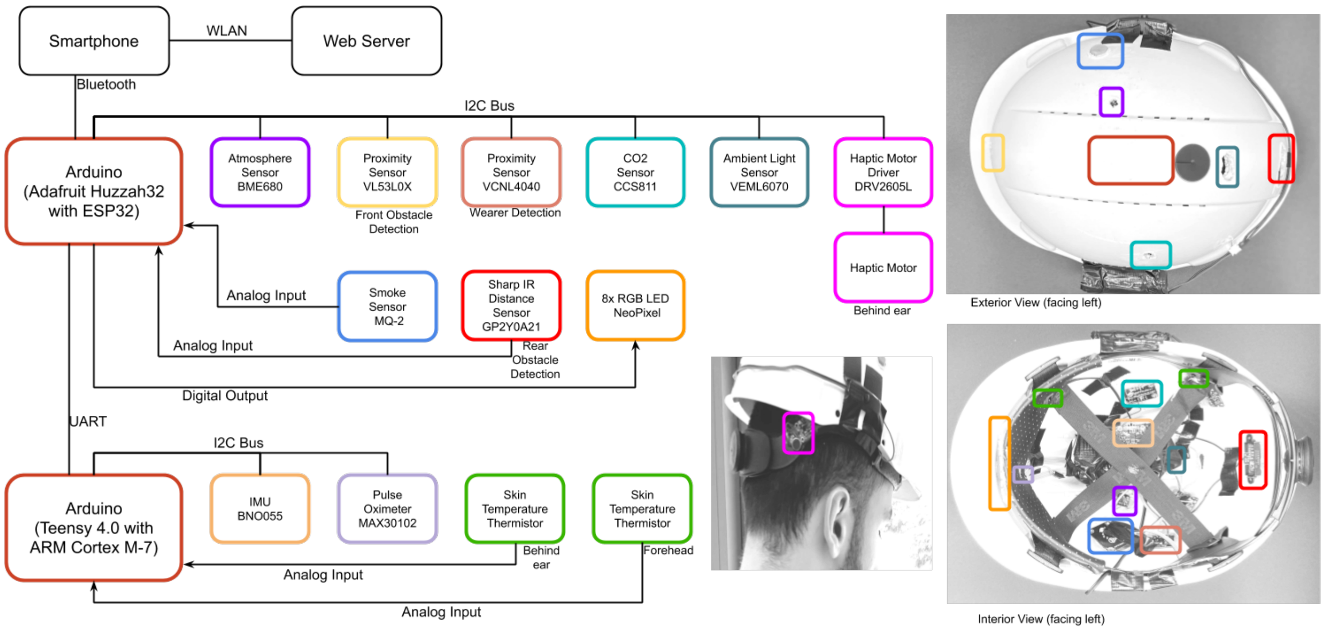

Figure 2: Overall Diagram

accommodate various sensors and actuators, which often of heterogeneous nature. We selected the Arduino ecosystem for its rich collection of sensors, actuators and microcontroller units (MCUs) that are all easily accessible.

2.1 Hardware Capabilities

Figure 2 shows the hardware structure of the HeadgearX prototype. We use two Arduino-compatible MCU boards: Adafruit HUZZAH32 with a dual-core ESP32 microprocessor and Teensy 4.0 with a single-core ARM Cortex M-7 microprocessor. All the sensors were placed inside the helmet. Apertures were opened for specific sensors to receive exterior data such as proximity, UV light, smoke etc.

Most of the sensors are connected through the I2C bus to the MCU. We designed the hardware with two different Arduino boards to reduce the electrical load on the I2C bus and the computational load on each processor, which also enables easy future expansions.

Some sensors output analog values, requiring analog input pins. The LED strip is controlled by a digital pin with its own protocol. The two MCUs communicate with each other through the UART interface. The HUZZAH32 streams both, its sensors' data and the data received from the Teensy board, to the smartphone through Bluetooth.

The system is powered by a single cell Li-ion or Li-Po battery with the nominal voltage of 3.7V. The majority of the components operate on 3.3V voltage, with the exclusion of several components that requires 5V. A power booster (Adafruit PowerBoost) converts the 3.7V power input to 5V to supply those components, which also supports further expansion for components that also require 5V.

The power consumption is measured with the R&S HM7042-5 power supply under different operating conditions: **Idle**, when all hardware is initialized and idle, the whole system consumes 480 mA. **Streaming**, when the NeoPixel LEDs are turned off, while the Bluetooth is streaming all the data, the whole system consumes 580 mA. **Peak**, when the LEDs are turned on (white full brightness) and the Bluetooth is streaming all sensor data, the whole system consumes 890 mA.

2.2 Wearer Awareness Functionalities

The following functionalities allows the system to monitor and interact with the wearer.

Motion Activity provide information about the wearer's physical state and can be leveraged to implement activity recognition functionalities [1, 4]. A *BNO055* 9 degree-of-freedom IMU sensor is used for this functionality.

Wearer Detection checks if a person wears the helmet correctly. VCNL4040 is used to detect if the helmet fits a user's head properly. It is a proximity sensor with a precise range up to 200mm. Compared with other prior approaches that we have tried such as a light sensor inside the helmet, this setup removes the false positive cases when the helmet is laid on a surface or hanged against a wall.

Vital Signals gives critical information about the personnel's health conditions, especially in hazardous environments. For body temperature, we use two *thermistors* (temperature sensitive resistors) on the inside of the helmet's harness, touching the user's the skin at the forehead and behind the ear. A *MAX30102* pulse-oximeter sensor is located at the harness's forehead part to monitor the wearer's heart-rate and blood oxygen levels.

Visor Visual Cue functionality is useful to deliver notifications as the construction sites can usually be noisy. In our prototype, a *NeoPixel* 8x RGB LED array is positioned on the helmet's forehead harness, shining into the helmet's visor. The LED array is reflected to the user's eyes from the helmet's visor, providing vivid but not distracting visual cues. We've tested 15 different patterns with several users in our evaluation, including static patterns, such as directions and color/position-coded notifications, and animated patterns such as a pixel moving to one direction.

Haptic Feedback can also be helpful when the visual cue is difficult to distinguish, or when the person is visually distracted due to the on-site environment. A *DRV2605L* haptic motor driver is placed at the helmet's rear harness, which the user can feel at the back of their scalp. Through our test, some users comment on the haptic feedback as 'very pleasant'.

2.3 Environment Awareness Functionalities

Our system also has a rich capability to provide awareness of the user's environment.

Atmosphere Awareness requires information about the exterior elements such as humidity, gas resistance, temperature, air pressure, specific gas, etc. We included various sensors for these functionalities, including the *BME680* (atmospheric sensor), *MQ-2* (analog sensor for smoke, Liquefied petroleum gas - LPG, and carbon monoxide - CO levels), and *CCS811* (air quality gas sensor for total volatile organic compounds - TVOC and carbon dioxide - CO2 levels).

Obstacle Proximity allows to detect obstacles surrounding a user, especially when their attention is occupied. We included different proximity sensors in our prototype to demonstrate the flexibility of the system. *VL53L0X* (time-of-flight digital sensor with up to 2m range) is used for the froward direction and *GP2Y0A21* (infrared analog proximity sensor with up to 80cm range) is positioned for the backward direction.

UV Light Exposure is of growing concern in the industry as they can be harmful for the user after prolonged exposure [2]. We use *VEML6070* for this functionality.

Automatic Flashlight can be helpful in many construction settings. The *VEML6070* that is used for the UV exposure functionality can also provide darkness detection. The NeoPixel LEDs for the visor feedback can also provide white flashlight. the LEDs can provide white light with 8 candela brightness at close range, which is sufficient to light up the wearer's surrounding. It is strong enough for the user to read documents at normal range in the dark. Yet with the visor directing the light downwards, as shown in Figure 1c., it will not blind other personnel.

3 USABILITY AND COMMUNICATION

3.1 Programmable Functionalities

Figure 1 demonstrates some use cases of HeadgearX. Once the physical hardware *capabilities* are fixed, there is still a great degree of flexibility in the *functionality* layer to adapt the system to different usecase scenarios. Many functionalities can be combined or reconfigured.

For example, the users can distinguish the direction of the obstacle proximity from the visor's color combination, i.e. front obstacles is indicated by red colors in the center of the visor and the back obstacles is indicated by red colors on both ends of the visor. The visor visual cue can still function when the flashlight is on. The wearer can see the clearly light pattern reflected from the visor of the safety helmet, which is subtle and not distracting even with the full brightness flashlight function. These combinations can warn the users of dangerous obstacles in the darkness.

Also, the wearer detection function can be further improved by combining the user's vital signals. Combined with the motion activity, as the data can be send to the manager's central server, 'agent down' or 'slack detection' can be readily implemented in the software to help improve the workplace safety and efficiency.

3.2 Companion Smartphone Application

A companion Android application is developed for the user of the HeadgearX helmet to provide additional functionalities and connectivity (Fig. 3). The user interface contains 5 tabs: 'Connect', 'User', 'Environment', 'Chat' and 'Settings'. After pairing the app with the helmet via Bluetooth, the data from multiple sensors is being received and processed in real-time in the background on the smartphone, and visualized together as smaller plots in the 'User' and 'Environment' tabs depending on the category of the sensor. The 'User' tab includes the sensors related with the user awareness functionalities such as heart-rate, blood oxygen saturation and body temperature. The 'Environment' tab contains graphs for ambient temperature, pressure, humidity, altitude, and various gas indicators that are relevant for construction applications, including gas resistance, carbon monoxide, carbon dioxide, smoke, total volatile organic compounds (TVOC) and liquefied petroleum gas (LPG). Pressing on any plot will extend the view with the numerical values. Since the HeadgearX contains the IMU sensor. Its values can be used for construction related activities recognition, such as building, carrying an object, welding etc [1]. For this purpose, pedometer and activity blocks are reserved in the 'User' tab as further development for motion activity functionalities. The user can communicate with other co-workers in the 'Chat' tab. The 'Settings' tab offers a range of miscellaneous and useful functions, including checking battery level, setting parameters for the embedded system over-the-air, setting warning threshold for certain sensor values. It also includes debugging options, such as logging and exporting data, sending custom command to the HeadgearX device. The app also prompts notifications upon defined events, for example, above-threshold values of the smoke or LPG levels. For example, the user can set a threshold value of a dangerous gas on the companion app, and the system will provide alarm through the visor's visual cues, haptic feedback, as well as the app's notification and sound.

3.3 Centralized Web Server

A web server based on the Firebase framework is implemented to gather the data from individual smartphones to a centralized computer where the construction project management can monitor the on-site personnel's real-time status (Fig. 4).

The HeadgearX streams sensors data to a smartphone through Bluetooth. The smartphone writes received data into the Firebase cloud-hosted real-time database. The website, which is also hosted on the Firebase, retrieves the data from the database and visualizes the data on the webpage. A user can reach the website through any device connected to the internet: smartphone, pc, tablet etc. On the website a list of workers appears. By clicking on any worker in the list, all the data and current status of a specific worker can be observed.

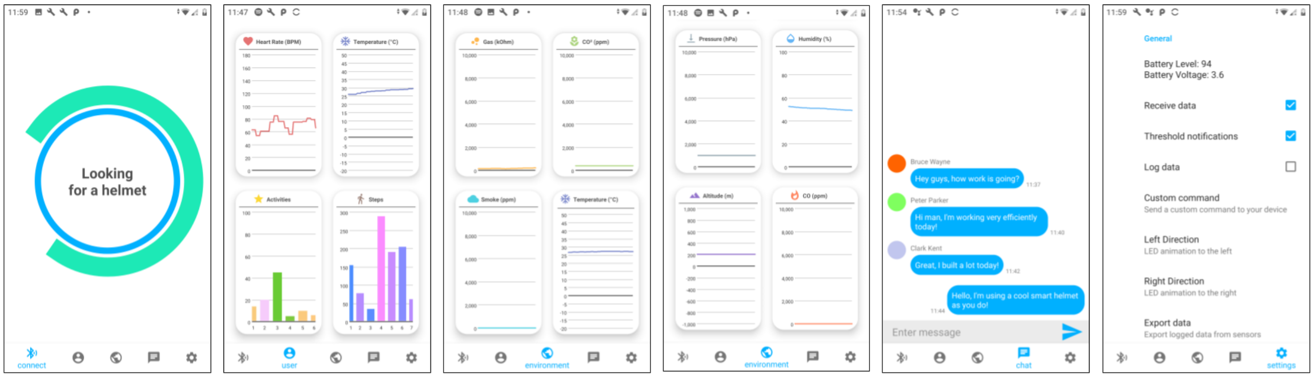

Figure 3: Mobile Application

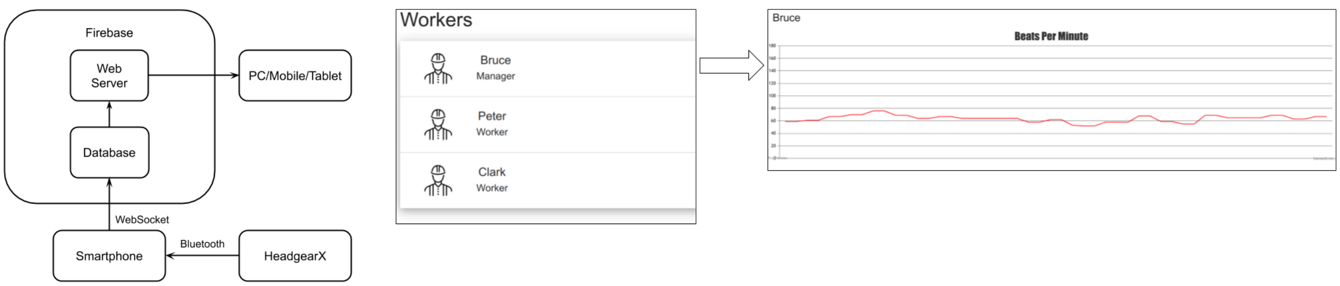

Figure 4: Web Application for Managers

On the other hand, managers can communicate with workers, they can broadcast emergencies or individual notifications. The data flow in that case will be in reverse order.

4 CONCLUSION AND OUTLOOK

In summary, HeadgearX provides a flexible sensing platform for building connected smart helmets. Our demonstration prototype includes hardware capabilities of ten sensors and two types of actuators. The architecture supports further expansion or reduction of sensing and feedback capabilities. A smartphone companion application and web server are developed to elaborate the connectivity of the HeadgearX system. On top of the hardware capabilities, companion app, and web server connectivity, various functionalities can be programmed, from the basic wearer or environment awareness, to more complex usecases.

Our future work will focus on bringing the system to the construction sites. In our system, most of the components are off-the-shelf modules. Integrated circuit design can deduce the footprint once the desired sensing and actuation capabilities are fixed for specific requirements. Moreover, most of the sensors contain embedded sleep mode functionalities, which can be also leveraged to improve the overall power consumption. As a safety helmet, the space between the harness and the shell is supposed to be a safety buffer zone. For the showing of concept, most of the electronics are placed inside this buffer zone. As part of the future exploration, we will look into integrating designs while addressing ergonomics, safety and robustness concerns.

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