Automated PPE Misuse Identification and Assessment for Safety Performance Enhancement

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Abstract

The misuse (including nonuse) of personal protective equipment (PPE) directly catalyzes the changes from incidents to critical accidents and diseases. The main control over PPE use is visual inspections, which is time-consuming and its effectiveness depends largely on the observer's safety knowledge and experience, which often results in omissions or bias. To solve this problem, this study introduces a novel approach towards automated remote monitoring and assessing how the PPEs are worn. The real time location system (RTLS) and virtual construction are developed for worker's location tracking to decide whether the worker should wear helmet and give a warning, while the silicone single-point sensor is designed to show whether the PPE is used properly for further behavior assessment. The process of data synchronization and fusion of location coordinates and pressure data is described in detail and the system is tested in an open area experiment to prove its feasibility.

INTRODUCTION

According to Occupational Safety and Health Council (OSHC), PPE means any protective equipment that protects users from being exposed to a potentially hazardous environment. Undoubtedly, using PPE is a factor which would be positively correlated to safety performance on construction sites and became one of the most important factors affecting safety performance (Sawacha et al. 1999). Unluckily, PPE misuse is often neglected because current assessment is mainly focused on visible outcomes such as critical injuries and accidents, and it is hard to identify hazardous behaviors in time. PPE misuse records are mainly kept by self-reporting, which is inhibited by a blame culture for error, time-consuming paperwork, and lack of feedback on how the information reported has been used (Vander And Kanse 2004). To solve these problems, current activities mainly involve modifying PPE use behavior through safety regulations and training (Kaskutas et al. 2013), and improving safety attitude through better organizational safety culture (Fung et al. 2012). These methods are useful but do have disadvantageous such as: being unable to remedy the limitations of human vision and ability to detect all surrounding danger sources; largely relying on wandering inspection and lagged (outcome) measurement, which leads to biases and fails to provide feedback to change unsafe behaviors in time.

To realize efficient behavior inspection, many technologies like Mobile passive Radio Frequency Identification (RFID) was applied to perform automatic site access, time recording, and completeness control (Kelm et al. 2013). And there was cyber physical system set up for real-time PPEs monitoring by keeping the PPEs in close range (Barro-Torres et al. 2012) But regretfully, these similar methods and technologies have three weaknesses: cannot ensure workers use PPEs properly since being close to the body does not mean use; or do not take conditions into consideration where different kinds of PPEs are needed, and the wearable devices are heavy and uncomfortable.

METHODOLOGY

All these PPE misuse behaviors are reminded by warnings and assessed according to the later responses represented. Only if the worker enters the danger zone without PPE, the alarm will be given for reminding. Then if the worker still doesn't wear the PPE after a certain response time, this behavior will be recognized as a misuse behavior. At the beginning of the decision cycle, danger zone where need to wear PPE is identified based on a full discussion with experienced project managers and safety officers such that:

$$F \overset{\Delta}{=} \left\{ (x_1, x_2, x_3) \in R^3 \middle| \bigcap_{i=1}^{m} N_i X \le n_i \right\}; X = (x_1, x_2, x_3), i = 1, 2, \cdots, m \tag{1}$$

where (x_1, x_2, x_3) are the coordinates of points in the danger zone, and the danger zones can be designed as a space, a plane, a line or a dot. Workers are informed through training of the danger zones and this training can be used to improve safety by directing attention to PPE misuse. In the inspection and assessment phase, traditional manual observations and subjective judgments are substituted by automated misuse warning and response assessment:

$$g(Y,t) = \begin{cases} 1; & Y \in F, P(Y) = 0 \\ 0; & else \end{cases} \tag{2}$$

where the worker's real-time location Y and helmet pressure $P(Y)$ are measured by positioning and sending technologies and recorded in a database. If the worker enters a danger zone ($Y \in F$) without a helmet ($P(Y) = 0$), a misuse warning rings out as in-time feedback to workers. After this warning, the unqualified behavior is identified by:

$$g(Z, t+\Delta t) = \begin{cases} 1; & Z \in F, P(Z) = 0 \\ 0; & else \end{cases} \quad (3)$$

where Δt denotes the response time after the warning. In this phase, there are two kinds of corresponding activities: a) if the worker is still located in danger zone ($Z \in F$) PPE ($P(Z) = 0$), this behavior is recognized as a misuse response; but b) if the worker leaves the danger zone ($Z \notin F$) or takes on the PPE ($P(Z) = 1$), this response is regarded as a safe behavior.

The timestamps are encoded into float numbers by seconds starting from the beginning of each experiment. For three kinds of data shown in Figure 1, video time is regarded as the ground truth, and it is assumed that the propagation of time difference consists of two parts: initial time shift and continuous time shift:

$$\Delta t_i = \Delta t_0 + \alpha t_{sensor}; \quad \Delta t_i = t_{video,i} - t_{sensor,i} \quad (4)$$

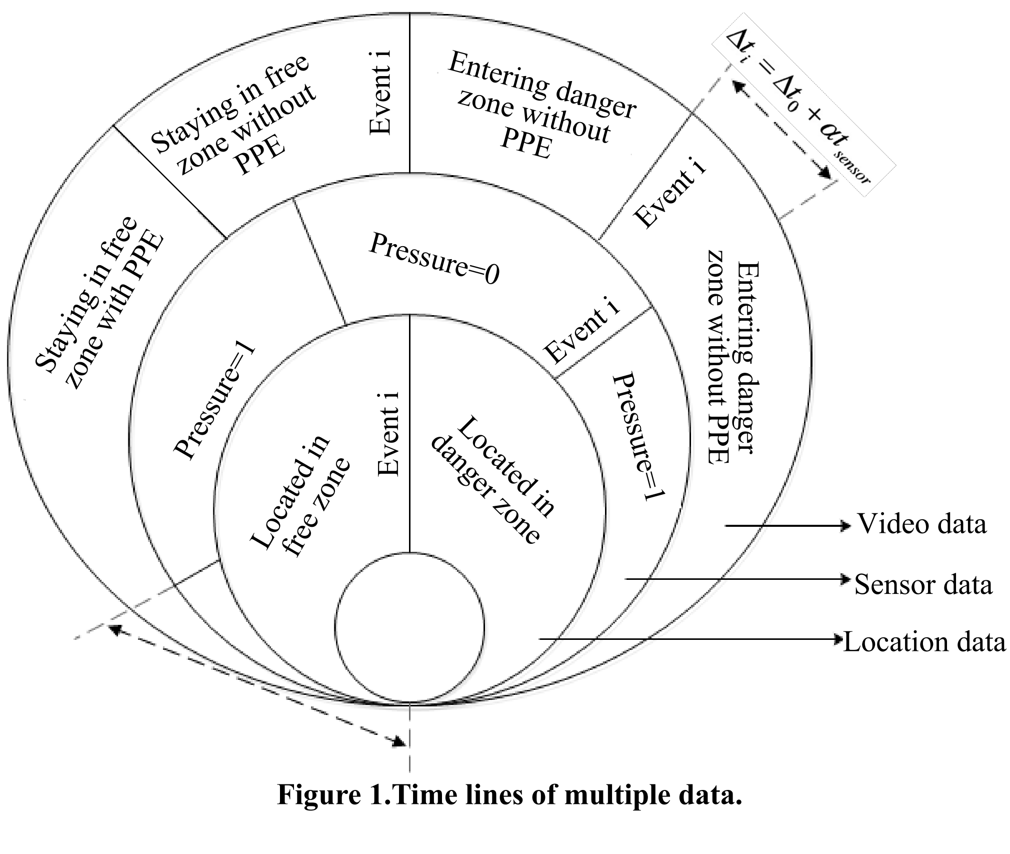


Figure 1.Time lines of multiple data.

Where Δt_i means time lag between sensor and video when a specific event i occurs. An event refers to taking on/off PPE or moving between free and danger zones. Term $t_{video,i}$ is the video time when event i (e.g., enter a danger zone without PPE) is observed. While term $t_{video,i}$ is the event i time recorded by sensor's clock. When $i = 0$, t_i refers to the initial status of location system and sensor when they start recording data, then Δt_0 represents the initial time shift between sensor and video recordings. In addition, αt_{sensor} refers to the built-in drifting time of sensor, where α is time adjustment factor correcting the second from sensor to be equal to the video. A positive α means the sensor clock runs slower than video clock while the negative one indicates the opposite situation. To calculate the parameters α and Δt_0. The linear time lag propagation algorithm is applied on a set of random events, which is shown as:

$$\alpha = \frac{\sum\left(t_{sensor,i} - \bar{t}_{sensor}\right)\left[\Delta t_i - \left(\bar{t}_{video} - \bar{t}_{sensor}\right)\right]}{\sum\left(t_{sensor,i} - \bar{t}_{sensor}\right)^2} \quad (5)$$

Once the time lag propagation parameters are determined, the time of sensor and video can be synchronized:

$$\hat{t}_j = \Delta t_0 + (1+\alpha)\, t_{sensor,j}; \quad \varepsilon = t_{video,i} - \hat{t}_j \quad (6)$$

Where $\hat{t}_j$ predicts time on the corresponding video timeline. Event j is recorded from the sensor at sensor time $t_{sensor,j}$ and ε means predicted error.

SYSTEM ARCHITECTURE AND APPLIED TECHNOLOGIES

This multi-user on-line supporting system, which is named as PPEs Use Management System (PUMS), consists of three parts: Real Time Location System, Virtual Construction System and PPEs Sensing System shown in Figure 2. Real Time Location System applies tags and reference anchors in detecting and sending the ranging information through wireless signals. And Virtual Construction System is responsible for measuring the relative 3D positions of workers and their surrounding danger sources/zones, and recording real-time 3D movements of workers and moving equipment. Meanwhile, PPEs Sensing System is developed for sensing, collecting, transferring and saving the PPE use status. If deemed necessary by PUMS, warnings will be sent to alert workers through tags installed on their helmets.

The PUMS comes true by help of four main parts shown in Figure 3: End nodes, repeater/checkpoint and coordinator. End nodes are the critical part of the system which is worn by workers and responsible for gathering information about PPEs and location. These devices are composed by a central unit microcontroller to regulate the behavior of the device, a pressure button sensor for pressure information collection and a radio module for location detecting and transmitting information. After the data is collected, the repeater or checkpoint will help the end nodes connect with coordinator wirelessly. At last, the coordinator will collect, store and synchronize the data from pressure sensor and location. It is also responsible for node configuration and activating alarm.

Specifically, Chirp Spread Spectrum (CSS) technology is employed for ranging, which estimates physical distance between two devices by Time of Flight (TOF) of radio frequency signals. CSS is a spread spectrum technique defined in the

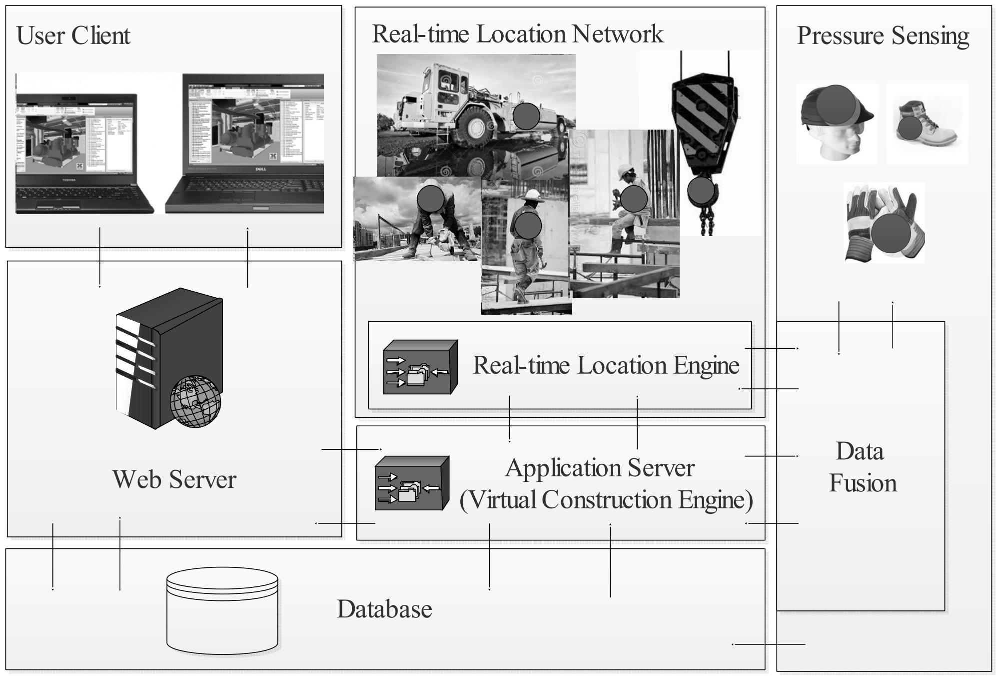


Figure 2.General architecture of PUMS.

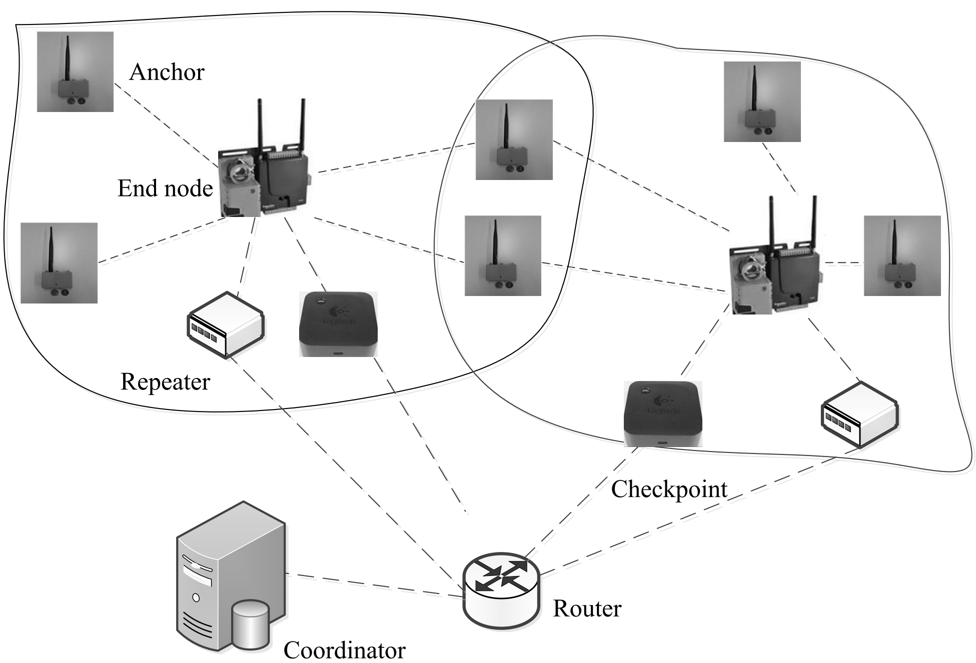


Figure 3.System deployment.

standard IEEE 802. 15. 4a (Cho and Kim 2010) and uses wideband linear frequency modulated chirp pulses to encode information which is relatively less time-consuming, robust against disturbances, against multipath fading, low power consumption and easy to implement in silicon. Based on price/responsiveness ratios and their capacity to resist harsh conditions of construction, silicone single-point sensor is initially selected to detect if PPE is being worn by the site workers. PPEs Sensing System is developed for integrating sensor technologies and wireless communication, as indicated in Figure 4. Sensors automatically track real-time behavioral data on whether real-time behavioral data indicating whether workers are wearing the required PPEs and transmitting through Bluetooth technology.

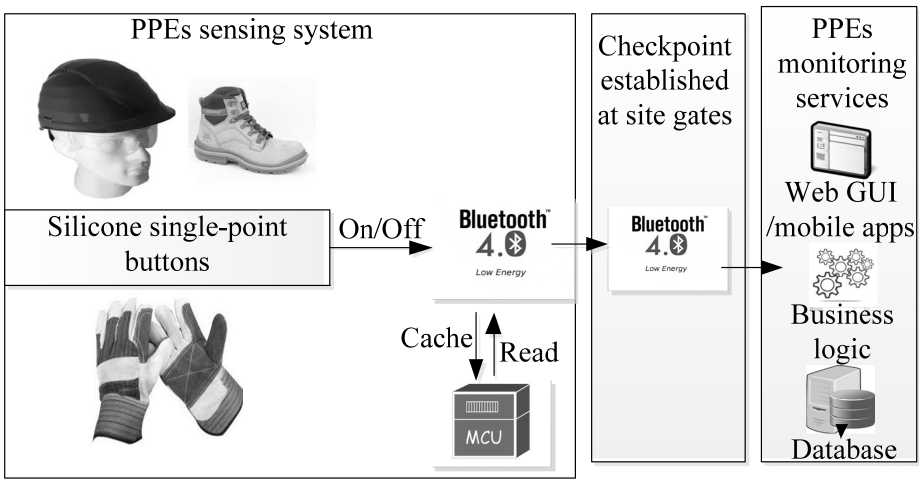


Figure 4.Sensing system architecture.

EXPERIMENT

Since PPE misuse behaviors involve multiple scenarios and complicated operations, this study selects safety helmet in the primary experiment because the head is the most critical area of a human body and severe trauma to the head can lead to death or long-term disability. Helmets not only prevent the skull from being perforated but also dampen the force of the impact object transmitted to the wearer (Long et al. 2013). It can be effective in reducing both head accelerations and compressive neck forces for large construction objects in vertical impacts (Suderman et al. 2014).

Experiment setting. The experiment was designed at the North Court of Hong Kong Poly Technic University to simulate construction tasks. This open test site is surrounded by many tall buildings and has many stairs, which is incident-prone and similar to the real construction site. Two research staffs, named as Tag 1, Tag 2, shown in Figure 5, were selected from Construction Virtual Prototype Laboratory as the tracking objectives and were required to act many scenarios on the test site and this test was conducted from 1 PM to 3 PM.

According to The US Department of Labor’s Occupational Safety and Health Administration (OSHA) requires employees to wear head protection if: objects might fall from above and strike them on the head; they might bump their heads against fixed objects; or, there is a possibility of accidental head contact with electrical hazards. As a result, two danger zones were identified in system: danger zone 1 (DZ1) was a macro slope with many stairs and danger zone 2 (DZ 2) was between two buildings. The parameters of the danger sources were recorded on a map or virtual model such as in figure 5, including the danger type and the shape, radius and location of the danger zone. And then the anchors were added on map with their coordinates as location references. For real time tracking, tags fixed on helmets were utilized to track the location of workers. The tags were then matched with the personal information of the workers, such as work type and permission to work in the danger zone. Through careful calculation and prolonged discussion among those involved, the response time to the warning signal was set as 3 seconds.

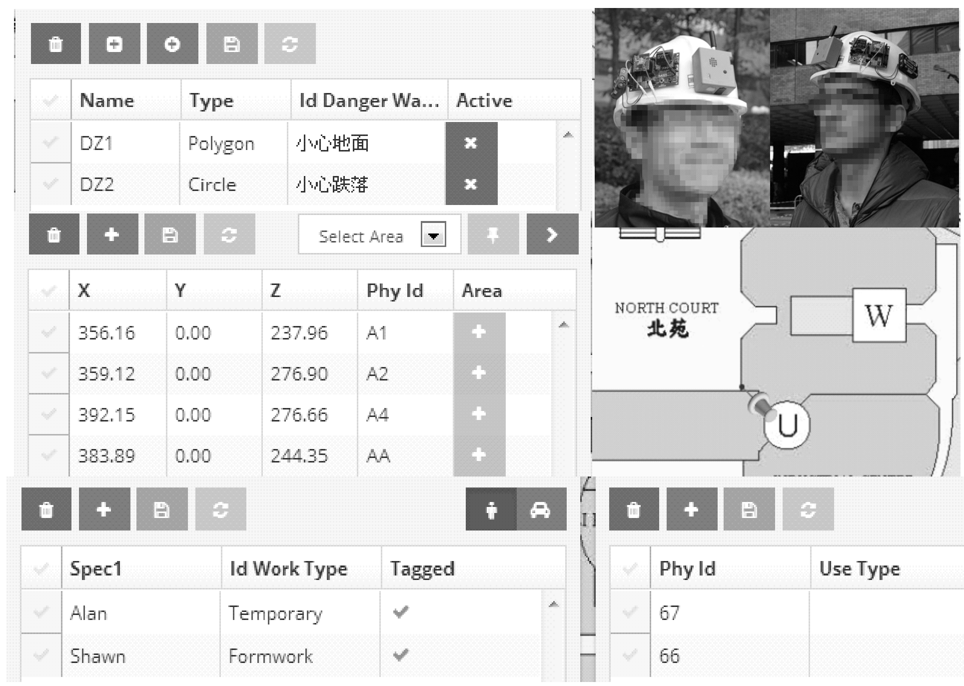
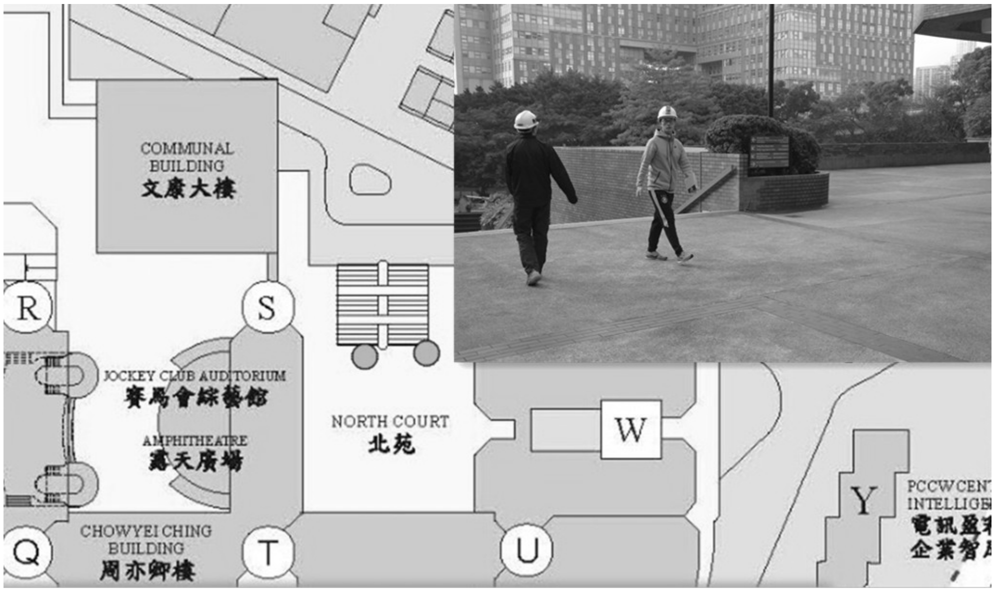


Figure 5.Endnote devices and experiment deployment.

Data analysis. The real time location of the work site was calculated and synchronized on the virtual map as shown in Figure 6(a), where the green spots indicate the movement of tag carriers. Meanwhile, the status of helmet use was synchronized and shown on computer, which is illustrated as Figure 6(b). The synchronized movement, the real-time coordinates of both the tag carriers, and helmet use status were recorded in the database as video, (X, Y, Z) and 0/1 respectively. Since the signals can be distorted by occasional outliers, a Robust Kalman Filter was applied to reject outlier measurements shown Figure 7. Since there had been no similar cases previously, two representative scenarios were chosen as examples for the response analysis. As indicated by the results shown in Figure 8, the first misuse warning was triggered by being in danger zone without helmet and the carrier ignored the danger warning. This was identified by the system and recorded as unsafe behavior. In another case, the carrier put on the helmet within 3 seconds of the warning and this it was therefore not recorded as a misuse behavior.



(a)

Helmet Phy Id	Time On	Time Off
6DE98E9D667C	09:10:49.000 26/03/2015	09:10:52.000 26/03/2015
6DE98E9D667C	09:11:09.000 26/03/2015	09:11:23.000 26/03/2015
6DE98E9D667C	16:05:55.000 23/03/2015	16:05:57.000 23/03/2015
6DE98E9D667C	16:06:50.000 23/03/2015	16:06:53.000 23/03/2015
6DE98E9D667C	16:07:41.000 23/03/2015	16:07:45.000 23/03/2015
6DE98E9D667C	15:26:20.000 13/03/2015	15:27:30.000 13/03/2015
6DE98E9D667C	15:25:17.000 13/03/2015	15:25:49.000 13/03/2015
6DE98E9D667C	15:20:09.000 13/03/2015	15:20:33.000 13/03/2015
6DE98E9D667C	15:18:41.000 13/03/2015	15:18:55.000 13/03/2015

(b)

Figure 6.The synchronization and visualization of locations and pressures.

A total of 91 helmet misuse records occurred during the trial time and were recorded in database for further personal safety performance assessment. These are shown in Figure 9(a) in terms of the warning times of each tag carrier in different danger zones during various working times. Danger zone 1 (DZ1) was associated with much more warnings than DZ2. And Tag carrier 2 (TAG2) had much more warnings, which suggests that safety managers should pay special attention to this worker and provide him with more reminders and instructions. What's more, the misuse warnings can be compared chronologically like Figure 9(b) to investigate the effects of in-time feedback and interventions on safety performance.

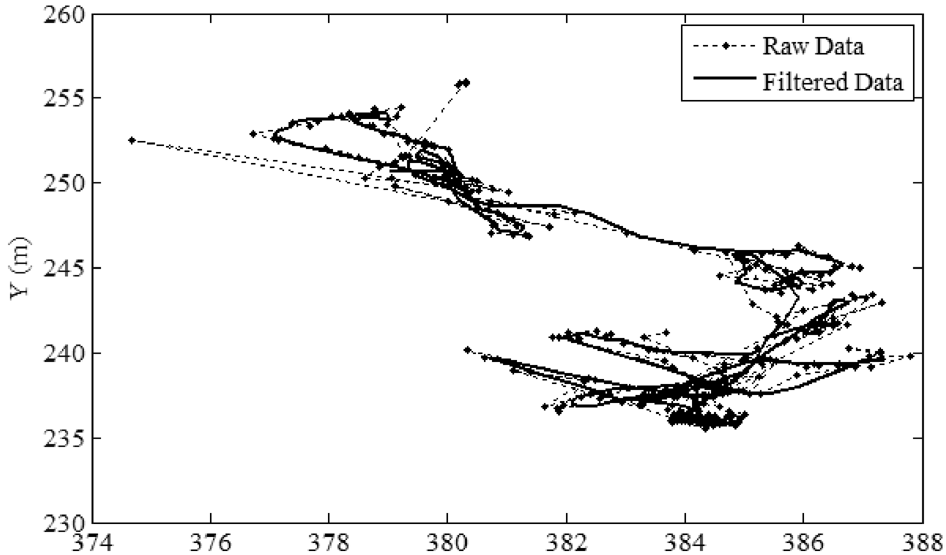


Figure 7.The Robust Kalman filter example.

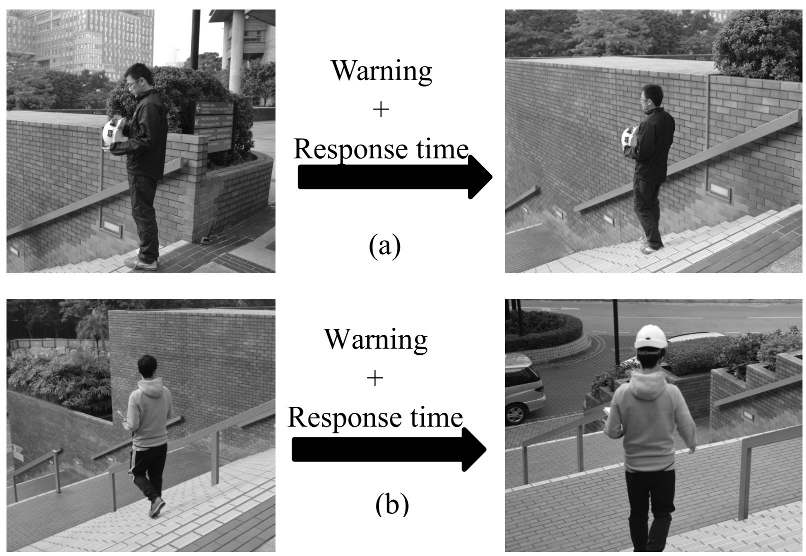


Figure 8.Helmet misuse behavior assessment.

CONCLUSIONS

Traditional PPEs use management methods have failed to be widely effective because it is highly dependent on a manual and experienced inspection process, and lacks accurate personal assessment and timely feedback. This paper solves this problem by providing an effective approach to automatically identifying PPEs misuse behaviors with integrating positioning technology and pressure sensor, and assesses the personal safety performance of workers according their response to danger warnings. This involved the development of a supporting multi-user platform to obtain the real-time position of workers in relation to virtual hazardous zones. A controlled open field experiment study was conducted that verified its ability to identify PPEs misuse behavior in specific condition, issue timely warnings and capture worker responses. The warning and response data were then analyzed to assess individual safety performance and locations over time for effective safety behavior improvement.

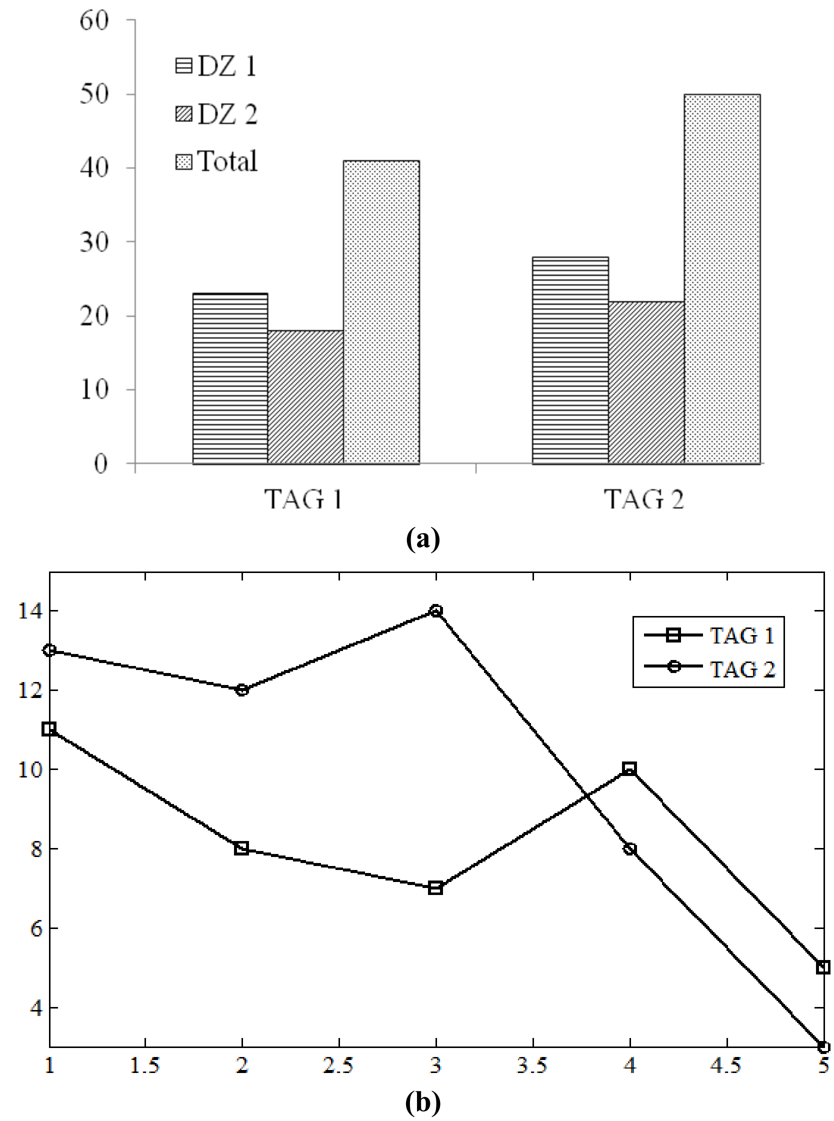


Figure 9.Statistical analysis results.

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