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Bluetooth-based positioning techniques for the cold chain application

Abstract: In cold chains, the essentials of cold storage are the chilling and freezing storage sections. Due to occupational safety concerns for the warehouse workers in such a cold environment, this paper describes a Bluetooth-based Access Management and Positioning System (BAMPS) to monitor worker location and movement in chillers and freezers, inspired by the growth of Internet of Things. In complying with the ISO11079, their occupational safety in term of exposure duration and recovery time in cold environments can be controlled. The Bluetooth Low Energy module is used for the transmitting and receiving sensing data in the cold storage environment. The positioning module is designed using Kalman filtering to eliminate signal variations instead of pre-requested calibration. Hence, the workplace ergonomics and monitoring in cold storage environment are enhanced. The significance of BAMPS is in exploring occupational safety management and real-time positioning in cold storage facilities.

Keywords: positioning techniques; occupational safety; cold chain; Bluetooth Low Energy; Kalman filtering

1. Introduction

With fierce market competition in the supply chain for fresh agricultural products, frozen food and pharmaceutical products, the cold supply chain has become a current focus of supply chain management nowadays. Unlike conventional supply chain management, products in cold supply chains usually have shorter shelf life as well as high environmental sensitivity, particularly temperature and humidity (Chen et al., 2014). It implies that the products need to be refrigerated and monitored under tight environmental control during transportation and storage. Since the warehousing tasks are labor-intensive, in a cold environment, the focus of this study is to explore the occupational safety concerns and remedy measures in cold storage facilities. In general, chillers and freezers which are maintained at low ambient temperatures are two types of cold storage facilities used in cold chain operations. As product handling takes place in hard environmental conditions, warehouse workers encounter two major problems, as illustrated in Figure 1. Firstly, it is dangerous for an operators' health and safety aspect to work without any alerts and controls related to work duration and conditions in such a cold environment. It may lead to poor monitoring strategies and unguarded facility hazards, resulting in high accident frequency rates and ineffective warehouse management (Vela-Acosta et al., 2002). Secondly, lack of real-time traceability of workers inside a cold storage facility is another problem; being time-consuming to locate a worker if any accident occurs. Therefore, access control and positioning of warehouse workers are essential to improve the workplace comfort, ergonomics as well as operational efficiency.

As a result, an effective access management and positioning system is necessary with regard to the health and safety concerns in the cold storage workplace. With the growth of Internet of Things (IoT) paradigm, a Bluetooth-based access management and positioning system (BAMPS) is proposed in this paper, with the adoption of wireless communication technologies to identify and locate workers inside cold storage facilities. The focus of the design of BAMPS is calibration-free with simple and rapid system installation and implementation. In order to generate improved identification and positioning results, the Kalman filter is used in reducing signal noise, thus resulting in less fluctuations of positioning. Through making use of the measured location and the exposure duration to the cold environment, ISO11079 can be complied with to enhance the occupational safety management in cold storage facilities. ISO11079 is an international standard for improving the ergonomics of the cold environment through determining the cold stress by using required clothing insulation (IREQ) and local cooling effects (International Organization for Standardization, 2007). The work duration inside the cold storage facilities and corresponding recovery time should follow the ISO11079 measurements.

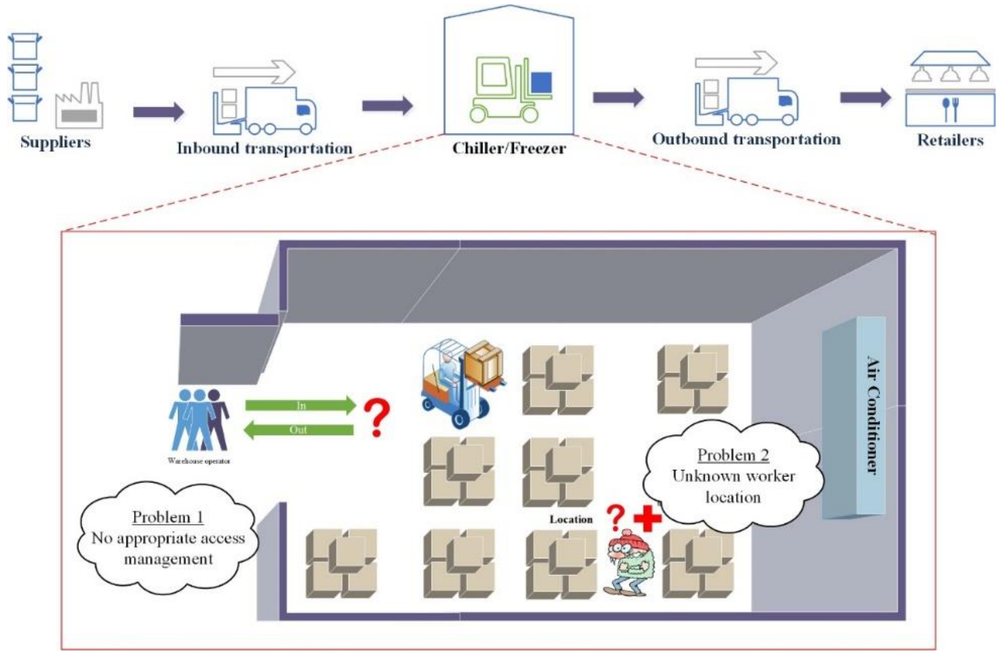


Figure 1. Existing problems of warehouse operators in cold storage

This paper is divided into six sections. Section II is the literature review which consists of an overview of the cold supply chain, comparison of wireless communication technologies, positioning algorithms as well as data processing techniques. The system architecture of BAMPS follows as Section III. Section IV is a case study to investigate the feasibility of the proposed system, followed by the results and discussion of BAMPS in Section V. Conclusions are drawn in Section VI.

2. Literature Review

Cold chain logistics play an important role in the supply chain for the huge production and consumption of products in two primary sectors, namely refrigeration and transportation (Kuo and Chen, 2010). Basic cold chain operations include production, processing, transportation and distribution, which is similar to conventional supply chain management (New and Payne, 1995). However, the cold supply chain has higher requirements in information integrity, data transference, and product quality (Chen et al., 2013; Chen et al., 2014). The environmental conditions and use-by-date are two significant factors for cold chain products, controlled by several standards and regulations, such as Hazard Analysis Critical Control Point (HACCP), Good

Agricultural Practice (GAP) and Food and Drug Administration (FDA) (Likar and Jevšnik, 2006; Marine et al., 2015). In order to maintain and monitor the prescribed product quality in a cold chain, enabling technologies including freeze-chill technology and temperature indicators are applied to control and record the information in cold supply chains (Gormley et al., 2000). These technologies are applied to cold storage facilities, for example the chiller and freezer, to keep the products in an appropriate storage environment. In view of such a cold working environment, there is a significant workplace hazard to warehouse workers, resulting in high risks of cold injury and illness, such as hypothermia (Thomas et al., 2001; Anderson and Chun, 2014). However, there is limited research related to designing and developing a systematic approach for enhancing occupational safety in the cold storage facilities. ISO11079 compliance is used in the study as it is an international standard for enhancing the workplace ergonomics in indoor cold environments, and provides systematic evaluation on the maximum exposure duration, required clothing insulation and recovery time. A computerized ISO11079 program is developed, having a simple table for inputting the required parameters for conducting the evaluations (Holmér, 2009). Although the ISO11079 program is well-developed, the execution and management of this standard in cold storage facilities is poor which should be enhanced by using certain enabling technologies. Radio Frequency Identification (RFID) and wireless sensing techniques, which are referred as Internet of Things (IoT), are modern technologies to capture product information as well as environmental data automatically (Corcoran, 2005; Wu et al., 2017). Apart from monitoring the products, the technologies can also be used for ensuring the health and safety of cold storage operators. Thus, it is essential and feasible to develop an IoT-based system for access control and positioning in cold storage.

Through the mature development of RFID, Wireless Sensor Networks (WSNs) and Smart Things, IoT is introduced for advanced fusion of sensing techniques, efficient wireless connectivity and predictive analytics (Li et al., 2014). The basic concept of IoT is that it is a unique, tailored interconnection system to link objects which are equipped with identifying and sensing technologies, and internet infrastructure so as to develop an IoT network (Pang et al., 2013). According to the literature (Ferro and Potorti, 2005; Wang et al., 2008; Zhou et al., 2011; Gharghan et al., 2014; Rawat et al., 2014), a comparison of three types of wireless communication technologies, namely Wireless Fidelity (Wi-Fi), RFID and Bluetooth Low Energy (BLE), has been discussed. A comparison of the above three communication technologies is conducted through summarizing the literatures, as shown in Table 1.

Table 1. Comparison of Wi-Fi, RFID and BLE

	Wireless Fidelity (Wi-Fi)	Radio Frequency Identification (RFID)	Bluetooth Low Energy (BLE)
Operating Channels	13 channels with 5MHz partitioned in each channel	Self-defined protocols	3 broadcasting channels out of 79 data channels
Cost	Moderate	Expensive	Moderate
Frequency	2.4GHz/5GHz	Low, High, Ultra-high, and Super-high	2.4GHz
Application Area	Internet access, data transmission	Inventory tracking, race timing, supply chain visibility	Wearable device, positioning beacon

These three technologies are common in developing an IoT network and play important role in transmitting or receiving the sensing data. The significant difference is that Wi-Fi merely has only 13 available channels operating for communication with 5MHz partitioned in each channel; RFID adopts self-defined protocols for various functions; BLE has 3 broadcasting channels out of 79 data channels. Regarding the equipment costs, RFID is the most expensive technology compared to the others when setting up an entire network (Lee et al., 2014; Rida et al., 2015). In order to select the most appropriate technology for access management and the positioning system, performance and costs are two primary considerations. Both technologies are suitable for developing an access management and positioning system. The set-up of RFID-based systems requires a fixed expensive cost for the middleware and RFID reader but a cheaper cost for the RFID tags, but the Bluetooth-based systems make use of the same Bluetooth modules which are slightly more expensive than RFID tags, to set the master and peripheral devices. Therefore, for small or medium scale industrial applications, Bluetooth-based systems should be appropriate and effective without huge hardware investment at the beginning. Hence, BLE is deemed to be a suitable technology due to the reasonable set-up cost and flexible channel design for positioning purposes between the transmitters and receivers. In addition, BLE operates in industrial, scientific and medical (ISM) radio bands of 2.4GHz, which implies that the applications can have a higher speed for data transfer and sensitivity.

Apart from hardware considerations, positioning algorithms and data processing techniques are also crucial for locating an object accurately in an indoor environment. In view of the current real-time locating systems, positioning algorithms are designed to locate an object in a smart environment, and can be divided into two types, namely uncluttered and cluttered environments. The design of the locating processes are automatic and short time, as required for data acquisition in the above environments (Boulos et al., 2012; Bocca et al., 2014). The received signal strength indication (RSSI) is one of the signal measurement indicators which expresses the signal attenuation with respect to distance (De Paz et al., 2012). It has a good positioning performance operating in a small-scale and cluttered environment using wireless sensor nodes (Jan et al., 2014). Oguejifor et al. (2013) proposed that the Power Law Model which expresses the relationship between RSSI values and distance can be applied to the trilateration algorithm, and two or more wireless sensor nodes should be installed for positioning. Trilateration-based localization is then found in a proposed algorithm in a wireless sensor network with the adoption and implementation of the Zigbee CC2420 module to locate objects using three anchors. By using the above methods, it is assumed that (i) the relationship between RSSI and distance must obey the Power Law Model; (ii) the radiation pattern of the wireless nodes is circular.

In an indoor cluttered environment, reflection, scattering, attenuation and diffraction cause signal errors and variations so as to affect the accuracy of the positioning. In view of operating at 2.4 GHz, signal attenuation can be easily caused by moisture and metallic materials. Therefore, a data processing technique, the Kalman filter, has been adopted to eliminate the signal variations. The Kalman filter is a filtering technique for stochastic estimation when applying in a noisy sensor environment. Its primary function is to minimize process and measurement noises such that estimated locations can be optimized in the positioning system (St-Pierre and Gingras, 2004). Bekkali et al. (2007) proposed a RFID indoor positioning system by using a probabilistic RFID map and Kalman filtering. By using Kalman filtering, the root mean square errors of the positioning results can be reduced significantly. In addition, the number of transmitters can be reduced, and separation of each antenna is independent of the positioning accuracy. However, there are limited studies to investigate the positioning performance, by applying Kalman filtering in a cold environment. Considerable interest has been drawn in the field of positioning techniques.

To summarize, previous research work has focused on RFID technology, positioning approaches as well as data processing techniques to provide accurate positioning results. However, limited attention has been paid on calibration-free positioning systems in a cold environment, with simple and rapid system implementation and installation. In cold storage facilities, access frequency and real-time location of workers provide the important information in regard to the health and safety concerns and in compliance with ISO11079 measurements. This study aims at developing an access management and positioning system by using Trilateration and the Kalman filter to locate operators and minimize the positioning errors. Therefore, the results of positioning and access control are applied to ISO11079 measurement to mitigate occupational safety risk in cold storage facilities.

3. Design of an Bluetooth-based Access Management and Positioning System (BAMPS)

To ensure occupational health and safety in cold storage facilities, a Bluetooth-based Access Management and Positioning System (BAMPS) providing a rapid approach is proposed, considering both positioning and data processing techniques. Figure 2 shows the system architecture of BAMPS that consists of five layers, namely (i) Data Acquisition Layer, (ii) Network Layer, (iii) Logic Layer, (iv) Data Processing Layer, and (v) System Output Layer.

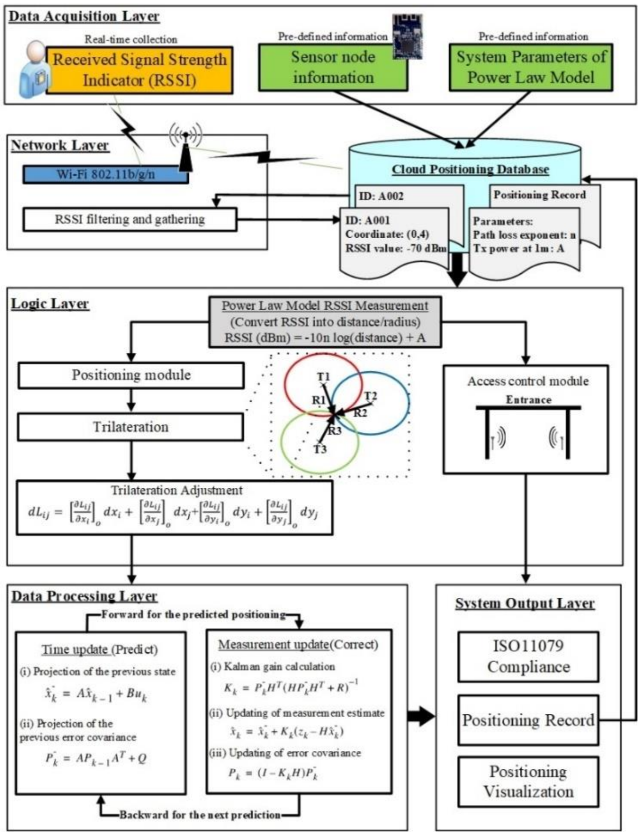


Figure 2. System architecture of the BAMPS

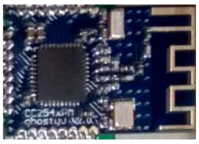
3.1 Data Acquisition Layer

Data, including RSSI, wireless sensor node information and the parameters of the Power Law Model, are collected to establish the access control module as well as the positioning module. In the proposed system, Ghostyu BLE4.0 CC2541 and USR-WIFI232-S are selected in order to collect and transmit the RSSI values in an indoor environment through BLE and Wi-Fi network, as shown in Table 2. The selection of the above two electronic modules are in accordance to their capabilities and costs. The BLE module and Wi-Fi module have relatively large receiver sensitivity values, namely -87 dBm to -93 dBm and -82dBm to -93dBm respectively. In addition, the costs of the two modules are economical, at RMB10 and RMB38 per unit respectively, and are used in developing such an access management and positioning system. The BLE module is used to determine the RSSI values and corresponding Service Set Identifiers (SSIDs) between central nodes and peripheral nodes, and the data package of RSSI values and SSIDs are then transmitted to the proposed system via an 802.111 b/g/n Wi-Fi network. Figure 3 shows the printed circuit board diagram of the central sensor nodes by combining the BLE and Wi-Fi electronic modules, which warehouse workers are required to wear when working in cold storage facilities. In addition, the peripheral nodes are designed by using only the mentioned BLE module, and its coordinates are needed in the positioning algorithm. In order to determine the positioning, the relationship between RSSI and distance is explored by the Power Law Model, as given in equation (1). *A* and *n* are two parameters which are required to be firstly determined and kept constant. Thus, the rate of change of RSSI over distance can be investigated by using regression analysis.

$$\text{RSSI} = A - 10n \times \log(d) \quad (1)$$

, where *d* is distance between the transmitter and receiver; *A* is received power in dBm at 1m; *n* is path-loss exponent.

Table 2 Specifications of BLE and Wi-Fi modules

Modules	Module specifications
 Ghostyu BLE4.0 CC2541	- Operating in Bluetooth Low Energy 4.0 - Multiple simultaneous connection in master mode - TX power: +3dBm to -23dBm - RX sensitivity: -87 dBm to -93 dBm - Transmission current: 27 mA
 USR-WIFI232-S	- Operating in 802.11 b/g/n between 2.412GHz and 2.484GHz - TX power: 11dBm to 18dBm - RX sensitivity: -82dBm to -93dBm - Operating current: 200mA

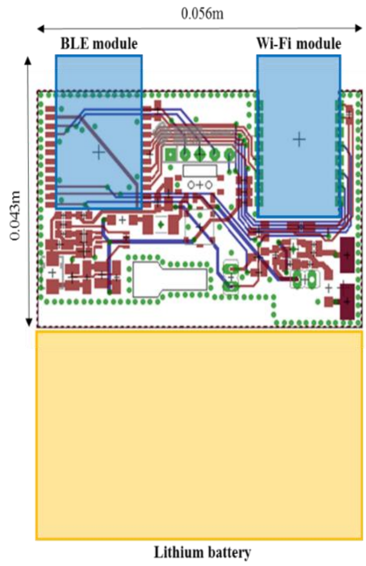


Figure 3. Printed circuit board diagram of central sensor nodes

3.2 Network Layer

In order to transmit the data package of RSSI values and other relevant information, such as SSID, in this layer, a Wi-Fi module, USR-WIFI232-S, is applied as mentioned above. In addition, this layer enables filtering and gathering of the RSSI values, as the data pre-processing, for the uses of access control and positioning approach. The RSSI data is grouped and indexed to the time when collecting data. Consequently, two groups of data, i.e. positioning algorithm configurations and sensor data package, used in the proposed are stored in a cloud database. For the sensor data packaging, it contains a series information on SSID, sensor node coordinates, and RSSI values; for the positioning algorithm configuration, it refers to the path loss exponent and transmitter power at 1m distance.

3.3 Logic Layer

In this layer, there are two modules, i.e. the access control module and positioning module, which provide access control and positioning functions in the cold storage environment. The deployment of the proposed system BAMPS is illustrated, in Figure 4, showing an example of the positions of the transmitters for access control (A) and positioning (P), and receiver (R) which is the central sensor node in the system setting. A1 and A2 represent the transmitters for the use of access control, whereas P1, P2, P3, and P4 are the transmitters for the use of positioning. Sensor node deployment is described in our previous work (Tsang, 2015). Strictly speaking, the BLE positioning nodes can be randomly placed in the facilities with known coordinates. The corners are suggested, as the coordinates of BLE nodes can be simply calculated.

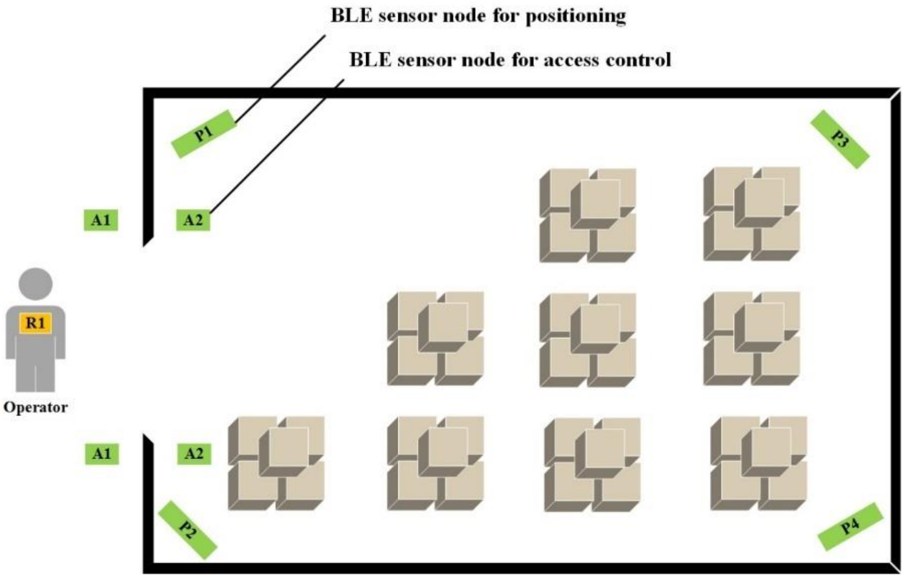


Figure 4. Illustration of the BAMPS deployment

(i) Access control module

When entering the cold storage facility, the logic is that A1 should record the highest RSSI value first. Within a short period of time, A2 records the highest RSSI value secondly. Therefore, it is implied that the warehouse workers have entered the cold storage facility. When exiting the cold storage, the logic is similar to the entering process. The logic is that A2 records the highest RSSI value firstly, and A1 will record the following highest RSSI value after another short period of time. Therefore, this module can collect information on the frequency of entering and exiting the cold storage facilities, the number of warehouse workers inside the facility, and their corresponding duration of stay.

(ii) Positioning module

In this module, transmitter information and relative RSSI values are two necessary data to compute the positions. Through the defined Power Law Model, all RSSI (dBm) values are converted in the form of distance (m). To calculate an unknown coordinate in a 2D-Cartesian coordinate plane, at least three sets of transmitter information and RSSI values have to be used. In order to adopt trilateration for positioning, the modern concept of trilateration adjustment is considered in this study, derived by Taylor's Series, due to the non-linear characteristics. Trilateration adjustment has the error-corrective characteristics while computing the positioning by trilateration. Therefore, the accuracy of positioning results are expected to be improved.

To calculate two-point distance of $P_i(x_i, y_i)$ and $P_j(x_j, y_j)$, the distance equation is expressed as equation (2) and (3):

$$L_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{2}$$

$$L_{ij(adj)} = O_{ij} + R_{ij} \tag{3}$$

, where L_{ij} is actual/ideal length between P_i and P_j; $L_{(adj)}$ is the adjusted length; O is the observed length between P_i and P_j; R is the corresponding residual error.

Since the above non-linear equation has observation and adjustment characteristics, Taylor's Series is therefore applied to establish the relationship between actual length and adjusted length, as shown in equation (4). Therefore, the distance observation equation can be summarized in equation (5).

$$
\begin{aligned}
L_{ij(adj)} &= \sqrt{\left[(x_i + dx_i) - (x_j + dx_j)\right]^2 + \left[(y_i + dy_i) - (y_j + dy_j)\right]^2} \\
&= \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (dx_i - dx_j)^2 + (dy_i - dy_j)^2} \\
&\approx \mathrm{L}_{ij} + dL_{ij} \qquad (4)
\end{aligned}
$$

, where

$$dL_{ij} = \left[\frac{\partial L_{ij}}{\partial x_i}\right]_o dx_i + \left[\frac{\partial L_{ij}}{\partial x_j}\right]_o dx_j + \left[\frac{\partial L_{ij}}{\partial y_i}\right]_o dy_i + \left[\frac{\partial L_{ij}}{\partial y_j}\right]_o dy_j$$

$$\mathrm{dL}_{ij} = L_{ij} - O_{ij} + R_{ij} \qquad (5)$$

By applying this concept, a matrix of trilateration adjustment, as equation (6), can be formulated to study the relationship of equation (5). Through numerous iterations, the positioning results can be generated and updated, and become more accurate. In addition, the iteration termination is dependent on the correction threshold of the positioning results or maximum number of iterations.

$$
\begin{bmatrix} \vdots \\ R_{ij} \\ \vdots \end{bmatrix} = \begin{bmatrix} & \cdots & \cdots & \cdots & \cdots & \cdots & \\ \vdots & \dfrac{\partial L_{ij}}{\partial x_i} & \dfrac{\partial L_{ij}}{\partial y_i} & \cdots & \dfrac{\partial L_{ij}}{\partial x_j} & \dfrac{\partial L_{ij}}{\partial y_j} & \vdots \\ & \cdots & \cdots & \cdots & \cdots & \cdots & \end{bmatrix} \begin{bmatrix} \vdots \\ dx_i \\ dy_i \\ \vdots \\ dx_j \\ dy_j \\ \vdots \end{bmatrix} - \begin{bmatrix} \vdots \\ L_{ij} - O_{ij} \\ \vdots \end{bmatrix} \qquad (6)
$$

3.4 Data Processing Layer

In this layer, it aims at further eliminating the positioning variations by using the Kalman filter. In a discrete-time controlled process, the state *x* is estimated by the linear stochastic difference equation, with process noise *Q* and measurement noise *R*, as follows:

For $\mathrm{x} \in \mathrm{R}^n$, $\mathrm{z} \in \mathrm{R}^n$, $\mathrm{p(w)} \sim \mathrm{N(0, Q)}$, $\mathrm{p(v)} \sim \mathrm{N(0, R)}$,

Process model: $\mathrm{x}_k = Ax_{k-1} + Bu_k + w_k$ (7)

Measurement model: $\mathrm{z}_k = Hx_k + v_k$ (8)

, where A is the state transition function; B is the control input function; H is the sensor function; u is the system control input.

The computation using the Kalman filter is divided into two sections, namely time update equations and measurement update equations. The function of the time update equations is to generate a priori estimate by predicting the current state *x* and estimating the error covariance. On the other hand, the function of the measurement update equations is to correct the priori estimate to obtain an improved a posteriori estimate.

In order to apply the Kalman filter into the positioning algorithm in the proposed system, the process noise is assumed to be small, hence negligible, compared with the measurement noise. A lower process noise Q requires a higher time lag, but the estimation accuracy can become more accurate, whereas, measurement noise represents any noise characteristic of the sensor, which is the BLE sensor node in this system. The sensor accuracy is defined by the standard deviation of the measured values in the calibration. In addition, there is no input control in the state system, i.e. $B=0$, and the direct noisy measurement is the given by $H=1$. The equations (7) and (8) are simplified as follows:

$$\text{Process model:} \quad x_k = x_{k-1} \tag{9}$$

$$\text{Measurement model:} \quad z_k = x_k + v_k \tag{10}$$

3.5 System Output Layer

The system output layer integrates all the results from the access control and positioning modules. It primarily has three functions, namely ISO11079 compliance, positioning record and positioning visualization. The real-time positioning can be displayed for monitoring the movement of operators. Afterwards, the positioning records are stored in the database for further analysis and recording. Through considering the time of stay inside the cold storage facilities, the ISO11079 compliance can be applied to define the definite limited exposure duration, recovery time, as well as required basic clothing insulation. Figure 5 shows the model of ISO11079 measurement between various input and output variables. In the ISO11079 measurements, the neutral and minimal required clothing insulations ($IREQ_{neutral}$ and $IREQ_{min}$) are calculated first and compared to the available basic clothing insulation ($I_{cl,r}$). If $I_{cl,r} > IREQ_{neutral}$, the warehouse workers are in the overheating zone such that their clothing insulations need to be reduced. If $IREQ_{neutral} \geq I_{cl,r} \geq IREQ_{min}$, the clothing insulation for the warehouse workers is appropriate for working in the specific workplace. If $I_{cl,r} < IREQ_{min}$, the warehouse workers are in the cooling zone such that either the clothing insulation should be increased, or they have to follow the limited exposure duration calculated in the ISO11079 measurement, as shown in equation (11). After exposure to the cold environment with the limited exposure duration, the recovery time is suggested to restore the normal body heat balance, which is also calculated by using the same equation for limited exposure duration, but the denominator, called as the rate of body heat storage, becomes a positive value rather than a negative value.

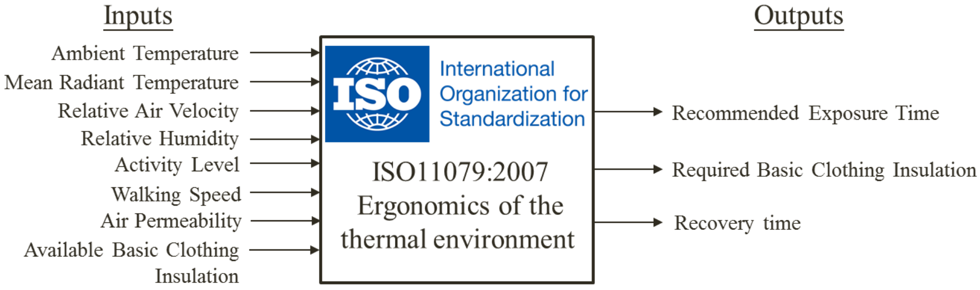


Figure 5. Model of ISO11079 measurement

Limited exposure duration/Recovery time:

$$D_{lim} \text{ or } D_{rec} = \frac{Q_{lim}}{M - W - E_{res} - C_{res} - E - R - C} \quad (11)$$

, where Q_{lim} is limit value of Q in ISO11079; M is metabolic rate; W is effective mechanical power; E_{res} is respiratory evaporative heat flow; C_{res} is respiratory convective heat flow; E is respiratory heat flow at the skin; R is radiative heat flow; C is convective heat flow.

With the help of BAMPS, it addresses the health and safety concerns in the cold storage facility. Therefore, the warehouse workers can receive sufficient monitoring when working in cold environmental conditions, and workplace comfort in the cold storage facilities can be enhanced.

4. Case Study

The proposed methodology is applied in a case company in this section. It covers the (i) company background, (ii) existing problems in the cold storage facility, and (iii) implementation of BAMPS in the case company.

4.1 Company background

Chevalier Cold Storage and Logistics Limited is a third-party logistics (3PL) service provider in Hong Kong, especially for cold supply chain logistics operations. The company was founded in 2002 and boasts an 18-storey, 28,000 metric tons capacity building. The warehouses include freezer, chiller, climate-controlled, bonded, and international standard fine wine sections. In the toughest environment, the freezer's temperature is kept at -16°C to -20°C in order to meet the requirements to store the meat, seafood and other kinds of frozen food. In the chiller, the temperature is maintained at 1-4°C for storing vegetables, fruit and dairy products. General air-conditioned regions and public bonded warehouses have the same range of temperature at 18-22°C. In the fine wine section, the temperature and humidity are maintained at 13-16°C and 65% respectively. In response to the growing demand for cold chain services, the company was accredited and upgraded to ISO 9001:2008. Thus, the workflow and operation procedures have been standardized to provide a high level of quality service. In addition, the warehouse has 24-hour security personnel with rigorous patrols, round-the-clock CCTV surveillance, and anti-theft system. Therefore, it provides comprehensive services alongside with the provision of transportation, one-stop logistics services, and other professional cold chain services.

4.2 Existing problems in cold storage facility

In order to maintain the quality of frozen products, Chevalier Cold Storage and Logistics Limited provides five types of warehouses, as mentioned above. In view of the operations in the freezers and chillers, warehouse personnel are required to store, pick and pack the goods in the low temperature environment. Figures 6 and 7 show the freezing and chilling storage sections respectively. The warehouse layout and design are similar to the general warehouses; however, a refrigeration system is installed to keep the warehouse in a low temperature range, i.e. -18ºC in freezing sections and 0 ºC in chilling sections. Without the appropriate and protective warm clothing, it is hazardous to work inside these facilities. In the cold storage market, the case company is one of the market leaders to provide a one-stop cold storage services to customers. In most of the cold storage facilities, the managers are facing the similar challenge on occupational safety issue. Although the company has installed CCTV surveillance at the entrance of the cold storage facilities, it is insufficient to monitor the operations inside the facilities. Therefore, there are two major problems in the case company. The first problem is that staying duration of operators inside the cold storage cannot be monitored in real-time. If the operators stay too long in the facilities, excessive exposure to the cold environment may cause serious cold injuries, even fatality. Another problem is that the operators' location cannot be visualized inside the facilities for management purposes. Positioning visualization is critical in knowing the real-time locations for prompt rescue if unexpected industrial accidents occur. The above two problems may jeopardize the health and safety of warehouse personnel. Therefore, there is a need to design the BAMPS in the case company in order that effective occupational workplace health and safety management can be attained.

Figure 6. Freezing storage section in the case company

Figure 7. Chilling storage section in the case company

4.3 Implementation of BAMPS

In this section, the BAMPS is studied through pilot tests in the cold storage facilities. Figure 8 shows the implementation roadmap of the proposed system, BAMPS, in the case company, which consists of three phases, i.e. formulation of power law model, experimental study in positioning, and evaluation of ISO11079 measurement. The Power Law Model is constructed for the computation of both access control and positioning algorithms. In addition, the experimental results of BAMPS are used regarding to the positioning errors and comparison between observed values and values from BAMPS.

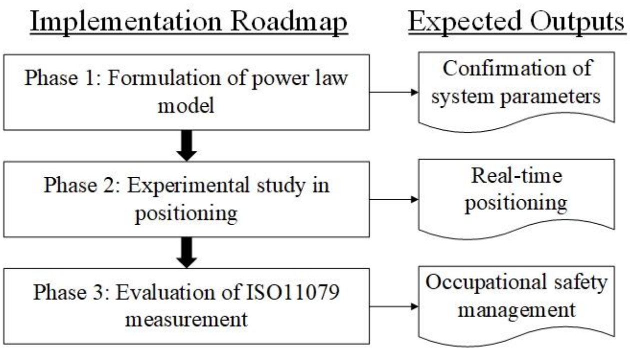


Figure 8. Implementation roadmap of BAMPS

(i) Power law model

Before processing BAMPS, the environmental parameters have to be defined in the Power Law Model in order to convert the RSSI values to distances between the transmitter and receiver. Six fixed location points are used in plotting the Power Law Model, as shown in Figure 9. Through regression analysis, a unique Power Law Model is generated which can be applied to BAMPS, expressed as equation (11). As the coefficient of correlation is 0.8482, it is proven that the logarithmic relationships between the RSSI values and distance are appropriate. By using the definitive Power Law Model, all RSSI values can be converted into radii around the transmitters. Therefore, it is sufficient to compute the positioning with the known coordinates of the transmitters and the corresponding radii.

Power Law Model: $$RSSI = -11.15\ln(Distance) - 50.067 \quad (11)$$

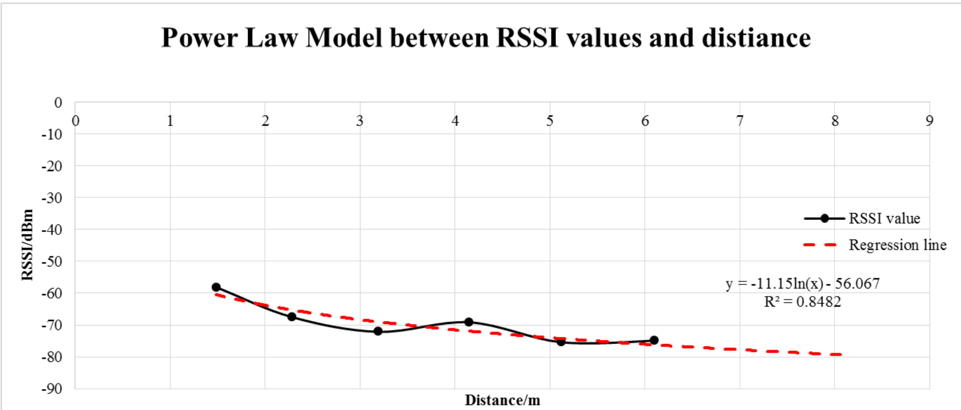


Figure 9. Power Law Model of BAMPS

(ii) Experimental results in positioning

After modifying the Power Law Model in BAMPS, the RSSI values and corresponding transmitters' coordinates are used in computing the accurate positions through the Kalman filter. In this study, all the computations and demonstrations are generated in the MATLAB® environment. Table 3 shows the positioning results with the positioning errors. There are four test points, i.e. (0,0), (1,1), (2,0) and (4,0), to illustrate the performance of BAMPS by comparisons of the measured coordinates, standard deviation and positioning error in order to differentiate the observations by using Power Law Model and the proposed approach BAMPS. Since the data package may be lost due to the fluctuation in Wi-Fi signal and interference from the cluttered environment, the sample sizes are varied among the testing points. The average standard deviation and positioning error for the observation are 0.85 and 2.11m respectively; the average standard deviation and positioning error for the proposed system BAMPS are 0.28 and 1.07m respectively. Therefore, with implementing BAMPS, the average standard deviation and average positioning error are reduced by 66.8% and 49.3% respectively. On the one hand, a lower signal standard deviation implies less fluctuation in the data collected so that the drift of the positioning locations can be minimized. On the other hand, the proposed system has a positive influence on improvement of the positioning error such that the positioning results are more accurate, compared with the merely application of Power Law Model.

Table 3. Results of the observation and BAMPS models

Testing Point		1	2	3	4	Average
Actual Coordinate		(0,0)	(1,1)	(2,0)	(4,0)	
Observation by Power Law Model	Coordinate	(3,1.5)	(1.6,0.3)	(3.6,2)	(3.8,0.3)	
	Standard deviation	0.90	1.05	0.33	1.12	**0.85**
	Positioning Error (m)	3.70	1.50	2.33	0.90	**2.11**
BAMPS	Coordinate	(1.5,0.9)	(1.9,1.2)	(1.94,0.5)	(5.1,0.25)	
	Standard deviation	0.20	0.45	0.04	0.44	**0.28**
	Positioning Error (m)	1.75	0.92	0.50	1.12	**1.07**
Summary	**Sample Size**	**112**	**104**	**131**	**171**	

(iii) Evaluation of ISO11079 measurement

Since the positioning approach has been tested and the time of stay inside the cold storage facilities can be measured, the ISO11079 measurement can then be applied to establish definite threshold values for limited exposure duration and recovery time for the warehouse workers. Table 4 shows the ISO11079 measurements in cold storage facilities, including freezing and chilling stores. The environmental conditions, including temperature and relative humidity, are the average values of the cold storage facilities in a day. For working inside the freezing stores, the company provides a set of clothing ensemble with 2.0 clothing insulation which includes over-jacket, over-trousers, hat and gloves; for working inside the chilling stores, the provided clothing insulation is 1.5 which includes insulated coveralls. The activity level, walking speed, and relative air velocity in the cold storage facilities are assumed as $120Wm^{-2}$, $0.6ms^{-1}$, and $0.4ms^{-1}$ respectively, which are measured by the domain expert in the field of cold storage. Therefore, the $IREQ_{neutral}$, $IREQ_{minimal}$, limited exposure duration (D), and recovery time (RT) can be calculated. Through integrating with real-time positioning and access control modules, the warehouse workers should compliy with the ISO11079 measurements.

Table 4. ISO11079 measurements in cold storage facilities

	Freezing Store A	Freezing Store B	Freezing Store C	Chilling Store A	Chilling Store B	Chilling Store C
Store Temperature	-18.2°C	-17.5°C	-20.5°C	-2.5°C	1.2°C	0.8°C
Relative Humidity	45.2%	44.8%	47.4%	52.5%	55.6%	53.8%
$IREQ_{neutral}$	2.9	2.9	3.1	1.8	1.5	1.5
$IREQ_{minimal}$	3.3	3.2	3.4	2.1	1.9	1.9
D (in hour)	0.7	0.8	0.7	1.2	2.1	1.9
RT (in hour)	0.5	0.5	0.5	0.5	0.5	0.5

5. Results and Discussion

The results from the positioning approach and ISO11079 compliance can be combined and deployed in a web-based platform. Figure 10 shows the user interface of BAMPS. In the proposed system, the store temperature and relative humidity of each cold storage facility are shown accordingly. In addition, real-time movement and positioning of the workers who are inside the cold store area are also displayed in the simulated store floor plan with their name and remaining duration of stay inside the store. In the managerial perspective, logistics companies having cold storage facilities may not pay sufficient attention to the occupational safety risk management such that the industrial accident frequency rate cannot be controlled effectively, resulting in huge expenses in compensation and an unstable workforce level. In addition, since some cold storage facilities are large, with the scale of 10,000ft^2 or above, it is difficult to locate and rescue the injured. In the experimental setting, numerous BLE positioning sensors are installed in the cold storage facilities to evaluate the RSSI between sensors and receivers. Two highest RSSI values with the node coordinates are then processed to calculate the position. The room size in the experiments are approximately 1,000ft^2, which is sufficient to obtain the mentioned positioning accuracy by deploying the sensors in the corners. The proposed system, BAMPS, is also capable of being implemented in larger scale facilities only if the RSSI data and node coordinates are known and collectable. It is because the BAMPS is flexible and can be rapidly implemented in any indoor environment. However, more BLE positioning sensors are required in larger scale facilities in order to obtain the similar positioning accuracy. Hence, the cold storage companies need to strike a balance between positioning accuracy and costs. In this era of IoT, the wireless sensor networks (WSNs) and other IT-enabling technologies are becoming mature so that the proposed system can be created through the integration between WSN and practical ISO11079 compliance. Currently, the traditional method in access control is in using RFID-based access control system containing entrance reader and RFID cards. However, such a system is not user-friendly as the workers have to place the cards on the entrance point when entering and leaving the cold storage facilities, and it is difficult to estimate accurate positioning without installing specific and expensive RFID antennas all around the facilities. However, the proposed system is designed to overcome the aforementioned challenges so as to develop an effective access management and positioning system. On the other hand, the proposed system is a rapid and calibration-free approach which is sufficiently flexible to deploy in any cluttered environment. The installation of the proposed system is simply setting up the peripheral sensor nodes and distributing the central sensor nodes to the warehouse workers, without changing the existing facility infrastructure.

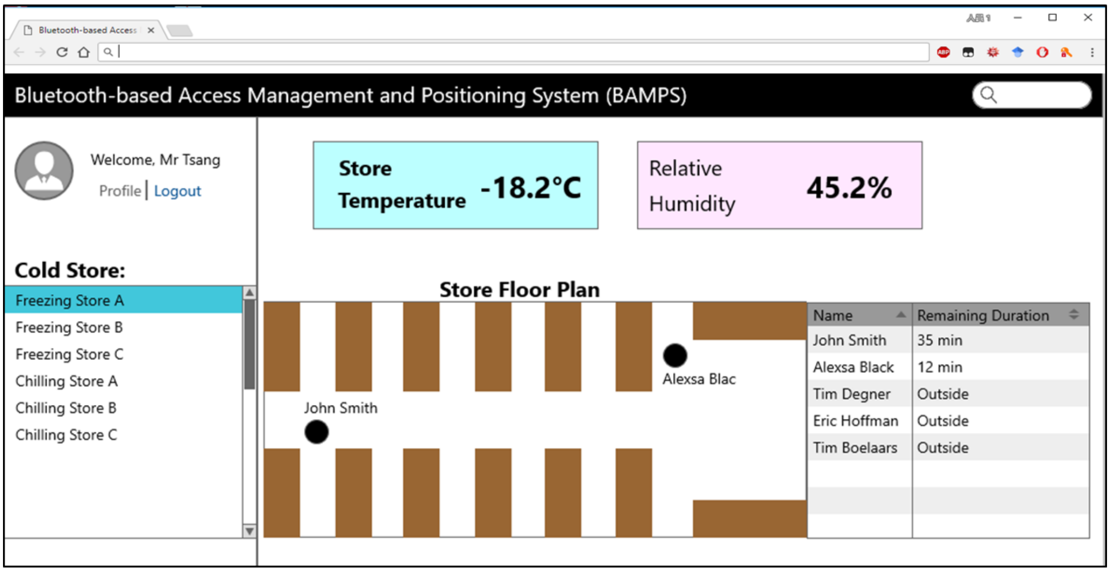


Figure 10. User interface of BAMPS

5.1 *Comparison with other positioning systems*

A cold environment may affect the performance of wireless communication through EM wave propagation for the BLE modules, due to exceeding the limits of the operating temperature. However, the reductions of the average standard deviation and positioning error are still significant so that BAMPS is effective in locating an object in 2D dimensions. With the lower standard deviations, it implies that the positioning point can be stable so as to be visualized in the system interface. According to past research, the positioning accuracy is dependent on the type of communication technologies and calibration requirements. Table 5 shows a comparison of the positioning errors for various positioning systems. Compared with other positioning systems, the positioning error is higher than those systems with required calibrations. Since BAMPS does not require pre-request calibrations to implement and install the system, the positioning error of 1.07m is acceptable in the case company.

Table 5. Benchmarking of other positioning works

Work	Wireless communication technology	Calibration required	Error (m)
Bocca et al. 2014	RFID	Yes	0.55
Liu et al. 2014	Wi-Fi	No	1.99
Jan et al. 2014	Bluetooth	Yes	0.53
BAMPS	Bluetooth Low Energy 4.0	No	1.07

5.2 *Advantages of BAMPS*

The entire implementation of BAMPS lasted for one month. The proposed system was implemented in three freezing warehouses and three chilling warehouses, whereas another three freezing and three chilling warehouses remain the settings unchanged, so as to investigate the differences before and after implementing the proposed system. The total timeframe of the comparative study takes one-month duration which is sufficient to inspect the changes in the occupational safety management, and to show the improvement of deploying real-time monitoring in cold storage facilities. Firstly, it has the function of access control such that the access frequency and exposure duration to cold environment of the warehouse workers can be under real-time monitoring. When the operators stay too long and exceed the limitation of exposure duration inside the cold storage facility, the system will display a signal to the workers, managers and controllers. The workers are required to leave the cold store immediately so as to recover their body heat balance. On the other hand, near real-time positioning is applied to keep track of the locations of the warehouse operators. Other colleagues and controllers can easily locate the position of the operators when any accidents occur. Table 6 shows the performance of BAMPS implementation before and after implementation so as to validate the proposed system in the case company. The accident frequency rate was reduced from 3 times to 1 time weekly, with a decrease of 66.7%; the staff satisfaction on the workplace comfort design was increased from 6.5 to 8.8, with an increase of 35.4%; the compensation for accidents was reduced from HK$9,000 to HK$4,300 monthly, with a decrease of 52.2%. Last but not least, the real-time worker positioning can be provided after the implementation of BAMPS. Furthermore, in the society perspective, the proposed system is developed due to increasing concern on occupational safety which is important in our people-oriented society and business environment. Apart from cold storage facilities, in most of indoor cold environments, BAMPS is feasible for locating the positioning and applying the ISO11079 standard so as to enhance the awareness and execution of occupational safety strategies. The Government always advocates occupational safety and health in the society through holding various trainings and programmes in improving safety design. The proposed system can be one of the essential elements to safety and ergonomics design to minimize workplace hazards in the indoor cold environment.

Table 6. Performance of BAMPS implementation

Performance Indication	Scale	Before implementing BAMPS	After implementing BAMPS	Percentage Change
Accident frequency rate	Number/week	3	1	-66.7%
Staff satisfaction	1-10	6.5	8.8	35.4%
Compensation for accidents	HK$/month	9,000	4,300	-52.2%
Real-time worker positioning	-	No	Yes	-

6. Conclusions

Due to the expanding supply chain network for fresh food and pharmaceutical products, cold storage facilities play a vital role in maintaining the desired product quality with a certain period of time. Warehouse workers have to finish the warehousing operations inside the cold storage facilities, so occupational safety and health risk management becomes a critical concern for most logistics service providers. Without an effective approach in managing the occupational safety risk, it increases accident frequency rate and has a negative impact on operational efficiency. In this paper, a Bluetooth-based access management and positioning system (BAMPS) is proposed which integrates several positioning techniques, i.e. Power Law Model, adjustment of trilateration, and Kalman filtering technique, complying with ISO11079 for the practical application. The accurate worker positions, access frequency, and duration of exposure to cold environments can be located and measured by applying the above positioning techniques. Consequently, the compliance of ISO11079 provides the threshold values for exposure duration and recovery time. Therefore, warehouse workers will be given sufficient protection after implementing the proposed system. In order to validate the proposed system, a case study was conducted to investigate the performance before and after implementing BAMPS. It is found that the implementation of BAMPS has the effect of reducing the accident frequency rate and expenses in compensation, leading to an improvement in staff satisfaction regarding the workplace comfort design. The main contribution of this paper lies in the exploration of emerging positioning techniques and occupational safety management. It benefits companies involved in cold chains to establish strategic planning in health, safety and environment. Furthermore, this study contributes to society in improving their awareness regarding occupational safety and health, and in exhibiting a systematic approach to minimize workplace hazards. It can be further widely applied in other indoor cold workplace environments. The limitation of this study is a lack of consideration of individual factors, such as body mass index and age. Future research could focus on customization of ISO11079 measurement for warehouse workers so that personal occupational safety plans can be formulated, according to their own health condition.

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