Indoor positioning-based mobile resource movement data management system for smart factory operations management

Jin Sung Park¹, Sung Jin Lee², Jesus Jimenez³, Soo Kyun Kim⁴ and Jun Woo Kim¹

Abstract
The primary role of modern information and communication technology infrastructures in smart factory is to collect a wide range of digital data from manufacturing resources; however, many manufacturing companies still have significant trouble in collecting data relevant for operations management. Especially, it is difficult to collect data about movement of mobile resources, such as human operators and material handling equipment. Moreover, managers of manufacturing companies often have significant troubles in utilizing the raw data collected by information and communication technology infrastructures due to its complexities and vast amount. To fill these gaps, this article proposes indoor positioning-based mobile resource movement data management system, which can be used to collect and process the mobile resource movement data flexibly. The indoor positioning technologies enable to track the positions of physical objects in real time; however, they generate time series data for 3D coordinates of object position not suitable for practical use. Therefore, this article aims to integrate the indoor positioning technology with a specialized user application, which allows the users to define what kinds of data should be collected and how the raw data should be transformed.

Keywords
Indoor positioning, smart factory, mobile resource, movement data, data collection

Date received: 8 November 2019; accepted: 3 February 2020

Handling Editor: Pascal Lorenz

Introduction
With the advent of the Industry 4.0 era, much attention is being paid to smart factory, which is implemented through integration of traditional manufacturing resources with modern information and communication technology (ICT) infrastructure.¹⁻³ The ultimate goal of smart factory is to strengthen the competitiveness of manufacturing system using ICT capabilities for handling digital data.⁴ In other words, the primary role of modern ICT infrastructures in smart factory is to collect a wide range of digital data from manufacturing resources, and the collected data should be utilized

¹Department of Industrial and Management Systems Engineering, Dong-A University, Busan, South Korea
²Department of Computer Engineering, Dong-Eui University, Busan, South Korea
³Ingram School of Engineering, Texas State University, San Marcos, TX, USA
⁴Department of Computer Engineering, Jeju National University, Jeju, South Korea

Corresponding author:
Jun Woo Kim, Department of Industrial and Management Systems Engineering, Dong-A University, Nakhodongdae-ro 550beon-gil, Saha-gu, Busan 49315, South Korea.
Email: kjunwoo@dau.ac.kr

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
in a systematic way for effective operations management. Moreover, advancement of technologies, such as wireless sensor networks and Internet of things (IoT), enable to collect digital data from physical objects in real time.\(^3\)\(^5\)

Nevertheless, many manufacturing companies still have significant trouble in collecting data suitable for them. Especially, it is difficult to collect and utilize appropriate data about movement of mobile resources, such as human operators, forklifts, and material handling equipment. Such mobile resources are important components of conventional manufacturing systems, and they typically travel within manufacturing facilities to perform various tasks, including transportation, machine control, and maintenance. Movement of mobile resources can contain much useful information for operations management. For example, stay of human operator in a specific area can imply that a specific operation is being performed. Similarly, duration of stay in a specific area might be highly related with the processing time of a specific operation. Number of stay in a specific area might indicate the number of completed products. However, the movement of mobile resources has been not considered within the existing smart factory environments. Another problem is that the raw data collected by ICT infrastructures are typically not easy to interpret and analyze directly. In other words, the raw data often should be properly transformed into more structured form for practical use. For example, modern indoor positioning technologies can be used to track the positions of mobile resources.\(^6\)

However, indoor positioning equipment inherently generates streams of 3D coordinates for physical objects, difficult to interpret and analyze directly.

To fill these gaps, this article proposes indoor positioning-based mobile resource movement data management system (IMMMS), which can be used to collect and process the mobile resource movement data flexibly. IMMMS utilizes conventional indoor positioning equipment to track the positions of physical objects in real time. However, indoor positioning equipment generates time series data for 3D coordinates of object position not suitable for practical use. Therefore, this article aims to integrate the equipment with a specialized user application, which allows the users to define what kinds of data should be collected and how the raw data should be processed. The remainder of this article is organized as follows. Section “Research backgrounds” provides a brief literature review on indoor positioning technologies, and section “IMMMS” outlines the overall concepts and structures of IMMMS. Section “Prototype of IMMMS” illustrates a prototype of IMMMS, and section “Conclusion and further remarks” concludes this article and suggests some future research topics.

**Research backgrounds**

The objective of indoor positioning is to locate the position of a physical object inside buildings by applying wireless communication technology. Indoor positioning technologies can be categorized into two main types: active and passive. In active technologies, the position of target object is determined using electronic devices that can recognize the signals generated from the object. In contrast, target object in passive technologies must be equipped with capabilities for determining its own location. Examples of active indoor positioning technology include Active Badge\(^7\) and Active Bat\(^8\) of AT&T that utilize ultrasonic waves, RADAR\(^9\) of Microsoft that utilizes propagation delay of radio signals, Precision Asset Location (PAL) system of Multispectral Solutions, Inc., which is based on ultra-wideband (UWB) communications,\(^10\)\(^11\) and so on. On the contrary, Cricket Location System\(^12\) of MIT is an example of passive indoor positioning technology.

UWB communication is a kind of wireless communication technology, which uses a bandwidth of higher than 500 MHz or has non-bandwidth (bandwidth corresponding to the center frequency) of more than 20%.\(^13\) Wider bandwidth can increase the precision of indoor positioning and makes it possible to recognize multipath signals. Moreover, UWB technology enables robust indoor positioning, since it is less affected by channel fading. IEEE 802.15.4a is a technological standard for UWB communication, and its main objective is to overcome the problems related with accuracy of distance measurement, stability of communication range, recognition of multipath effect, interference with other wireless communications, mobility, and so on.\(^14\)\(^15\) According to the technological standards for UWB communication established by Task Group 4h, there are two physical layers (PHYs): chirp spread spectrum UWB (CSS-UWB) and impulse radio UWB (IR-UWB).\(^15\)\(^16\) Among them, IR-UWB, which emits signals at \(-41 \text{ dBm/MHz}\) in 3–10 GHz bandwidth, is more suitable for low-powered wideband communications.\(^17\) Taking costs and performances into account, this article applies active type indoor positioning equipment based on UWB communication to develop a prototype of IMMMS.

Thus far, there are only few examples of UWB-based indoor positioning technology identified in previous literature. Korea Institute of Electrical and Electronics Engineers has developed real-time position recognition system by applying IR-based UWB, which uses an impulse signal with time width of several nanoseconds or less.\(^18\) Seo et al.\(^19\) applied UWB communication to locate the positions of mobile robots in real time. However, previous studies primarily focused on precise detection of the positions of physical objects. On the
contrary, the objective of IMMMS proposed in this article is to obtain a wide range of data useful for operations management in a flexible manner.

IMMMS
Concept and overall structure

Figure 1 illustrates the concept of IMMMS, where we can see that it consists of two main parts: indoor positioning equipment and user application. The role of indoor positioning equipment is to track the position of a mobile resource within manufacturing facility in real time. If the position of a mobile resource is detected, the indoor positioning equipment generates digital data that contains 3D coordinates of the position. Since the position of mobile resource is tracked continuously, we will obtain a series of 3D coordinates, which is the raw data collected by the indoor positioning equipment. The raw data can contain various valuable information about position, movement, and performance of the mobile resource; however, it might be difficult to interpret and analyze the raw data due to its structure and volume. Therefore, this article designs a specialized user application and integrates it with the indoor positioning equipment.

The user application is used to extract more useful information from the raw data or transform the raw data into more structured form. To this end, the user application utilizes two important entities: event to track (EtT) and inspection zone. EtT denotes various events that can be triggered by the tracked mobile resource and detected from the raw data generated by indoor positioning equipment. An individual EtT must be associated with an inspection zone, a sub-area of the entire tracking area monitored by the indoor positioning equipment. In other words, an EtT can occur within an inspection zone. Moreover, the user application allows the users to define EtT and inspection zone flexibly, and they should be registered to the proposed system in advance.

During the transformation of raw data to the user application, it continuously determines if any specific EtT occurs. If an occurrence of any EtT is detected, the user application executes data processing procedures, including event observation, segmentation, and event record. First, event observation is a procedure for collecting basic event-related statistics, such as duration and location of occurrence. For each EtT occurred, one observation record containing event-related statistics is made, and repetitive occurrences of an individual EtT generate multiple observation records, which are stored in summary data. Consequently, the summary data contains information on basic features of mobile resource movement, and we can also obtain descriptive statistics, such as average duration, from the data. In this context, the summary data can be used to obtain useful parameters for additional analyses, such as performance evaluation and facility layout design. Second, segmentation is a procedure for splitting the raw data into sub-time series. During the operation hours, mobile resources, such as human operators and forklifts, perform various tasks iteratively. Hence, a large volume of raw data might contain information on multiple iterations of a specific task, such as transportation of material. In this case, splitting the raw data into sub-parts for individual iterations can be helpful for...
additional analysis, and the EtT can be used as the splitting points for data segmentation. Third, event record procedure is used to accumulate event log data, which contain history of event occurrence. Typically, log data should contain three important features: event owner identifier, event identifier, and time stamp. The user application assigns appropriate identifiers to mobile resources and EtT, which can be used as event owner identifier and event identifier, respectively. Moreover, the obtained log data can be used to identify the problems in manufacturing processes or to obtain process model by applying process analysis techniques, such as sequence mining and process mining.

Indoor positioning equipment for tracking mobile resources

Figure 2 shows the components of indoor positioning equipment for IMMMS. First, anchor, tag, and listener in Figure 2 are physical devices used to recognize the position of mobile resources and collect the raw data in real time. A mobile resource to track must be provided with a small device called tag. Anchor is an electronic device used to locate the positions of tags in real time. In other words, the anchors recognize the 3D coordinate values of the tags during the execution of IMMMS. To obtain precise position data, we deploy four anchors, and the area tracked by them is called tracking area in this article. Note that the anchors can recognize the position of a tag if and only if it is inside the tracking area. Moreover, the position data of tag are transferred to the anchors through UWB communication. The anchors transfer the recognized position data to the listener, an electronic device connected to server computer. The listener is used for communication between anchors and server computer, and its role is to receive input signals from anchors and transfer the real-time position data to server computer. The user application utilizes the position data transferred to server computer to perform event-detection and additional data processing procedures.

Figure 2. Tracking mobile resource using indoor positioning equipment.

Figure 3 illustrates an example of indoor positioning devices manufactured by DecaWave Company used to develop a prototype of IMMMS in this article. The devices can communicate with each other through UWB communication and they can be used to implement active type indoor positioning environments. We can see 12 devices in Figure 3, and all of them can be used as tag, anchor, and listener. Since we deploy four anchors in this article, six devices are required to track a single mobile resource in that one tag, four anchors, and one listener are needed.

EtT and inspection zone

The user application of IMMMS is based on two important entities: EtT and inspection zone. Inspection zone is a sub-area of the entire tracking area, where the tracking area is created by four anchors, where an inspection zone is defined by the users. After IMMMS is configured for a specific area within a certain manufacturing facility, the tracking area is automatically visualized as a rectangle within the user application. This rectangle is called virtual tracking area. After the virtual tracking area is rendered, user can create more rectangles and overlay them onto the virtual tracking area, and the rectangle defined by the user is inspection zone. A mobile resource equipped with tag is visualized as a point in the tracking area of the user application and this is called tracking object in this article. The position of the tracking object within the virtual tracking area is determined according to the latest position of the associated mobile resource within real tracking area. Since the indoor positioning equipment generates the position data continuously, the tracking object moves in virtual tracking area whenever the mobile resource moves in real tracking area. While the mobile
resource is being tracked, the tracking object can interact with the inspection zone in various ways as shown in Figure 4 and such interactions can trigger EtT.

EtT denotes the events that can be triggered by the interaction between the tracking object and the inspection zone in virtual tracking area. In this article, EtT is classified into two types: simple event and complex event. As shown in the lower part of Figure 4, this article considers four types of simple event, namely, enter, stay, exit, and pass. The meanings of four types of simple event are quite straightforward. Enter (exit) type event occurs when the tracking object moves from outside (inside) of an inspection zone to inside (outside). Let us assume that a tracking object enters an inspection zone at time $t$ and leave there at time $t + \Delta t$. If $\Delta t$ is larger than user-defined threshold MinDuration for stay, stay type event occurs. On the contrary, if $\Delta t$ is smaller than user-defined threshold MaxDuration for pass, the movement is regarded as pass type event. A user can create any type of simple event after he or she chooses an associated inspection zone within the virtual tracking area. Moreover, an individual simple event has several properties listed in Table 1, which must be determined by the user to complete the creation of simple event. The properties of simple event are categorized into two groups: basic and condition. The basic group includes name, associated zone, associated object, and type. The name property is used as an identifier of simple event. Moreover, associated zone and associated object are references to the associated inspection zone and tracking objects, respectively. Note that the value of association zone property is automatically determined when the creation of simple event begins. The properties of condition group specify several conditions that must be met by simple event. For example, MinDuration and MaxDuration properties are minimum duration for stay type event and maximum duration for pass type event, respectively. If EnterDirection or ExitDirection property is specified, a simple event occurs if and only if the tracking object crossed the corresponding border line of the associated inspection zone. On the contrary, complex event is a series of two or more registered simple events. For example, let us assume that the role of a human is to process a raw material at a machine and transport the processed material to a rack. Then, stay type event for the inspection zone around the machine and enter type event for another inspection zone around the rack will occur in series. Moreover, a series of these two simple events indicate that the operator has performed the given task once. In this context, complex type event can also provide useful information about the movement of mobile resource. A complex event can be created after the simple events to be included are registered, and it has several properties listed in Table 2. The simple events included within a complex event must be specified by the element property of basic group. On the contrary, the properties of condition group define when an

### Table 1. Properties of simple event.

| Group  | Property   | Value                      |
|--------|------------|----------------------------|
| Basic  | Name       | Text                       |
|        | Associated zone | Reference to a registered inspection zone |
|        | Associated object | References to registered tracking objects |
|        | Type       | Enter/exit/stay/pass       |
| Condition | MinDuration | Numerical (stay type only) |
|          | MaxDuration | Numerical (pass type only) |
|          | EnterDirection | Up/down/left/right/all (enter, stay, pass types) |
|          | ExitDirection | Up/down/left/right/all (exit, stay, pass types) |

### Table 2. Properties of complex event.

| Group  | Property   | Value                      |
|--------|------------|----------------------------|
| Basic  | Name       | Text                       |
|        | Elements   | Sequence of references to simple events |
|        | Associated object | References to registered tracking objects |
| Condition | MinInterval | Numerical (for each pair of consecutive elements) |
|          | MaxInterval | Numerical (for each pair of consecutive elements) |
|          | StopEvent  | References to registered simple events |
occurrence of complex event is aborted. MinInterval and MaxInterval properties are lower and upper bounds for the time interval between $i$th and $(i + 1)$th elements ($i = 1, 2, 3, \ldots$). For example, a complex event is not tracked by the user application if time interval between two consecutive elements is larger than MaxInterval. StopEvent property contains references to simple events, where the occurrence of a complex event is aborted when one of those simple events occurs.

**Workflow of IMMMS**

Figure 5 depicts the entire workflow of IMMMS proposed in this article. The first three steps, including installation and setting, tag and anchor registration, and tracking area detection, are required for initial configuration of the entire system. When these steps are completed, the position data of tags are transferred to the server computer and it can be visualized in user application.

Next, user can define inspection zones and EiTs, and the information on these entities is stored in database. After inspection zones and EiTs are registered, the tracking task can be started. During the tracking task, the indoor positioning equipment, including tags, anchors, and listener, generate the position data of mobile resources and transfer it to the user application. Then, raw data are used to visualize the movement of mobile resources on the virtual tracking area of the user application. Moreover, the user application performs event-detection procedure using the tracked object and inspection zones within the virtual tracking area. Consequently, summary, segmented, and log data for the tracking object are obtained during the tracking task, and they are provided to the user through reporting and analysis procedure.

**Prototype of IMMMS**

In this article, the user application for IMMMS is developed using C# language and Unity Engine, and Figure 6 shows the virtual tracking area rendered in the user application, where black circle and gray rectangle indicate tracking object and inspection zone, respectively.

After indoor positioning devices are deployed, user can initiate the real-time tracking procedure by clicking the start button in the upper right-hand side of the user application. Then, the tracking object automatically appears within the virtual tracking area whenever the associated mobile resource exists in the real tracking area. The inspection zone is a rectangular area defined by user, and Create Area button is used to create an inspection zone. User can create an inspection zone in a click-and-drag manner after clicking Create Area button. On completion of above configurations, ID and
location of tag and anchors are displayed in real-time location tracking view as shown in Figure 6. Moreover, the basic EtTs, including enter, exit, stay, and pass, are applied to each inspection zone. Besides, the user application has several other buttons and their roles are summarized in Table 3.

In this article, we apply the prototype of IMMMS to measure the processing time of a simple manual task. It is straightforward that processing times of specific tasks and processes are important input parameters for a wide range of analyses, such as production system modeling and performance evaluation. Especially, variations and statistical distributions of processing times should be carefully modeled and considered in analysis for operations management. Nevertheless, many manufacturing companies assume processing times to be constant, and this can cause significant inaccuracies in analysis results. Note that processing time of the manual task to be observed was also assumed to be constant, and its standard processing time was 210 s. In this context, our objective is to observe the actual processing times and identify its statistical characteristics by applying IMMMS.

For experiment, we set up an experiment environment as shown in Figure 7. The width and height of the real tracking area is 4.5 and 3.5 m, respectively. We can see that four anchors are deployed at the corners of the area, and they are fixed at 2 m high from the ground. In this article, one human worker participates in the experiment. Since the human worker is the tracking object, the worker is provided with a tag. Initially, materials are stored at the storage box, and the human worker has to bring the materials to the workbench to start his manual task. When the task is finished, the human worker visits the storage box again.

**Table 3.** Buttons in real-time location tracking view.

| Button          | Functionality                                                                 |
|-----------------|-------------------------------------------------------------------------------|
| Start/Stop      | Activate/deactivate the tracking mode                                         |
| Create Area     | Create inspection zone. For each inspection zone, information on simple EtTs will be collected during the real-time tracking procedure |
| Enter Log       | Shows histories about entry time and stay time for a specific inspection zone |
| Anchor Log      | Shows the details of registered anchors                                       |
| Tag Log         | Shows the details of registered tags                                          |
| Area Log        | Shows the details of registered inspection zones                             |
| Area Reset      | Remove all inspection zones and initialize the virtual tracking area         |

**Figure 6.** Real-time location tracking view of user application.

**Figure 7.** Real tracking area for observing processing time.
Our objective is to observe the actual processing times of the manual task, which is carried out at the workbench. Therefore, the area around the workbench was defined as the inspection zone. Moreover, we assume that the stay time for the inspection zone is equivalent to the processing time for an individual material. Table 4 provides the details of hardware components used in this article. In addition, we observe the human worker’s movement while he processes 10 materials, and Figure 8 shows the collected stay time data displayed in enter log view of user application. The experiment results are summarized in Table 5.

In Table 5, we can see that the processing time has a certain degree of variation in that standard deviation is 17.13, though its average, 222.53, is similar with the standard processing time, 210 s. This means that assumption of constant processing time is not appropriate for this manual task. To consider such variation, we have to choose a statistical distribution suitable for the variable. To this end, we analyze the collected processing time data using ExpertFit software, which can be used to identify a statistical distribution suitable for a variable. As shown in Table 6, ExpertFit software recommends Johnson SB distribution as the most suitable distribution for the processing time, and Beta and Chi-Square distributions were the next suitable ones.

In general, many manufacturing companies have significant trouble in collecting data about the movement of mobile resources in real time. On the contrary, IMMMS proposed in this article enables to observe the movement of mobile resource very conveniently and obtain a wide range of statistics useful for further analysis, such as production system modeling and performance evaluation.

| Table 4. Hardware components of prototype of IMMMS. |
|-----------------------------------------------|
| **Hardware** | **Specifications** |
| Sensor | Manufacturer: DecaWave |
| | Part: DWM1001-DEV |
| | Features |
| | UWB Channel 5 printed PCB antenna (6.5 GHz) |
| | 6.8 Mbps data rate |
| | 60 m line-of-sight range typical |
| | IEEE 802.15.4-2011 UWB compliant |
| | Nordic Semiconductor nRF52832 |
| | Bluetooth® connectivity |
| | Bluetooth chip antenna |
| | Motion sensor: three-axis accelerometer |
| | Current consumption optimized for low-power sleep mode: <15 µA |
| | Supply voltage: 2.8–3.6 V |
| | Size: 19.1 mm × 26.2 mm × 2.6 mm |
| PC | CPU: Intel(R) Core(TM) i7-9750H CPU at 2.60 GHz |
| | RAM: 16GB |
| | Mainboard: ASUSTek COMPUTER INC—G731GW |
| | Graphics: NVIDIA GeForce RTX2070 |
| | OS: Microsoft Windows 10 Professional 64 bit |

| Table 5. Observed processing times. |
|-------------------------------------|
| **Repetition** | **Stay time(s)** |
| 1 | 242.5350 |
| 2 | 233.5331 |
| 3 | 213.5088 |
| 4 | 198.5256 |
| 5 | 198.5256 |
| 6 | 237.5412 |
| 7 | 231.3251 |
| 8 | 243.1452 |
| 9 | 209.4711 |
| 10 | 199.7230 |
| **Average** | 222.53 |
| **Standard deviation** | 17.13 |
| **Max** | 243.15 |
| **Min** | 198.53 |

| Table 6. Statistical distribution for processing time. |
|-----------------|-------------|-----------------|-----------------|
| **Rank** | **Distribution** | **Relative score** | **Parameters** |
| 1 | Johnson SB | 99.19 | Lower endpoint | 195.93 |
| | | | Upper endpoint | 242.60 |
| | | | Shape #1 | -0.12 |
| | | | Shape #2 | 0.47 |
| 2 | Beta | 97.58 | Lower endpoint | 196.82 |
| | | | Upper endpoint | 242.31 |
| | | | Shape #1 | 0.70 |
| | | | Shape #2 | 0.63 |
| 3 | Chi-square | 79.84 | Location | 49.34 |
| | | | d.f. | 171.96 |

Figure 8. Enter log view of user application.
Conclusions and further remarks

Recently, we can collect a wide range of digital data from manufacturing facilities by applying modern ICT infrastructures, including indoor positioning technology. However, such technologies often generate a huge amount of raw data iteratively, and it is difficult for the practitioners to interpret and utilize it effectively. Thus, the modern ICT infrastructures for digital data collection should be integrated with appropriate capabilities for data manipulation and processing. This article especially proposes an indoor positioning technology-based application, IMMMS, which enables to collect more useful data conveniently. Consequently, it is expected that the proposed system will help managers and engineers in manufacturing companies to make decisions on operations management in more systematic way.

Nevertheless, the details of IMMMS should be further refined in future. First, the user interface should provide various types of EtT that can be applied to represent a wide range of movements of mobile resources in manufacturing facilities. Although this article suggested four types of simple event and concept of complex event, the authors continue research on applicability of them and necessity for additional types of event. Properties of EtT also should be revised if required. Second, the user application will be more helpful if it supports appropriate reporting and analyzing functionalities. Currently, we focus primarily on transforming the raw data into summary, segmented, and log data. Therefore, other tools and softwares might be needed to analyze the data provided by the user application. To mitigate this inconvenience, the authors consider developing a reporting and analysis module for IMMMS. Third, a few seconds delay has occasionally occurred in data transfer from anchor to listener. Although the delay does not affect the accuracy of the collected data, we are making efforts for optimizing the data transferring procedure of IMMMS for its practical use. Finally, the development of IMMMS is currently in prototype design phase, and the authors plan to apply it to a wide range of tasks in real manufacturing facilities to identify its limitations and develop revised versions of IMMMS.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by the Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE: Ministry of Trade Industry and Energy; Grant No. N0002429).

ORCID iD

Jun Woo Kim https://orcid.org/0000-0002-0875-8364

References

1. Radiziwon A, Bilberg A, Bogers M, et al. The smart factory: exploring adaptive and flexible manufacturing solutions. Proc Eng 2014; 69: 1184–1190.
2. Longo F, Nicoletti L and Padovano A. Smart operations in industry 4.0: a human-centered approach to enhance operators’ capabilities and competencies within the new smart factory context. Comput Ind Eng 2017; 113: 144–159.
3. Kim JW, Park JS and Kim SK. Application of FlexSim software for developing cyber learning factory for smart factory education. Multimed Tool Appl. Epub ahead of print 13 September 2019. DOI: 10.1007/s11042-019-08156-1.
4. Kusiak A. Smart manufacturing. Int J Prod Res 2018; 56: 508–517.
5. Lee J. Smart factory systems. Informatik Spektran 2015; 38: 230–235.
6. Du P, Zhang S, Zhong WD, et al. Real-time indoor positioning system for a smart workshop using white LEDs and a phase-difference-of-arrival approach. Optical Eng 2019; 58: e084112.
7. Want R, Hopper A, Falcao V, et al. The active badge location system. ACM Trans Inform Syst 1992; 10: 91–102.
8. Harter A, Hopper A, Steggles P, et al. The anatomy of a context-aware applications. In: Proceedings of 5th annual ACM/IEEE international conference on mobile computing and networking, 15–19 August 1999, pp.59–68. New York: ACM.
9. Bahl P and Padmanabhan VN. RADAR: an inbuilding RF-based user location and tracking system. In: Proceedings of IEEE INFOCOM, Tel-Aviv, Israel, 26–30 March 2000, pp.775–784. New York: IEEE.
10. http://www.multispectral.com
11. Fontana RJ, Richley E and Barney J. Commercialization of an ultra wideband precision asset location system. In: Proceedings of IEEE conference on ultra wideband system and technologies, Reston, VA, 16–19 November 2003, pp.369–373. New York: IEEE.
12. Priyantha NB, Chakraborty A and Balakrishnan H. The cricket location-support system. In: Proceedings of the 6th international conference on mobile computing and networking, Boston, MA, 6–11 August 2000, pp.32–43. New York: ACM.
13. http://www.fcc.gov/oet/info/rules
14. Sahinoglu Z, Gezici S and Guvenc I. Ultra-wideband positioning systems: theoretical limits, ranging algorithms, and protocols. Cambridge: Cambridge University Press, 2008.
15. IEEE Standard 802.15.4a-2007, https://standards.ieee.org/standard/802_15_4a-2007.html
16. IEEE Standard 802.15.4-2011, https://standards.ieee.org/standard/802_15_4-2011.html
17. Joshi M. Ultra wide bandwidth. In: Proceedings of 2nd international conference on education technology and computer, Shanghai, China, 22–24 June 2010, pp.374–378. New York: IEEE.
18. Park YJ, Lee SW, Kang JM, et al. Application of impulse UWB technology based real-time location system. *J Korean Inst Commun Sci* 2011; 28: 37–43.
19. Seo JH, Jeong YH, Bae YJ, et al. Development of UWB-based indoor positioning system for robot tracking. *J Korean Inst Commun Inform Sci* 2019; 44: 701–708.