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BBUNS: Bluetooth Beacon-Based Underground Navigation System to Support Mine Haulage Operations

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Abstract: A Bluetooth beacon-based underground navigation system (BBUNS) was developed to identify the optimal haul road in an underground mine, track the locations of dump trucks, and display this information on mobile devices. A three-dimensional (3-D) geographic information system (GIS) database of the haul roads in an underground mine was constructed, and the travel time for each section was calculated. A GIS database was also constructed for 50 Bluetooth beacons that were installed along the haul roads. An Android-based BBUNS application was developed to visualize the current location of each dump truck and the optimal haul road to the destination on mobile devices, using the Bluetooth beacon system that was installed in the underground mine. Whenever the BBUNS recognized all of the Bluetooth beacons installed in the underground mine, it could provide the dump truck drivers with information on the current location and the two-dimensional (2-D) and 3-D haul road properties. The operating time of each dump truck and the time spent on each unit task could be analyzed using recorded data on the times when Bluetooth beacon signals were recognized by the BBUNS. The underground mine navigation system that was developed in this study can contribute to the improvement of haul operation efficiency and productivity.

Keywords: underground mine; navigation system; Bluetooth beacon system; truck haul operations

1. Introduction

All over the world, as high-quality ore deposits near ground surfaces have been extensively mined and are now almost exhausted, the mining industry is increasingly using large machines to mine low-quality ore deposits at greater depths at mining sites. At highly mechanized mining sites, the efficient operation and management of equipment are crucial not only for productivity and safety during mining work, but also for the profitability of mining corporations. Various types of fleet management systems (FMSs) have been developed at mining sites for the efficient operation and management of mining equipment [1–4]. The key technologies that are provided by FMSs in relation to loading and haul operations at mining sites include dispatching technology [1,5–18] that identifies optimal combinations of equipment and adjusts dispatch intervals, routing technology [19–22] that identifies optimal equipment travel routes, and tracking technology [23] that monitors the current location and operational status of each piece of equipment.

FMSs include navigation systems that identify the optimal haul road to the destination, track the location of each piece of transport equipment at a mining site, and display information, such as the optimal haul road, the current location of the equipment, and the cycle time, on a device that is mounted in each vehicle. The navigation systems have been introduced recently at mining sites as new solutions for maximizing the efficiency or haul operations. For instance, Hexagon Mining's Jtruck (2017, Brisbane, QLD, Australia) [24], which is a typical navigation system for use in open-pit mines, updates haul vehicle dispatch information and haul road information in real time through a wireless communication infrastructure and tracks the current location of each dump truck using global positioning system (GPS) signals. In addition, terminals are installed in each vehicle to provide the driver with real-time information on the current location of the vehicle in the mine and the distance along the haul road to the destination. In underground mines, however, it is difficult to share haul operation information with people outside of the mine and to track the location of the equipment in real time, because the haul operations are conducted with disconnected GPS signals and wired/wireless communication [25].

The development of a navigation system for underground mines requires three types of techniques. The first technique can determine the optimal haul road from a certain departure location to a workplace destination for haul operations. Geographic Information System (GIS)-based network analysis is a typical technique that is used to analyze the travel routes that connect a departure point and destination point and then identify the optimal travel route—i.e., the one with the lowest travel cost—in an environment in which vector networks such as roads, railways, and waterways are constructed [22,26–28]. The travel cost factors that are considered when analyzing the optimal travel route include distance, time, speed, terrain slope, resistance, and other factors that are related to various phenomena that may occur in a network environment [29–33]. Several studies have been conducted using the GIS-based network analysis technique to identify the optimal travel route and minimize the haul operation time of load–haul–dump (LHD) equipment in underground mine environments [6,19,20,34].

The second type of technique that is required for a navigation system for underground mines is one that can recognize the exact location of each dump truck using wireless sensor technologies. Recent installations of wireless sensor networks [35,36], Wi-Fi [37,38], Zigbee [25,39], and radio frequency identification (RFID) tags [40–42] in underground mines have made it possible to track transport equipment and communicate between the inside and the outside of underground mines. In addition, various mining corporations have commercialized products for use in accurately locating and tracking transport and loading equipment in underground mines. Among these products are Minetec's Trax+Tags TM II (2017, Perth, WA, Australia) [43], which uses a wireless ad hoc system; Modular Mining Systems' Dispatch (2017, Tucson, AZ, USA) [44]; and Mine Site Technologies' Asset tracking system (2017, Sydney, NSW, Australia) [45], which uses RFID tag technology. Technologies that can be used to recognize the location of individual dump trucks and measure travel times using a Bluetooth beacon system have attracted attention recently [46,47]. Bluetooth beacon systems are based on Bluetooth low-energy (BLE) technology, which is part of Bluetooth 4.0 wireless technology, and is mainly used for indoor positioning using smart devices [48]. BLE technology is designed to operate for many years with lower power consumption than the existing Bluetooth technologies, and the reduced packet size enables efficient data transmission [49]. A comparison between BLE and other communication technologies, such as reverse RFID for mining applications can be found in Baek et al. [50].

The third requirement is a technique that displays the current location of each dump truck in the underground mine, along with the travel route to the destination. Terminal-type products that display the current location of each dump truck in an underground mine have recently been commercialized. For example, Maptek's MineSuite Fleet management system (2017, Denver, CO, USA) [51] identifies the location of each dump truck in an underground fleet using an RFID system that is installed in the underground mine and displays each location on terminals. MISOM Technologies' FARA application (2017, Tucson, AZ, USA) [46] recognizes the location of each dump truck using a Bluetooth beacon system in an underground mine and displays the current location and distance to the destination on mobile devices. Mobile applications can be implemented on various smart devices, such as tablets, and the acquired data can be shared outside the mine through wireless communications technology.

Nevertheless, a navigation system that combines routing, tracking, and display techniques has not been developed for underground mines.

The purpose of this study was to develop a Bluetooth beacon-based underground navigation system (BBUNS) that could track the exact location of each dump truck in an underground mine, analyze the optimal haul road from the current location to the destination, and display this on a mobile device. For this purpose, an underground limestone mine was selected as the study area, a three-dimensional (3-D) GIS database was constructed for all of its haul roads, and a Bluetooth beacon system was installed in the underground mine. In addition, a mobile application was developed to recognize the current location of each dump truck in the underground mine using the signals that are transmitted by the Bluetooth beacons and to visualize the haul road to the destination. The results of the field application of this navigation system are presented.

2. Materials and Methods

2.1. Study Area

In this study, the Daesung MDI underground limestone mine (37°19′7″ N, 129°6′14″ E) in Samcheok city, Gangwon-do, South Korea was selected as the study area (Figure 1). This underground mine produces 1,500,000 tons of high-quality limestone every year through the room and pillar mining method. The limestone produced is used for various purposes, such as iron and cement manufacturing. The height of the uppermost workplace in the underground mine is 590 m above sea level, and the depth of the workplace is 170 m.

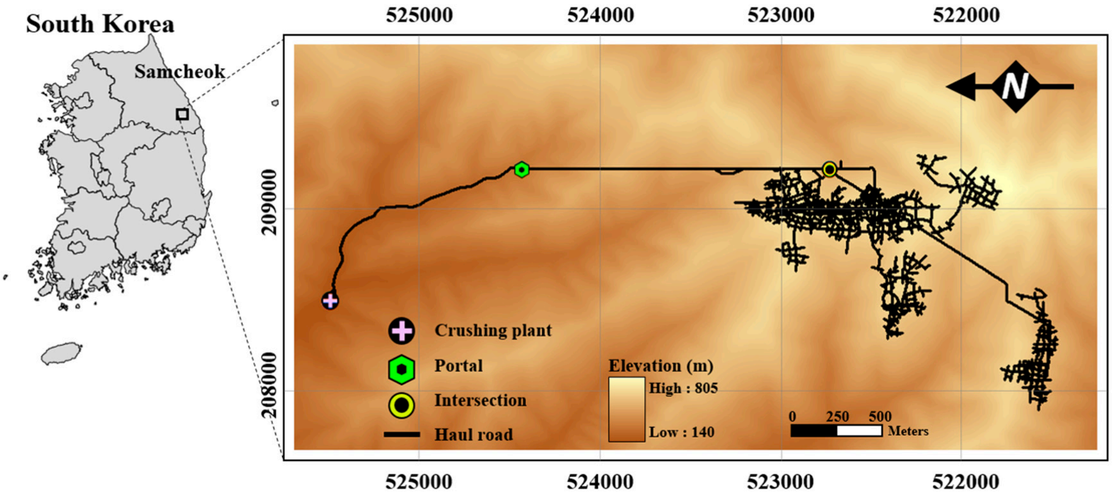


Figure 1. Illustrations of the study area. The reference grid is in m. The origin of the local Transverse Mercator coordinate system is 38°00′00″ N, 127°00′00″ E (map datum: GRS1980).

The underground mine in the study area mainly uses dump trucks for the transport of ore and waste stone. The dump trucks carry the ore produced in the workplace to a crushing plant located outside the underground mine and drops it into a crusher. The waste mined during ore production is carried by the dump trucks to a waste dump located inside the underground mine, where it is discharged. In this study, an underground mine navigation system was designed for the dump trucks that carry ore while traveling between the underground mine and the crushing plant that is located outside the underground mine.

The destination of each dump truck carrying ore depends on the location of the workplace where the limestone ore is produced. The production of limestone ore in the study area is planned on a daily basis using a production planning system, and the location of the workplace is selected according to the production plan. Once the location of the workplace is determined, the task administrator provides the drivers of the dump trucks with the location information of the workshop. If production occurs in multiple workplaces at the same time, the task administrator analyzes the dump truck placement and informs each driver of the location of the workshop to which he is assigned. The dump trucks travel to the assigned workshops through the haulage way that is installed inside the underground mine and carry the ore to the crushing plant that is located outside the mine. The dump trucks travel back and forth between the crushing plant and the workplace to transport the ore. Each dump truck travels 8–9 times per day on average. Currently, limestone ore in underground mines is mainly produced in 420 ML, 520 ML, and 540 ML workplaces.

2.2. Design of the Underground Mine Navigation System

In this study, a BBUNS was designed for use in underground limestone mines. First, a 3-D GIS database was constructed for all of the haul roads in the underground mine to analyze the optimal haul road using a network analysis technique. Multiple Bluetooth beacons were then installed along the haul roads in the underground mine, and a location information database for the Bluetooth beacons was constructed. Finally, an Android-based underground mine navigation application was developed to detect the signals that are transmitted by the Bluetooth beacons and display the location of each dump truck and the optimal haul road on mobile devices.

2.2.1. Construction of the 3-D GIS Database

The travel time of a dump truck was set as the objective function for network analysis, and the optimal haul road was defined as the one that minimizes the travel time between the crushing plant and the workplace. The optimal haul road was analyzed using Dijkstra's algorithm [31], which is a graph theory-based route optimization algorithm. Figure 2 shows an example of an analysis of the travel route with the lowest travel cost on a vector network using Dijkstra's algorithm. A vector network consists of links and nodes that are connecting the links. In all of the links, the travel cost that is required to pass through them is recorded, and, in all of the nodes, the cumulative travel cost required to travel from the departure node (n0) to the corresponding node is recorded (see Figure 2a). First, the travel cost required to travel from the departure node (n0) to the neighboring nodes (n1 and n2) is calculated and is compared with the already recorded value (∞). The lower value is updated as the new cumulative travel cost (see Figure 2b). After the calculation, the departure node (n0) converts to a "fixed" state for which the cumulative travel cost is not changed, and node (n2) with the lowest cumulative travel cost converts to the new departure node (see Figure 2c). In the same manner, the cumulative travel costs of all the nodes on the vector network are calculated (see Figure 2d,e). When cumulative travel costs are provided to all of the nodes, the optimal travel route that connects the departure node (n0) and the destination node (n3) at the lowest travel cost is derived (see Figure 2f). A more detailed description of the network analysis process can be found in Huang et al. [52].

To analyze the optimal haul road for the dump trucks via a network analysis, a 3-D GIS database was constructed for all of the haul roads inside the underground mine of the study area (see Figure 3). The haul roads for dump trucks in the study area consists of a haul road outside the mine that connects the crushing plant and the portal of the mine, an adit that connects the portal of the mine to an intersection, declines that connect the intersection to the entrances to the levels, ramps that connect the levels, and the levels in the workplace. The declines and ramps are shafts with slopes between $-8°$ and $8°$, and the rest of the haul roads are drifts with slopes of approximately $0°$. The drifts were represented as new polylines along the haul roads that are marked on the mine drawing and were digitized in a way that provides an elevation value to each polyline. The shafts and ramps were digitized by forming points corresponding to the two end points of the polyline, providing them with different elevation values, and then forming a tilted polyline connecting the two points. After combining all of the digitized haul roads into one, the haul road was divided at regular intervals of 50 m, based on the signal output range of a Bluetooth beacon. For the haul roads that are constructed inside the workplace, all of the points where two or more haul roads with different travel directions cross were cut, and multiple haul roads were generated.

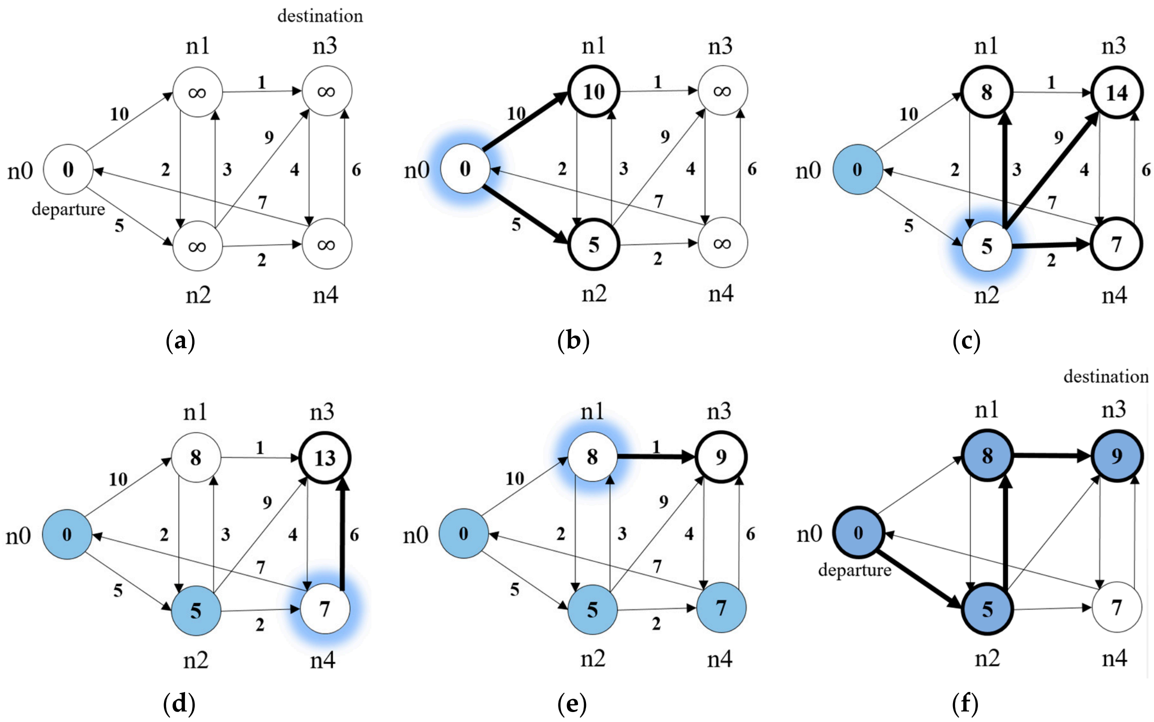


Figure 2. Example of analyzing the optimal path through a vector network using Dijkstra's algorithm. (**a**) Vector network consisting of links and nodes; (**b**) Calculating the travel cost required to travel from n0 to n1 and n2; (**c**) Calculating the travel cost required to travel from n2 to n1, n3, and n4; (**d**) Calculating the travel cost required to travel from n4 to n3; (**e**) Calculating the travel cost required to travel from n1 to n3; (**f**) The optimal travel route that connects the departure node(n0) and the destination node(n3) at the lowest travel cost.

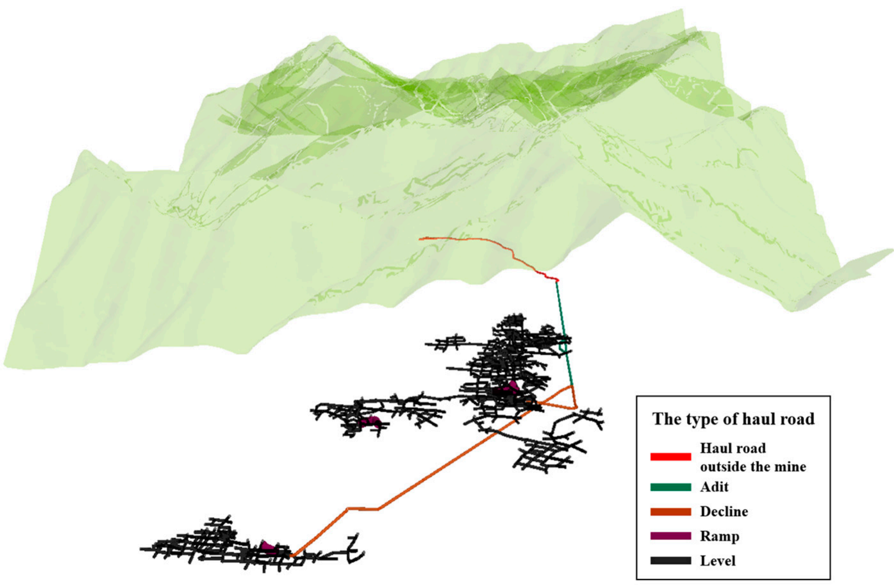


Figure 3. Three-dimensional view of haul roads constructed in the underground mine. Haul roads consist of an adit, declines, ramps, levels, and a haul road outside the mine.

The travel times required to travel along each polyline on a digitized 3-D haul road were calculated. To calculate the travel time for all of the polylines, estimates by Park et al. [34] were used for the average travel speed of a 15-ton dump truck for each type of haul road in the Daesung MDI underground limestone mine (see Table 1). The time required to travel along each polyline was calculated by dividing the length of the polyline by the average travel speed of the dump truck, and the calculated values were assigned as attributes of the polylines.

Table 1. Approximate speed and travel time of a 15-ton dump truck according to the type of haul road in the study area [34], where H denotes the haul road outside the underground mine, A denotes the adit, D denotes the decline, R denotes the ramp, and L denotes the level.

Type of Haul Road	Length (m)	Approximate Speed (km/h)		Travel Time (min)	
		Empty	Loaded	Route 1—Crushing Plant to Workplace	Route 2—Workplace to Crushing Plant
H	50	20	15	0.15	0.2
A	50	20	15	0.15	0.2
D	50	10	5	0.3	0.6
R	50	10	5	0.3	0.6
L	Variable	15	15	Variable	Variable

2.2.2. Installation of Bluetooth Beacons in the Underground Mine

In this study, a total of 50 Bluetooth beacons were installed in the 420 ML, 520 ML, and 540 ML workplaces in the underground mine where limestone is produced and along all of the haul roads on which dump trucks travel in order to enter the workplaces (see Figure 4). Bluetooth beacons have advantages for use in underground mines: (a) they offer outstanding signal detection and recognition capability in extreme environments; (b) it is possible to deploy them in an easier and cheaper way than other wireless communication systems, because smartphones can be used as beacon recognition terminals; and, (c) it is easy to develop applications for them, insofar as the Software Development Kit (SDK) for Bluetooth beacon products is available to the public [47,53].

(**a**) (**b**) (**c**)

Figure 4. Installing Bluetooth beacons (**a**) in the portal of the mine and (**b**) in the underground mine; (**c**) Bluetooth beacon with minor ID 22.

Four Bluetooth beacons were installed outside the underground mine. Inside the underground mine, Bluetooth beacons were installed at the center of each 50-m segment of each haul road. For the haul roads inside the workplaces, beacons were installed on curves with bends of 90° or more (see Figure 5). When considering the height of the driver in the type of 15-ton dump truck that is used in the study area, the Bluetooth beacons were installed 2.5 m above the road surface.

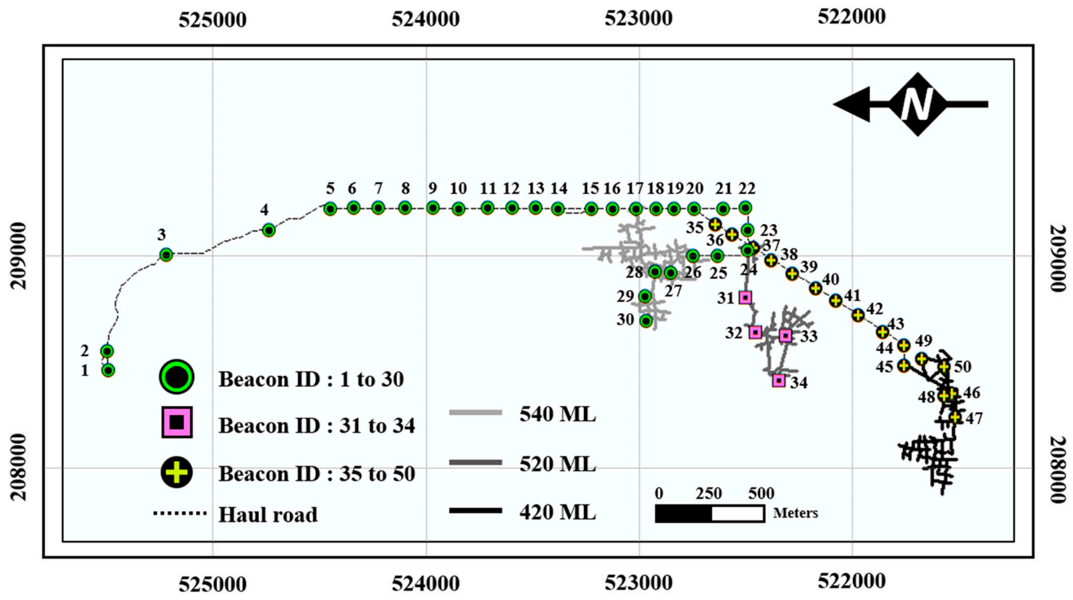


Figure 5. Underground mine map showing the installation position of Bluetooth beacons.

The beacons installed in the underground mine were RECO beacons (2017, Seoul, Korea) [54], manufactured by Perples. Each RECO beacon is a terminal that periodically transmits BLE signals. The user can set the signal strength and signal transmission cycle using the administrator application. A RECO beacon can be operated by Apple's iBeacon and Google's Eddystone, which are beacon standards used worldwide that are compatible with various iOS- and Android-based smart devices that support Bluetooth 4.0 technology. This equipment complies with electrical and communication standards, including the Federal Communication Commission (FCC), Korea Certification (KC), Conformité Européene (CE) marking, and the Technical Regulations Conformity Certification (TELEC) for operations in South Korean mines [47]. They are considered as suitable for the environment inside an underground mine, because these beacons are durable, waterproof, and relatively insensitive to dust [53]. In this study, the signal intensity of the Bluetooth beacons was set to 4 dBm to maximize the BLE signal recognition rate of smart devices inside the underground mine, and the signal transmission cycle was set to 0.01 s. Detailed specifications of the RECO beacons are listed in Table 2.

Table 2. Specifications of the RECO beacons (Perples, Seoul, Korea) installed in the underground mine.

Properties	
Dimensions	45 mm × 20 mm (Diameter × Height)
Weight	11.6 g (0.4 oz)
Processor	32-bit ARM® Cortex®-M0 (ARM Holdings, Cambridge, UK)
Chipset	Nordic nrf51822 (Nordic Semiconductor, Oslo, Norway)
Battery	CR2450 Lithium Coin Battery (3 V, 620 mAh, Panasonic, Osaka, Japan)
Casing	Acrylonitrile Butadiene Styrene (ABS) Plastic
Thermal Resistance	93 °C (200 °F)
Operating Temperature	−10–60 °C (14–140 °F)
Tx Power	−16–4 dbm
Signal range	1–70 m

For the efficient operation and management of the Bluetooth beacon system, a unique ID was assigned to each of the Bluetooth beacons that were installed in the underground mine. iBeacon can assign different universally unique identifiers (UUID) and major and minor values for different Bluetooth beacons so that all of the beacons installed in a certain area can be identified. For example, if the same UUID value is applied to all of the Bluetooth beacons installed by company A, with different major values applied according to the different installation area codes, and minor values starting from 1 are assigned to each Bluetooth beacon that is installed in the same area, all of the Bluetooth beacons can be easily identified and managed. The size of a UUID can be set up to 16 bytes, and the sizes of the major and minor values can be set up to 2 bytes. An integer between 0 and 65,535 can be assigned as a major or minor value. In this study, the same UUID and major values were applied to all of the Bluetooth beacons that were installed in the underground mine, while numbers from 1 to 50 were assigned as the minor values along the travel route of the dump trucks, as shown in Figure 5.

2.2.3. Development of the Mobile Underground Mine Navigation Application

A BBUNS application was developed to identify the location of each dump truck in the underground mine by analyzing the signals from the beacons and to display the locations and the optimal haul road to the destination on mobile devices. The BBUNS application was developed based on the Android operating system (Google, Menlo Park, CA, USA). Android applications can be developed easily using the Android application programming interface (API) and multiple libraries (e.g., SQLite and OpenGL), which are included in the Android software development kit (SDK) provided by Google. In addition, the key functions and development tools required to develop applications can be obtained easily, because Android provides an open-source platform. The BBUNS application was developed using Android Studio, one of the Android application development tools, and was implemented using the Java programming language. BBUNS applications can be used in various Android-based mobile devices, such as smartphones and tablets.

The BBUNS application developed recognizes the minor ID of the Bluetooth beacon that transmits a signal when the dump truck enters the Bluetooth signal reception area. To accurately recognize Bluetooth beacons, the BBUNS was designed to receive wireless signals from Bluetooth beacons at one-second intervals. If different signals from two different Bluetooth beacons are received, the minor ID of the closest beacon is recognized. The signal reception area can be extended by increasing the signal output intensity of the Bluetooth beacons. As the signal intensity is set higher, however, the batteries of the Bluetooth beacons are consumed more rapidly. Therefore, the user must set reasonable signal intensity. When the BBUNS recognizes a Bluetooth beacon, it stores all of the information concerning the beacon, such as the UUID, major ID, minor ID, signal intensity, recognition time, and recognized distance, in the database. The Bluetooth beacon signal recognition function was implemented using the Reco SDK provided by Perples.

The underground mine haul operation administrator analyzes the optimal haul road from the crushing area to the workplace where limestone is produced via network analysis. After the optimal haul road is identified and extracted as a new polyline, the minor IDs of all the Bluetooth beacons installed along the route are retrieved by means of a spatial query. The information about all of the minor IDs is then uploaded to a web server (see Figure 6). If the location of the workplace changes, then the process described above is performed again, and all of the minor IDs retrieved along the changed travel route are uploaded again to the web server. If the BBUNS application recognizes the Bluetooth beacon with minor ID 1 installed in the crushing plant, it logs into the web server and checks whether the version of the web server has been updated. As a wireless internet environment, such as Wi-Fi, is required to access the web server, the Bluetooth beacon with minor ID 1 was installed in an outdoor environment. An update of the web server means that the workplace has been changed, and thus that the optimal haul road has changed. Therefore, the BBUNS application downloads the modified Bluetooth beacon minor information and two-dimensional (2-D) and 3-D route pictures from the web server and stores them in the database of the device. If the version of the web server has not been updated, the route pictures that are stored in the database are used.

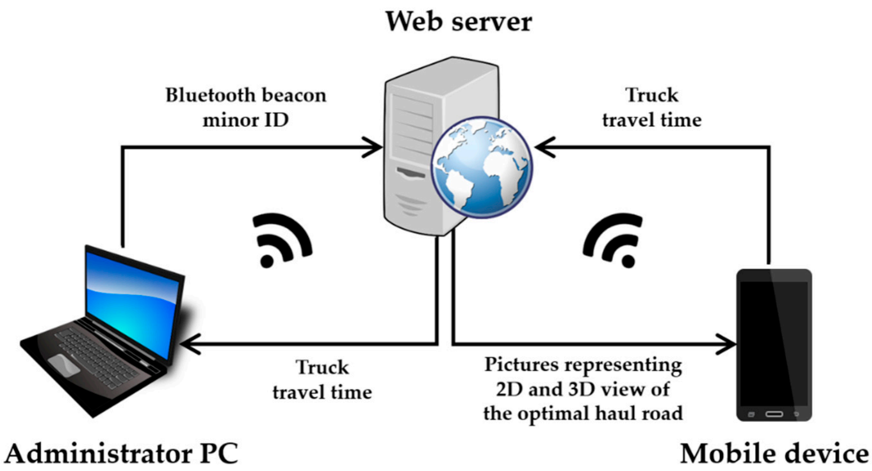


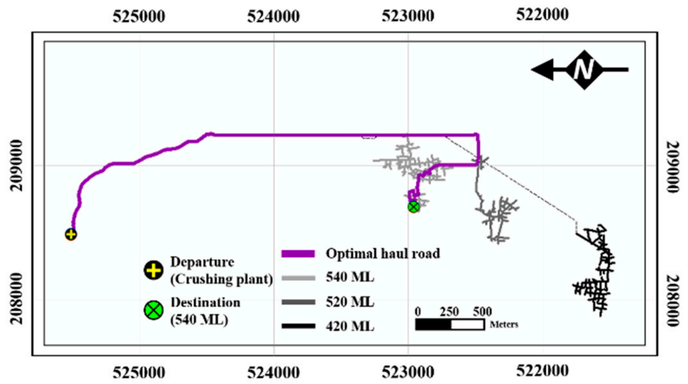
Figure 6. Conceptual view of data exchanges that occur when Bluetooth beacon-based underground navigation system (BBUNS) recognizes the signal of Bluetooth beacon that has minor ID 1.

After the download of data through the web server is complete, the BBUNS visualizes the optimal haul road to the destination through the graphical user interface (GUI) of the mobile device. The BBUNS visualizes new 2-D and 3-D views of the optimal haul road whenever it recognizes new Bluetooth beacons that are installed along the haul road. The 2-D pictures show a 2-D view of the haul road to the destination, the current dump truck location, travel direction, and all of the Bluetooth beacons along the route. The 3-D pictures display a 3-D view of the haul road from the point where the current Bluetooth beacon is recognized to the point where the Bluetooth beacon to be recognized next is located. As all of the haul roads start from the crushing plant, the optimal haul road picture for the Bluetooth beacon with minor ID 1 is visualized first, and the optimal haul road is visualized in the order of the Bluetooth beacon minor IDs installed along the optimal haul road. The dump truck driver travels along the route displayed on the mobile device to the workplace, loads limestone ore, and travels back to the crushing plant. The return route is visualized in the same manner as described previously. As the BBUNS application does not require a separate wireless Internet environment for visualization, it can be implemented in underground mines where a wireless Internet environment is not in place.

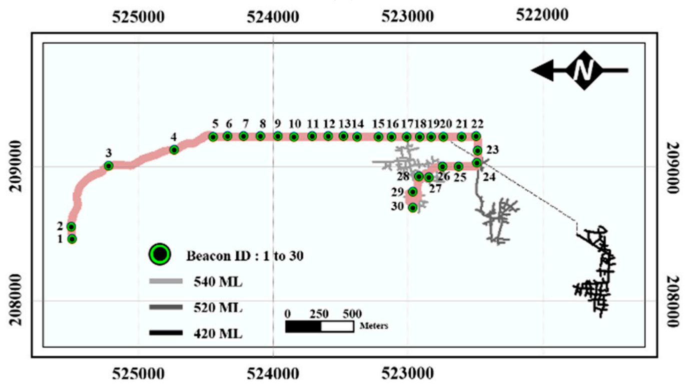
When the dump truck arrives at the crushing plant again, the BBUNS recognizes the Bluetooth beacon with minor ID 1. At this time, the information for all of the Bluetooth beacons (e.g., signal recognition time, UUID, major ID, minor ID, and RSSI) recognized by the application during the operation is uploaded to the web server and then deleted from the database. The dump truck again receives destination information and pictures through the web server and repeats the haul operation.

3. Results and Discussion

On 15 February 2017, the location of the limestone production workplace was determined to be 540 ML, and a total of four dump trucks were assigned to the 540 ML workplace. The crushing plant was set as the departure point, and the loading point of the 540 ML workplace was set as the destination. The optimal haul road that would minimize the truck travel time was determined via network analysis (see Figure 7a). The length of the haul road was determined to be approximately 4.56 km. As a result of the retrieval of the minor IDs of all the Bluetooth beacons that were installed along the optimal haul road through a spatial query, 30 Bluetooth beacons with minor IDs 1–30 were detected (see Figure 7b).



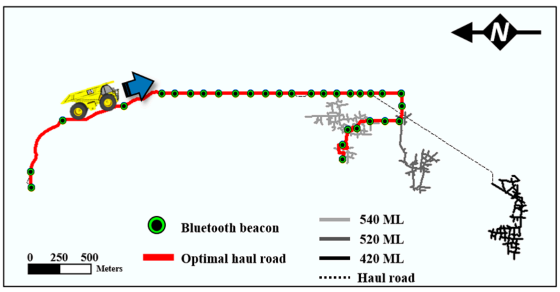
(**a**)



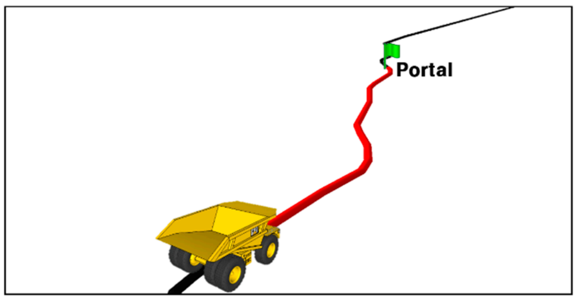
(**b**)

Figure 7. (**a**) Optimal haul road connecting the crushing plant and 540 ML workplace; (**b**) Bluetooth beacons that installed along the optimal haul road.

When the BBUNS application recognized the 30 different Bluetooth beacons, pictures showing the 2-D and 3-D views of the route to be displayed on the mobile device screen were downloaded from the web server and stored in the databases of the mobile devices. The route pictures were composed of 29 pictures in 2-D and 29 pictures in 3-D that displayed the crushing plant–workplace route and 29 pictures in 2-D and 29 pictures in 3-D that displayed the workplace–crushing plant route. Figure 8 shows two arbitrary pictures that were extracted from a total of 116 pictures in 2-D and 3-D. They were displayed on the mobile device screens when the BBUNS recognized the Bluetooth beacon with minor ID 3.



(**a**)



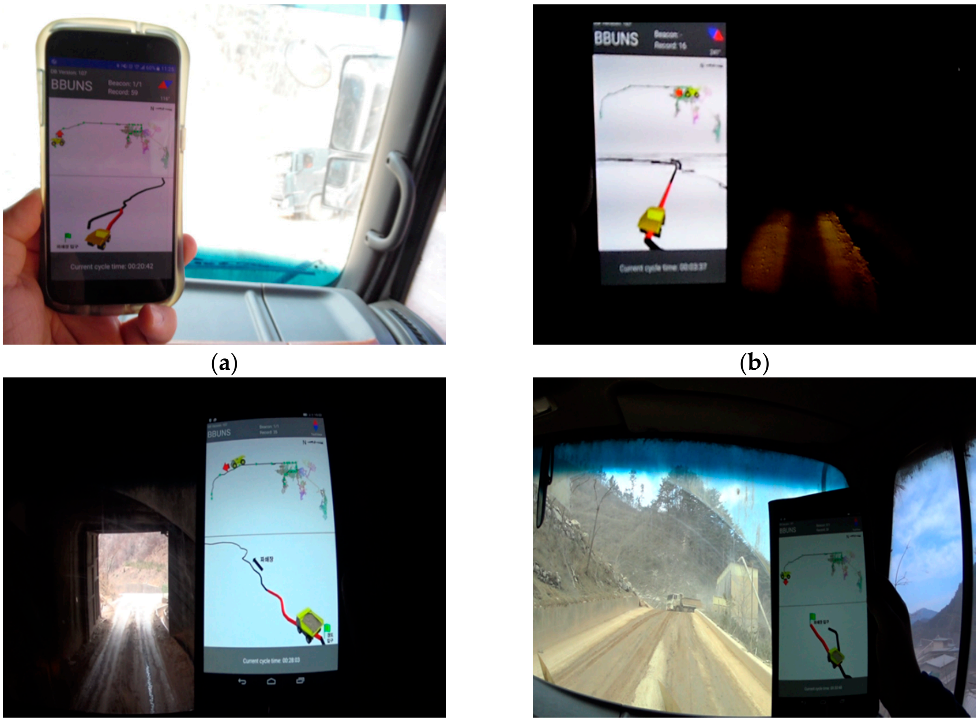
(**b**)

Figure 8. Screenshots of BBUNS application when the signal of a Bluetooth beacon with minor ID 3 is recognized. (**a**) Two-dimensional view of the optimal haul road showing the current location of the dump truck, the travel direction, and Bluetooth beacons installed along the path; (**b**) Three-dimensional view of the optimal haul road.

Four researchers boarded four dump trucks that were performing haul operations in the underground mine and tested the BBUNS application for three round trips. A Samsung Galaxy S5 smartphone, Samsung Galaxy S6 smartphone, Samsung Galaxy S7 smartphone, and Lenovo TAB were used in the application test. These devices were equipped with Bluetooth 4.0 technology or higher. Detailed specifications for the mobile devices are listed in Table 3. Figure 9 shows photographs of the mobile devices where the location of the dump trucks in the underground mine and the optimal haul road were visualized. The BBUNS application was able to recognize the Bluetooth beacons that were installed outside the underground mine as well as those installed inside the underground mine. In addition, whenever a Bluetooth beacon with a different minor ID was recognized, the 2-D and 3-D route pictures corresponding to the installation location of the beacon were displayed on the mobile device.

Table 3. Specifications of mobile devices used for testing the BBUNS application.

Model / Properties	Galaxy S5 (SM-G900)	Galaxy S6 (SM-G920)	Galaxy S7 (SM-G930)	Lenovo TAB (S850F)
Operating system	Android 6.0 (Google, Menlo Park, CA, USA)	Android 7.0 (Google, Menlo Park, CA, USA)	Android 7.0 (Google, Menlo Park, CA, USA)	Android 4.4.2 (Google, Menlo Park, CA, USA)
Android processor	Qualcomm Snapdragon 801 (Qualcomm, San Diego, CA, USA)	Exynos 7420 Octa (Samsung Electronics, Suwon, Korea)	Exynos 8890 Octa (Samsung Electronics, Suwon, Korea)	Intel Atom Z3745 (Intel, Santa Clara, CA, USA)
Bluetooth	Bluetooth 4.0	Bluetooth 4.1	Bluetooth 4.2	Bluetooth 4.0
RAM	2 GB	3 GB	4 GB	2 GB
Battery	2800 mAh	2550 mAh	3000 mAh	4290 mAh



(**a**) (**b**) (**c**) (**d**)

Figure 9. Results of testing the BBUNS application during the haulage operation when (**a**) leaving the crushing plant, (**b**) driving toward the 540 ML workplace, (**c**) passing by the portal of the underground mine, and (**d**) returning to the crushing plant.

The time spent in the haul operation was analyzed using the recorded data for the times when the Bluetooth beacons were recognized. It was assumed that the final time when a Bluetooth beacon was recognized was the time halfway between the time when the dump truck first entered the Bluetooth beacon signal reception area (i.e., the time when the Bluetooth beacon was first recognized) and the time when the truck exited the area (i.e., the time when the Bluetooth beacon was last recognized). Table 4 lists the times when Bluetooth beacons were recognized for one haul operation among a total of 12 haul operations. Twelve Bluetooth beacons out of 30 installed along the haul road were selected and displayed. It took approximately 8 min and 25 s for the dump truck to leave the crushing plant and reach the underground mine entrance, and approximately 9 min and 25 s to reach the workplace from the underground mine entrance. The dump truck remained at the workplace for approximately 4 min and 8 s for the loading operation. After loading, the dump truck traveled from the workplace to the underground mine entrance for approximately 13 min and 12 s. Traveling to the crushing area required approximately 5 min and 42 s. Therefore, the total time spent for one ore haul operation was approximately 40 min and 52 s.

Table 4. Time data recorded when Bluetooth beacons were recognized on the BBUNS mobile app during one cycle of haulage operations. In the location part of the table, C denotes the crushing plant, H denotes the haul road outside the underground mine, P denotes the portal, A denotes the adit, D denotes the decline, L denotes the level, and W denotes the workplace.

Route 1—Crushing Plant to Workplace			**Route 2—Workplace to Crushing Plant**		
Beacon Minor ID	**Location**	**Measured Time**	**Beacon Minor ID**	**Location**	**Measured Time**
2	C	09:21:54 a.m.	30	W	09:43:52 a.m.
3	H	09:26:29 a.m.	28	L	09:46:01 a.m.
4	H	09:28:16 a.m.	26	D	09:46:52 a.m.
5	P	09:30:19 a.m.	24	D	09:47:42 a.m.
10	A	09:33:36 a.m.	22	A	09:48:56 a.m.
14	A	09:34:33 a.m.	18	A	09:50:59 a.m.
18	A	09:35:34 a.m.	14	A	09:52:54 a.m.
22	A	09:36:38 a.m.	10	A	09:54:33 a.m.
24	D	09:37:16 a.m.	5	P	09:57:04 a.m.
26	D	09:37:53 a.m.	4	H	09:58:20 a.m.
28	L	09:38:31 a.m.	3	H	10:00:18 a.m.
30	W	09:39:44 a.m.	2	C	10:02:46 a.m.
Total travel time			00:40:52		

The dump truck travel time information that was analyzed in this study can be used as input data for underground mine fleet management systems, such as Maptek's MineSuite Fleet management system (2017, Denver, CO, USA) [51], Hexagon Mining's Jigsaw operations suite (2017, Brisbane, QLD, Australia) [55], Caterpillar's MineStar (2017, Peoria, IL, USA) [56], and Modular Mining Systems' Dispatch (2017, Tucson, AZ, USA) [44]. Furthermore, the information can be used in underground mine scheduling systems to identify optimal haul operation scenarios. When the information is used in such systems, the efficiency of haul operations using dump trucks in underground mines can be improved, and the productivity in mines can be increased.

The Bluetooth beacon-based underground navigation system designed in this study is limited by delays when visualizing the current location of the dump truck and the optimal haul road to the destination in the underground mine. For example, after the BBUNS application recognizes the signal from a Bluetooth beacon that is installed in the underground mine, there is a delay of several seconds before it recognizes the signal from the next Bluetooth beacon installed at the following location along the haul route. At this time, because the navigation functions recognize that the dump truck is remaining in the same location in the underground mine, it shows a static dump truck location and 2-D and 3-D view of the optimal haul road on the smart device during these few seconds. To overcome this limitation and to visualize the optimal haul road to the destination in real time, it is necessary to install more Bluetooth beacons at shorter intervals. Therefore, this work needs to be expanded as follows: (a) designing an optimal installation interval for a sufficient number of Bluetooth beacons in the underground mine, and (b) improving the BBUNS application for signal recognition delay time processing.

4. Conclusions

In this study, a Bluetooth beacon-based underground navigation system was designed for use in an underground limestone mine. The results of its field application are presented in this paper. For the field application, a 3-D GIS database was constructed for all of the haul roads in the underground mine, and 50 Bluetooth beacons were installed throughout the mine. An Android-based BBUNS application was developed that recognizes the signals that were transmitted by the Bluetooth beacons and displays the current location of each dump truck, as well as the travel route to the destination, on mobile devices. As a result of the application of the underground mine navigation system to the 540 ML loading point, it was confirmed that a dump truck driver could receive current location information and information on the optimal haul road through a mobile device whenever Bluetooth beacon signals were received by the BBUNS app. In addition, the travel time of the dump truck during the haul operation could be analyzed using time data for when the Bluetooth beacon signals were recognized.

The underground mine navigation system has the following advantages. As this system uses Android-based mobile devices to implement navigation functions, it is not necessary to manufacture separate terminals. In addition, the system installation cost is lower than other wireless sensor systems because there is no need to install a separate power network or communication network in the underground mine and because the Bluetooth beacons are inexpensive. Furthermore, the BBUNS application can be extended by implementing additional functions, such as real-time transport equipment location tracking, automatic attendance management, communication between administrators and workers, and navigation functions developed using the Bluetooth beacon SDK.

A navigation system for optimal ore haul operations in underground limestone mines was designed in this study. When waste stone is loaded instead of ore at the loading point, however, the loader operator frequently instructs the dump truck driver to haul the waste stone to a waste dump inside the underground mine. For such cases, it is necessary to develop a new routing method that can update the route information anywhere in the underground mine and exchange the acquired data with a receiver outside the mine. Therefore, further studies are required to implement effective navigation functions for haul operations performed inside underground mines.

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