Received: 16 February 2021 | Revised: 21 February 2022 | Accepted: 2 April 2022

DOI: 10.33012/navi.524

ORIGINAL ARTICLE

TrackMe—A Hybrid Radio-Optical System for Assets Localization in Industry 4.0 Plants

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Abstract

Precise localization is considered one of the most salient features of Industry 4.0 manufacturing facilities. For this reason, multiple solutions have already been proposed. The method presented in this paper entails the use of double-band radio and optical technologies for near-real-time location tracking and remote reporting, with a final tracking accuracy of 0.5 meters. To preserve low-energy operations, the system infrastructure part is deployed on passive radio-frequency identification (RFID) tags, whereas the part installed on tracked assets implements energy-saving mechanisms. The system was deployed in an automotive production plant which allowed us to draw practical remarks on such aspects as the separation of onboard Ultra High Frequency (UHF) antennas; proper electromagnetic isolation of radio modules to prevent signal blocking; the placement and mechanical securing of RFID tags on the floor; as well as how to implement procedures to decrease the duty cycle, allowing for a trade-off between system sensitivity and energetic efficiency.

Keywords

duty cycle, InFlux, localization, RFID, tracking

1 | INTRODUCTION

1.1 | State of the Art in the Field of Indoor Localization Systems

The issue of indoor localization has been a topic of the research field for several years now, even more recently as the precise tracking of assets in modern production plants and warehouses has become one of the distinguishing features of Industry 4.0 businesses. Since GPS services are limited or unavailable in these environments, localization is carried out using *wireless local area network* (WLAN) techniques, *wireless sensor networks* (WSNs), *ultra-wideband* (UWB) systems, and *radio-frequency identification* (RFID) technology.

From 2014 through 2017, Microsoft held a competition for an indoor localization system, the results of which can be found in Lymberopoulos and Liu (2017). The winning solutions that demonstrated the highest accuracy turned out to use light detection and ranging (lidar)—a radar equivalent emitting laser waves instead of microwaves. Lidar systems, in general, can be supported by cameras and GPS, as well as other UWB techniques.

It should be noted, however, that localization in industrial environments differs from other indoor environments. In the former, the telecommunication channel is characterized by considerable time variance (due to the constant movement of machines), which makes it impractical to resort to systems that are based solely on the *received signal strength indication* (RSSI) since this channel variability makes the signal strength site map creation impossible.

The need for precisely locating assets such as vehicles or human workers is recognized as one that also provides practical advantages that can lead to the optimization of internal traffic or vehicles (such as forklifts or automated guided vehicles [AGVs]) to avoid collisions at lane crossings or unnecessary queuing at loading/unloading ramps. This calls for further research of optimal methods for these environments, such as the research presented by Collotta et al. (2013) and Li et al. (2019).

Collotta et al. (2013) tested a localization system based on the RSSI technique and a trilateration algorithm, whereas Li et al. (2019) proposed a WLAN-based system that utilized time-of-arrival (TOA) and time-difference-of-arrival (TDOA) methods. Daely and Kim (2019), by contrast, proposed a localization algorithm based on the so-called Dragonfly Algorithm (DA) and particle swarm optimization (PSO). The algorithm proposed by the authors is dedicated to WSNs and optimized with respect to accuracy and computational time.

Tarkowski et al. (2016) presented a localization module also suited for WSNs that was equipped with an Ultra High Frequency (UHF) RFID subsystem with light-emitting diodes used in vision-based localization.

Another group of localization systems are those established on UWB technology. Schroeer (2018) presented a UWB system wherein localization was performed with the use of the TDOA method. Each module was equipped with independent transmitters to desensitize it from the multipath phenomenon, characteristic of industrial environments. Martinelli et al. (2019) presented the results of a UWB-based localization system applied in the galvanic industry, used for the precise localization of frames utilized in tubs for noble metal galvanization.

Karaagac et al. (2017) compared two localization systems in industrial conditions: one based on UWB technology and the other based on Bluetooth low energy. Both systems performed similarly in regards to accuracy, as long as the line of sight (LOS) was maintained. Their usability, however, drastically degraded in non-line-of-sight (NLOS) conditions or in the presence of large metal objects, both situations rather typical of industrial environments.

Wye et al. (2019) presented a localization system based on active RFID tagging, in which tags were battery-powered and the localization was carried out by means of measuring the RSSI. The authors divided the system operational area into zones with the number of RFID readers in each dependent on the activity of assets to be tracked.

Abdelgawad (2014) demonstrated a localization system for robotics based on passive RFID technology and the TDOA method. Alas, effective use of the latter technique requires three readers to be located in different places, which was a factor that limited the system's applicability. A passive RFID system was also described by James et al., (2012) for localization purposes in underground mines. They attached multiple RFID readers to a tracked object that disclosed the authors' positions as they moved along the mine walls with tags attached to them.

1.2 | An Overview of the New Hybrid Radio-Optical Indoor Localization TrackMe System

The proposed system was intended to fulfill several requirements and constraints of an automotive industry plant that can be summarized in the following:

- no additional cabling due to a vast area occupied by the plant;
- minimum electromagnetic radiation from both the tracking system static infrastructure and mobile devices; the only excess radiation would be short-range and low-power at 868 MHz from the external RFID antenna toward the ground for detecting RFID tags as shown in Figure 3;
- a high degree of energetic autonomy (the main system component—TrackMe—would be powered from a powerbank);
- a high network transparency (i.e., desirably not leading to any new networking, at best utilizing the existing connectivity); this requirement has been fulfilled by utilizing the plant's own WiFi network;
- a new infrastructure associated with the tracking system kept at minimum;
- the use of well-known and approved electronic solutions (i.e., Wifi, RFID, optical detection, NodeMCU microcontrollers, etc.); the innovation of the proposed solution is therefore defined not in a new algorithm or a hardware solution, but in the combination of best features in the already existing technologies, detection algorithms, data storage, and processing;
- minimized use of energy resources using passive RFID tags on the infrastructure side and implementing energy-saving procedures (see Section 3 for details);
- easily scalable tracking resolution (the current system version kept at about 0.5 m);
- a high robustness to accidental gaps in RFID infrastructure (e.g., due to damage to RFID tags done by vehicle wheels) in which case the tracking procedure would continue independently (though at the cost of lower accuracy) until the next RFID line resets its current position to absolute coordinates again (see Section 2 for details of the tracking procedure);
- fully random, asynchronic access (i.e., no central timing or scheduling is required; a device registers itself in a system upon activation, and from this moment on, its time stamps are recorded centrally);
- a high degree of reliability using two databases as described in Section 4;
- operation without the introduction of electromagnetic interference to the plant environment, achieved on one hand with the use of an existing WiFi network, and on the other hand using an extremely short-range (up to ~1 meter) solution for RFID detection in a frequency band of 868 MHz that is unused anywhere in the plant; and
- easy scalability in terms of adding tags for covering new paths if needed; the number of tags that the system can handle is not limited.

Carrying out comparative accuracy measurements with other systems (also based on other techniques) was not possible due to the lack of agreement of the founder to install other systems in the production hall, which is in continuous operation. However, literature research regarding the accuracy of various location techniques was carried out, as well as a discussion of their advantages and disadvantages.

Based on Obeidat et al. (2021), Zafari et al. (2019), Brena et al. (2017), Stojanović et al. (2014), and Oguntala et al. (2018), it can be concluded that the highest accuracy (about several dozen cm) is achieved using systems based on UWB and ultrasound techniques. Unfortunately, these are expensive systems with a limited operating range, which disqualifies them from the founder's point of view and application environment.

Cheaper solutions (based on WiFi, Bluetooth, or ZigBee) show accuracy at the level of single meters, which, however, is much lower than the accuracy of the proposed solution, which depends on the size of the vehicle's wheel (as presented later in the article). Additionally, due to the high variability of the propagation environment in the production hall, solutions based on signal power were impossible to use. The use of the RFID technique alone allows only localization, while the proposed system (through the use of an optical segment) would also enable continuous vehicle tracking and monitoring.

As there exists no single best-for-all candidate in the plethora of available and documented solutions, the authors have resolved to propose a novel hybrid radio-optical system. Since on the radio part, two frequency bands are involved, some engineering walk-arounds had to be implemented for signal-blocking avoidance between the two radio modules on each tracking device. Once operational, the system's energetic consumption was next reduced to a necessary minimum, allowing the system to retain its full detectability potential (i.e., ability to detect all RFID markers/tags).

The system's schematic operation is provided in Figure 1 with basic steps (1–5) represented by square labels. A basic component of the system is the *TrackMe* device mounted on each tracked asset (a forklift, an AGV, etc.; see Figure 3 for details). The system is powered by a power bank and activated upon first detection of an RFID line (each with a unique identifier) by scanning the floor with a short-range beam at the 868-MHz band (labeled *1*).

This detection is reported to the central system during the earliest of its regular reports (occurring at 1-second intervals) using the plant's WiFi (labeled *2*); and

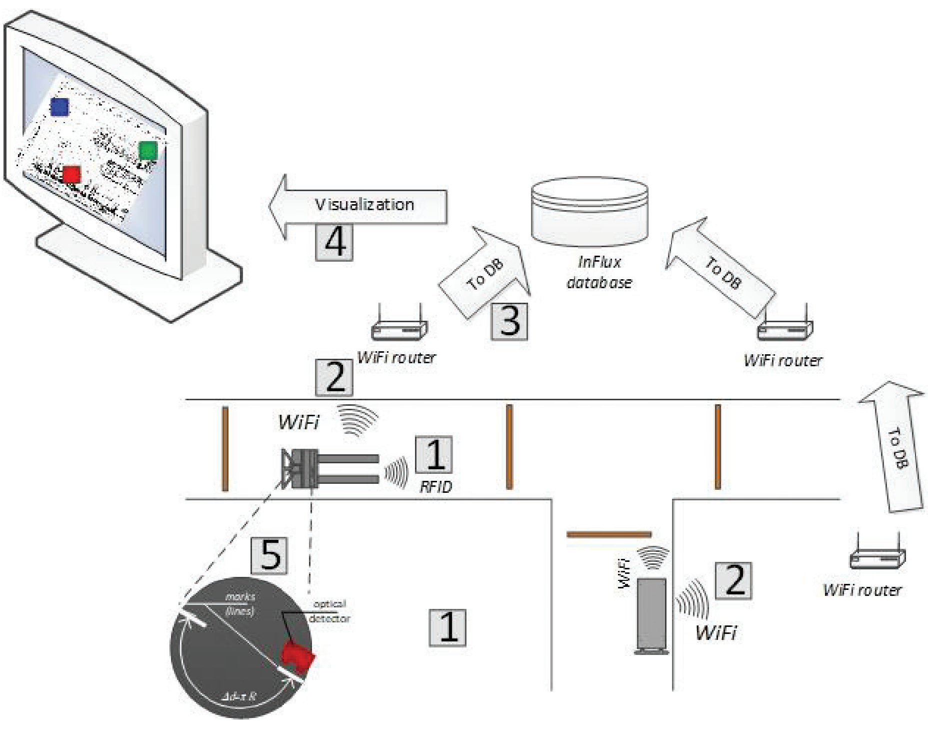

FIGURE 1 The tracking system general overview

from there, sent to the InFlux database (*DB* in Figure 1, labeled *3*) for storage and visualization on the plant's preloaded, high-resolution map (labeled *4*). Since RFID tags were located every 20 meters, the high-precision tracking was made possible by means of applying an optical system for detecting the number of wheels rotations (labeled *5*).

Since there is a limited number of vehicle types in a plant, it is possible to associate the wheel radius with a particular vehicle in the system for correct conversion of the number of reported rotations to the distance covered by the vehicle. Thus, a vehicle's position is reset to absolute fixed coordinates upon detecting an RFID line, whereas in-between these detections, fine tracking is enabled by informing (during the aforementioned reports taking place every second) the number of wheel rotations, which are converted to sub-meter sections. The system therefore allows for a stored history of all asset positions, and thus—after several days of operation—can create a data set for the possible optimization of vehicle routes for time-saving or collision-avoidance purposes.

1.3 | Article Structure

Section 1 introduces readers to some of the most common solutions for indoor localization, with distinction between environments in which they fit best. Section 2 lays out the proposed system's basic operational principles, technologies, and algorithms. This includes a discussion of threats and weaknesses associated with each involved technology (particularly significant if all fitted in the same enclosure for the ease of installation) along with a proposal of remedies.

Section 3 provides a detailed consideration of energy consumption reduction methods and the bearing they have on the tracking device's lifetime. The localization data transmission chain composed of the acquisition, transmission over the plant network, and finally the data placement in a database, is found in Section 4, while Section 5 is devoted to software issues. Section 6 enumerates practical recommendations, mainly regarding two issues—the tracking system energetic efficiency and the electromagnetic compatibility of the two radio modules (operating in different frequency bands) co-located in a single device, forced to operate in a scenario in which a simple time-division multiplexing is impossible due to the need for the continuous operation of one of them.

2 | THE TRACKME LOCALIZATION SYSTEM—OPERATIONAL PRINCIPLES AND TECHNOLOGIES

In a general scope, the proposed solution consists of exploiting two subsystems that are based on radio and optical technology for providing localization services. The roles they play in the combined system are complementary in that the radio technology provides absolute accuracy by serving as localization anchors of known positions (although scarcely spaced from each other), whereas the optical technology serves to provide sub-meter fine resolution to localization by enabling the counting of wheel rotations between consecutive RFID anchors as the vehicle moves between them.

As shown in Figure 2, RFID anchors (composed of a few RFID tags aligned perpendicular to the lane axis; photographed in Figure 14) are located at fixed and known positions along all lanes while locations between them are determined by counting the number of half-rotations of the vehicle wheel using an optical system.

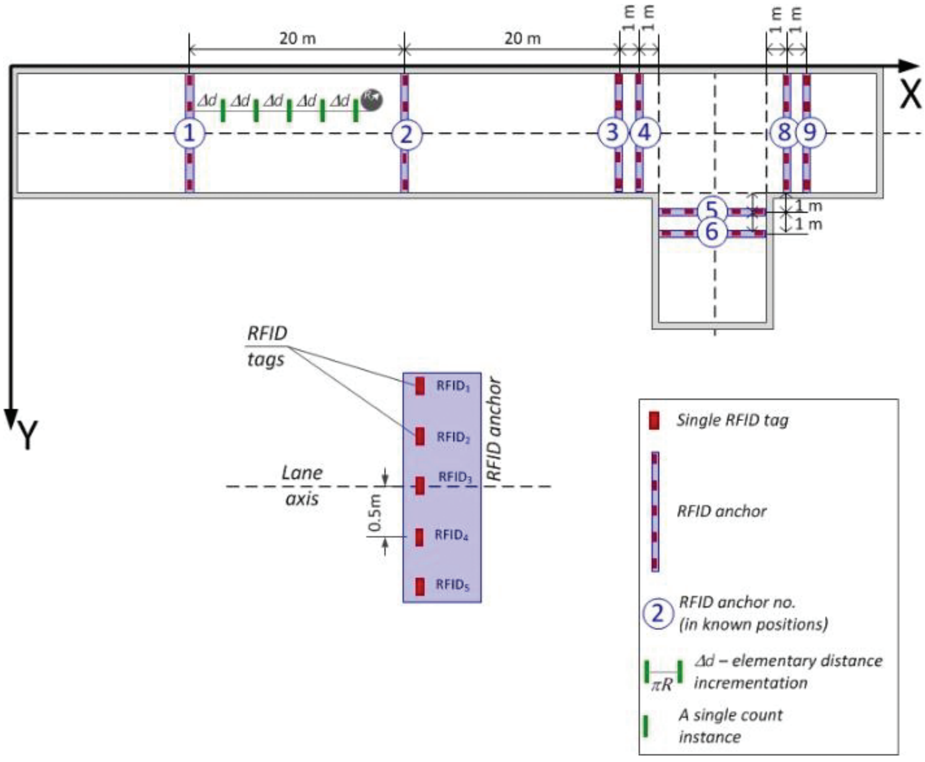

FIGURE 2 A concept of the hybrid radio-optical localization system deployment, operational, and basic components

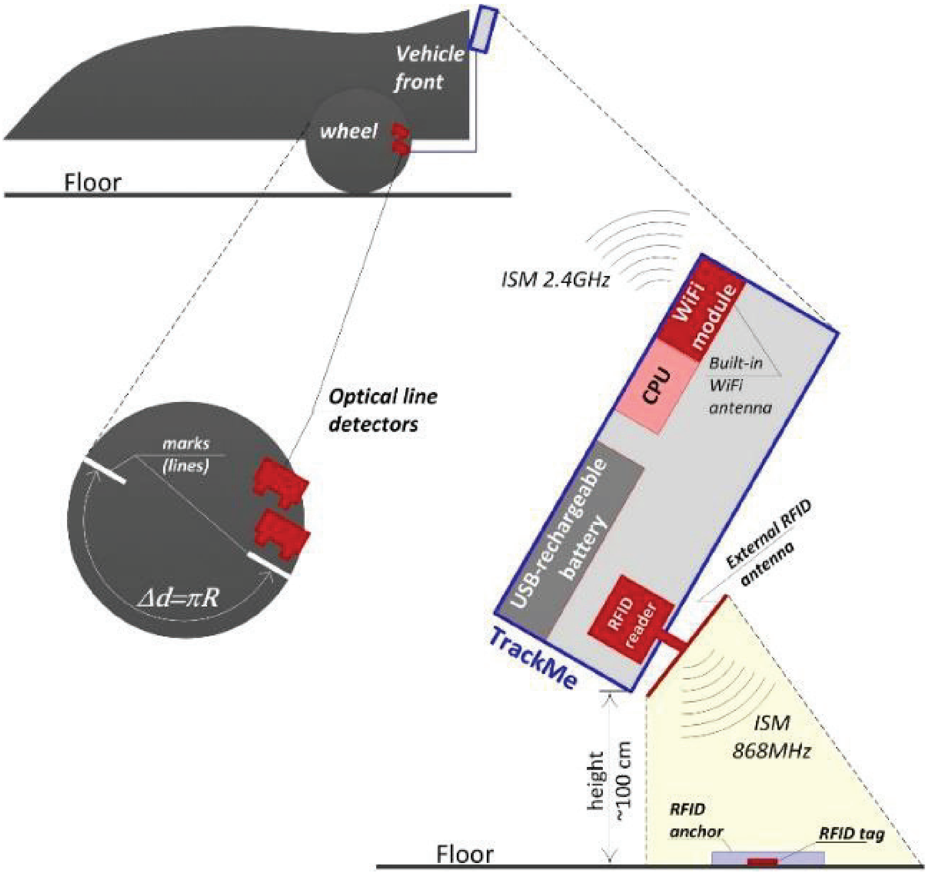

FIGURE 3 The TrackMe module composition and placement

In this project, the distance between the anchors was set to 20 m, but the distance is arbitrary as far as their precise positions are known.

The resultant localization resolution Δd therefore is a function of the wheel radius *R* and equals $\Delta d = \pi R$, since there are two marks on the wheel (on the chassis side) along its diameter as shown in Figure 3. The basic tracking algorithm expressed in a general form is given by Equation (1). The algorithm can, of course, be further extended, for example in predictive tracking in case the RFID reader has failed to read an anchor tag.

$$\text{Position} = \text{RFIDanchor}_{\text{last}} \pm \text{count} \cdot \Delta d_{=\pi R} \tag{1}$$

In the formula, $RFIDanchor_{last}$ is the well-known position of the last passed RFID anchor (numbered with indices 1–5 in Figure 2), *count* stands for the number of wheel half-rotations, and *Δd* is the elementary distance increment (and, at the same time, the system ultimate tracking resolution) defined as half of the wheel perimeter (=πR). As can also be seen, the ± sign in front of the *count* term denotes that the device is sensitive to whether the vehicle is moving forward or backward. This ability is provided by mounting two optical detectors on the wheel (as indicated in Figure 3), one beside the other, that allow it to distinguish—apart from the motion itself—its direction. Hence, an asset is successfully tracked irrespective of its path (which can be arbitrary, with no fixed routes) or its direction (i.e., forward or backward).

In summation, the radio subsystem provides an accurate but imprecise location limited to the distance between RFID anchors, whereas the optical subsystem refines its results by providing high-resolution estimates, although prone to errors (described in Section 2.1). These errors, however, are reset to zero upon passage of the nearest RFID anchor that has an absolute defined position. Both subsystems along with the WLAN module and the CPU (central personal unit) are contained in each tracking device called *TrackMe* (see Section 2.2).

Although RFID tags are flexible, they are also extremely susceptible to friction from wheels or other forms of mechanical damage likely to occur with vehicles in motion. In order to ensure proper protection of these vital system components, some installation precautions are highly recommended as shown in Figure 4. The adhesive back side of an RFID tag is placed on the clean floor surface. Its antenna thickness is usually on the order of less than 0.1 mm and therefore can be considered planar.

FIGURE 4 A procedure for placing an RFID tag on the floor ensuring protection from mechanical damage

Since the most vulnerable non-planar part of the RFID tag is its microchip, it should be covered from above with a protective attrition-proof adhesive foil. Moreover, one should avoid the tag's placement near lane crossings, where wheels often make turns and, thus, can cause severe damage to tags, even if they are protected by foil, due to shearing forces exerted on this protective layer by the turning wheels. Therefore, the last RFID anchor line should be located at least 2 meters (as indicated in Figure 2) from the crossing, where the vehicle can still be assumed to run straight ahead.

2.1 | The Radio Subsystem in the TrackMe Device

The radio subsystem consists basically of two components using separate frequency bands. The first component consists of RFID tags placed on the floor and readers located on vehicles, as described at length later, and the other is the WiFi operating at a 2.4-GHz band sending regular reports on the detected anchor tags and the number of counts.

The RFID component involves two parts for identification (and eventually localization), namely a set of passive RFID tags placed on the static infrastructure (i.e., the floor here), and RFID readers, operating in the industrial-medical-scientific (ISM) 868-MHz band. By *passive*, we mean that the RFID tags need no energy source of their own and rather rely on the energy absorbed from the RFID reader radiation and reflected or held back, according to a binary sequence (identifier) stored in the tag, by means of respective switching on/off the impedance-matching circuit built into each tag's microchip.

The RFID tags are deployed in lines perpendicular to the lane axis as shown in Figure 2 forming *RFID anchors*. The first tag is placed on the axis center, while the other tags are spaced 0.5-m away from each other toward the side edges of the lane. An *RFID anchor* in the system usually consists of three to 10 individual RFID tags, depending on lane width. As the tracked vehicle crosses an RFID anchor, some of its constitutive tags are read (usually one to three, depending mainly on how the reader module radiates its power; in the current system implementation equal to 20 dBm).

After their placement on the lanes of the floor, all tags would be read prior to the system initialization, and associated in a separate software table with their respective RFID anchors and known positions. During tracking, the read tag IDs are sent wirelessly by WLAN every 1 second during normal vehicle operation (or less frequently when idle to save energy; see Section 3 for details) to the main database wherein, based on the aforementioned association with RFID anchors, they are translated into particular positions.

Upon crossing an RFID anchor, the *count* parameter provides successive increments and Δd is reset to zero, which allows any deviations (errors) accumulated during the tracking to cancel out. These deviations might be caused by the vehicle traversing a path different than a straight one, such as a curved or sinusoidal path, along the section between successive RFID anchors as shown in Figure 5.

2.2 | The Optical Subsystem in the TrackMe Device

The optical subsystem consists of an optical line tracking sensor attached to the vehicle chassis in the direct vicinity (i.e., at a distance of <5 cm) of one of the wheels that have reflective marks attached alongside their internal diameter (i.e., spaced at πR from each other) as shown in Figure 3.

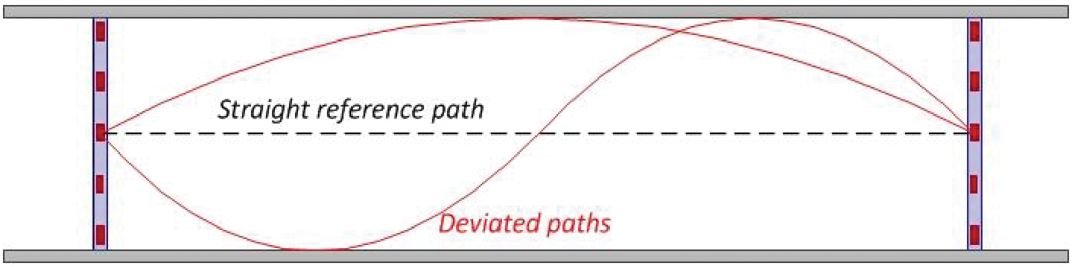

FIGURE 5 Possible deviations deriving from curved paths

During rotation, each time the sensor detects one of the two marks, an impulse is sent to the CPU that increments the current count value by one. Independently of this optical detection process, information containing the last-crossed RFID anchor and the current count value is sent every 1 second by the WLAN module (operating in the ISM 2.4-GHz band at the maximum allowable radiated power of 20 dBm or 100 mW) to the gateway, and from there to the main database.

Taking, for example, a wheel diameter of 200 mm in the tracked vehicles, the resulting measurement resolution (πR) would equal ~0.31 m.

2.3 | The Hardware Components

As said before, the designed localization system works based on the RFID technique and the wheel rotations count, which is used to determine the traveled distance and direction of the vehicle movement. A schematic representation of the TrackMe locating device is shown in Figure 6 (and photographed in Figure 13b).

A single TrackMe device to be mounted on the vehicle is based on the following fundamental hardware components:

- an RFID reader (numbered *3* in Figure 6): SparkFun Simultaneous RFID Reader–M6E Nano with external antenna applied (to be discussed later in this section);

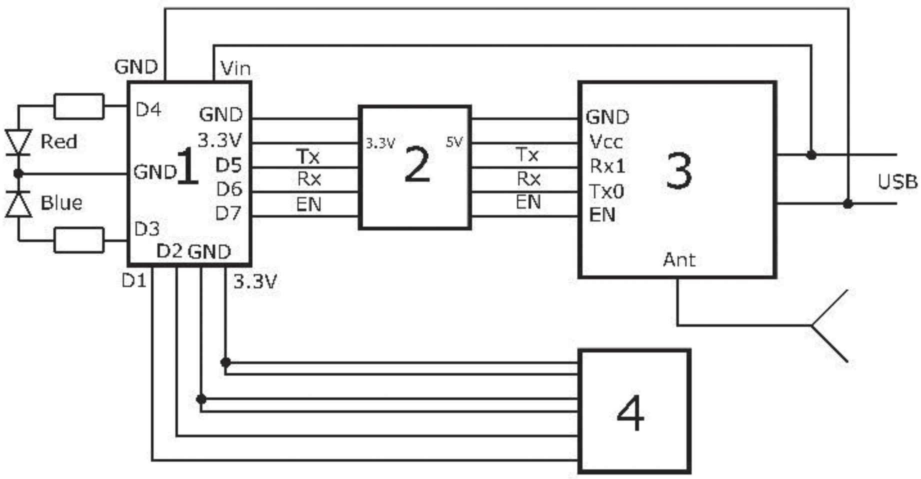

FIGURE 6 A schematic view of the TrackMe device

- an optical detector (numbered *4* in Figure 6; photographed in Figure 13a): Robodyn 72B2-746CE type, located at a distance of less than 5 cm from the wheel, assuming optimal marking for reading counts according to the procedure specified in Section 2.2—*Optimal* in this case means that the marks are made of a highly-reflective paint or tape (at best, metallic);
- an ESP 8266 NodeMCU v3 module (numbered *1* in Figure 6), marked also as *CPU* in Figure 3, which serves as the control unit for the entire TrackMe device; the ESP module is equipped with a WLAN network card used to communicate with the plant network, which allows messages to be sent to the main database. The ESP module is connected to the RFID reader through a logic level converter (numbered *2* in Figure 6). A red *light-emitting diode* (LED) indicates that a tag has been read by the RFID reader, whereas a blinking blue diode indicates a strong connection to the plant WiFi network. It is also recommended that the WiFi chip be embedded in a metal casing (as in the device used in the project) in order to avoid radio interference from inducing in its circuitry; and
- an external 868-MHz Molex flexible micro-coaxial cable antenna (photographed in Figure 13b) with 2.3-dBi gain; it should be noted here that despite the metal shielding of the ESP 8266 CPU, a λ/2 (~18 cm for the 868-MHz carrier) separation between these two elements should be preserved in order to head off signal blocking resulting in either missed tags on the RFID reader side or failed vehicle position reporting to the network on the WiFi side.

2.4 | RFID Reader Performance

The whole TrackMe device needs to be attached to each tracked vehicle side less than 100 cm from the ground to facilitate the proper reading of RFID tags by its onboard RFID reader. Despite radio transmission being an effective way of sending data wirelessly, RFID technology operates on the principle of backscattered energy. This form of communication is used, for instance, in radars in which the emitted *radio-frequency* (RF) energy is reflected on an object.

However, since there is no power amplification on the reflecting object side (tags here), the resulting power decay occurs at the fourth power of the distance between the RFID reader and the tag, according to Equation (2) that shows the amount of power P_{read} received at the RFID reader input port after the RF energy backscatter from the tag.

The formula reveals a dependence between the RFID reader *equivalent isotropic radiated power* (EIRP), its antenna gain G_{read} (2.3 dBi or 1.7 times in the linear scale, as specified by JADAK [2018]), the RFID tag antenna gain (which can be assumed equal to unity), the operating frequency f (868 MHz), and the distance d between the TrackMe device and the floor:

$$P_{read}[dBm] = 10\log\left[\left(\frac{75}{\pi f_{[MHz]} \cdot d_{[m]}}\right)^4 EIRP_{[mW]} G_{read} G_{tag}\right] \tag{2}$$

The tag is successfully detected (in free space) when the power appearing at the RFID reader input (reflected from the tag) exceeds its sensitivity. The sensitivity, P_{min}, in turn, is strongly affected by the amount of interference caused by

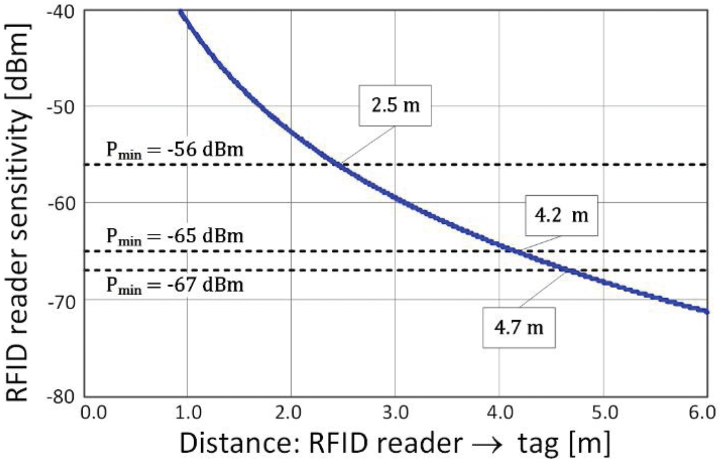

FIGURE 7 The RFID reader sensitivity vs. distance

the reader's own transmit signal. Therefore, this interference could be reduced by turning down the transmit power level by n dB that would add n dB of gain to the sensitivity.

In the project, 7 dB of gain in P_{min} was achieved with respect to the reference P_{min} = –60 dBm available in Europe at the slowest data rate (offering the highest sensitivity, according to the device datasheet; JADAK, 2018). It was possible by setting the reader EIRP to 20 dBm instead of the maximum available 27 dBm (hence improving P_{min} down to –67 dBm).

Faster reading capabilities, however, may turn out to be necessary if tracked vehicles pass over tags at higher speeds. In the RFID reader implemented in TrackMe, the two other sensitivities achieved at higher reading data rates were –58 dBm and –49 dBm for the medium and the high rates, respectively (all of which should then be augmented by 7 dB due to EIRP being lower than the maximum as shown in Figure 7).

Figure 7 is comprised of Equation (2) plotted against the three aforementioned sensitivities, allowing one to perceive distances between the reader and tag at which each of the three P_{min} levels has been achieved. The formula works well in free, unobstructed space, or with tags attached to dielectric objects. It should be noted, however, that similarly to conclusions drawn by Karaagac et al. (2017; see Section 1) regarding the placement of RFID tags on highly-reflective floor surfaces, also here the authors noticed a considerable drop in the detectability range (reduced to less than 1.5 m at the highest sensitivity).

This drop in detectability is one of the reasons that the recommendation regarding the distance between the RFID reader antenna and the concrete floor in Figure 3 (that it should be c.a. 1 meter) was put forth. This setting ensures proper reading of tags placed on the concrete floor and that the 868-MHz antenna beamwidth is wide enough to cover at least one tag at a time.

3 | ENERGETIC CONSIDERATIONS—POWER SAVINGS

The entire TrackMe module is powered by a single power supply in the form of a power bank of 20,000-mAh capacity. More capacious power banks could also be used but they must be applied with caution—commercially available devices, especially budget models, with the greatest capacities (on the order of 70–80 thousand mAh), by and large, are not able to hold these capacity figures nor maintain constant 5-V voltage on their USB outputs (floating down to 4.5 V), which may severely disturb the entire device operation.

Regarding the energetic issues of the system operation, the following recommendations should be upheld in order to provide energy-saving features:

- The RFID reader operates at a continuous reading mode with no exceptions, emitting radiation at a level of 20 dBm in the ISM 868-MHz band. It is a trade-off between the detectability of RFID tags (yielding at the most, a single missed tag during an entire vehicle circle) and power consumption. RFID readers usually allow for a wide span of EIRP values to be set. In the RFID reader used in this project (see Section 2.3), this range was from 0 dBm to 27 dBm (i.e., from 1 mW to 0.5 W).
- The CPU and RFID reader, identified as the most power-consuming elements of TrackMe, should operate at two modes: enabled/active (over the period T_E) and disabled (over the period T_D). Once the optical line detector has failed to detect a mark over a period of 30 seconds, both the CPU and the RFID reader are automatically disabled and switched to the low-current I_D consumption mode (sleep mode). This case applies to situations such as when a vehicle is halted for the loading or unloading of parts or is unused for any other reason and does not need to be tracked. Once a wheel rotation has been optically detected, the components are woken up back to the enabled (active, high-power) mode.
- The WiFi module transmits at regular 1-second intervals with no exceptions, emitting radiation at a level of 20 dBm in the ISM 2.4-GHz band. This EIRP should not be set to lower values, even for the sake of energy-saving purposes, since maintaining uninterrupted connectivity with the plant WiFi network is a crucial part of the TrackMe system operation. Instead, energy savings should be sought in putting the module to sleep on off-duty occasions. The proposed solution consists of sending only one keep-alive report per minute by the WiFi module once the TrackMe has entered into the low-power (sleep) mode, as described in the previous point regarding the CPU and RFID reader. After wake-up and its return to the active mode, the WiFi module also resumes its 1-second reporting intervals.

The estimated number of full workdays can be calculated from Equation (3), in which *days* represent the TrackMe device uninterrupted operation for 24 hours a day, with the active operation period defined by the duty cycle (DC).

$$T[days] = \frac{25 \cdot Cap}{6 \cdot [DC \cdot I_E + (100 - DC) \cdot I_D]} \tag{3}$$

where:

- *Cap*: the battery (power bank) capacity in [mAh] (=20,000 mAh in the proposed system)
- *DC*: the tracking module duty cycle in [%], defined as a ratio: $100\% \cdot T_E \cdot (T_E + T_D)^{-1}$
- I_E, I_D: the electric current consumption (in [mA]) in the active (enabled) and sleep (disabled) mode, respectively

- T_E, T_D: Time intervals when the TrackMe is in the active (enabled) and disabled mode, respectively.

According to the electric current consumption measured at the input to the reader module at its different operational modes, it was found that the current I_E demand in the enabled mode (active state) equaled 630 mA. In the *TrackMe disabled* mode, the current consumption is I_D dropped to 15 mA, as shown in Figure 8.

One of the fundamental criteria for evaluating the localization system is its length of battery-powered operation without recharging. As can be noticed in Equation (3) and pictured in Figure 9, a crucial role in the estimated battery lifetime is played by two parameters: the battery capacity *Cap* and the duty cycle *DC*. As for the capacity, the advantage for the battery longevity is obviously linear, however the *DC* influence is exponential with recommended values lying within the range of small values (say, up to 20%). This requirement appears to be fairly easy to meet in production plants where assembly parts are delivered by vehicles during a rather short time (corresponding to TrackMe up-time T_E) compared to the halt time (TrackMe down-time T_D) when the assembly parts are being loaded or unloaded and the vehicle stands still.

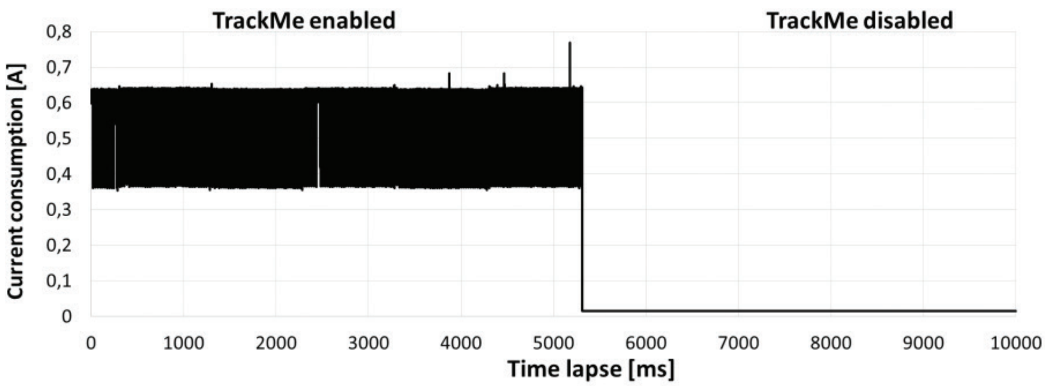

FIGURE 8 Measured electric current consumption by TrackMe in active (enabled) and sleep (disabled) modes

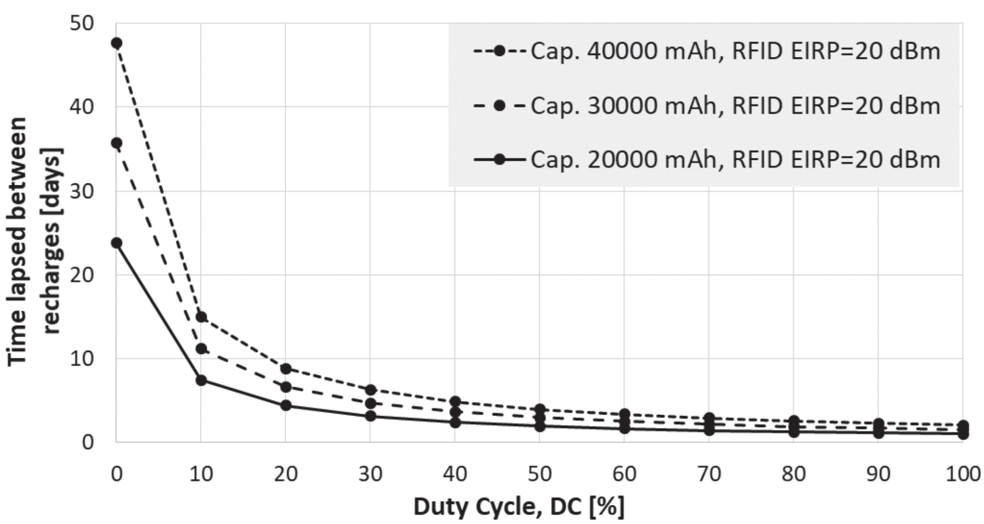

FIGURE 9 The battery lifetime as a function of duty cycle

4 | THE DATA GATHERING PROCESS

The location data sent from the vehicles is gathered in a gateway device on the same network as the location site. The gateway device stores data in a temporary database and sends it to the main database for further processing. The device is a single-board computer running a database and a data parser. Due to possible data congestion between vehicles and the gateway, data has to be gathered as quickly as possible with no or very little delay.

Taking into account that location devices are single-task microchips, all network requests block their normal operation. For this reason, it was necessary to resign from all kinds of Representational State Transfer Application Programming Interface requests involving Hypertext Transfer Protocol (HTTP) transactions and then use User Datagram Protocol (UDP) datagrams which were the least time consuming. Of course, UDP datagrams are sent with no acknowledgment, but bearing in mind that both the vehicle and the gateway are on the same network, the chance of data loss is low. Even if some datagrams are lost, it should not disturb proper location calculations.

In order to meet the conditions of low latency and high write throughput, a time series database was chosen instead of a classical relational approach. In this project case, InfluxDB was used as it had a UDP write mode and could write thousands of points per second. The database stores information about the last RFID anchor passed by each vehicle and the number of wheel rotations recorded after passing it. All positioning data is also marked with a precise nanosecond timestamp.

Simultaneously with vehicles sending data to InfluxDB, a data parser takes care of sending data to the main database where it is converted into the X-Y coordinate locations. The parser is written in Golang and uses Go co-routines for taking parts of data from InfluxDB and putting them into the main database. Each part of data is distributed between so-called *workers*, which in separate tasks take care of time-consuming HTTP requests, providing near real-time data passing between the gateway device and the main database. The whole data gathering process is shown in Figure 10.

The proposed solution uses two databases: the main database and a secondary database for fast and reliable operation. The small and fast secondary database, sharing the same network as the primary database (both installed on the location site), is used for temporarily storing vehicle data. An InfluxDB time series database was used here; a solution capable of writing thousands of points per second using UDP connections, each data point marked with a precise, nanosecond timestamp. The vehicle data is sent to the main database (used by the web application and

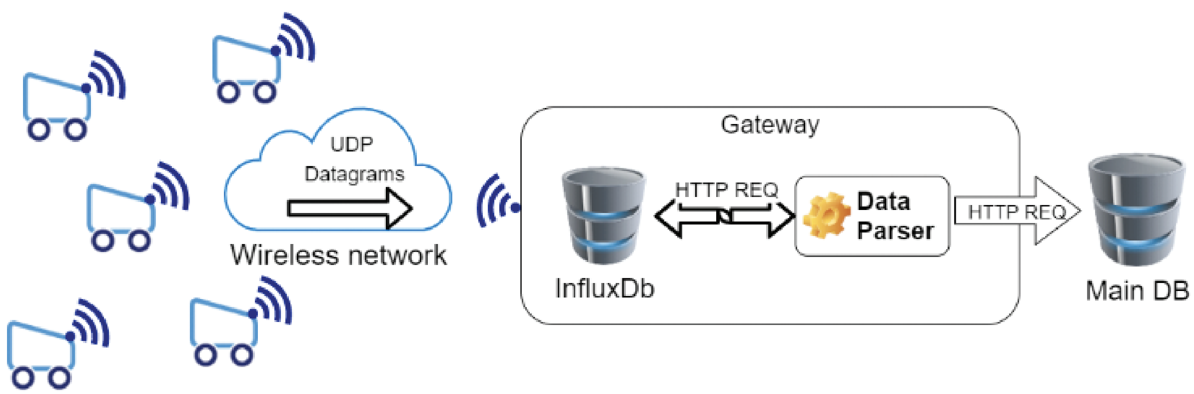

FIGURE 10 The localization data passing process

during post-processing) by a parser written in Golang and using Go co-routines. This solution is reliable and very fast.

5 | THE TRACKME SOFTWARE

The developed software provides for the simultaneous operation of a WiFi card, RFID tag reader, and wheel rotation detector. Its precise operational scheme, as presented in Figure 11, is now described in detail in a step-by-step manner.

After booting up, the auto-configuration of the device takes place, whereupon the device enters the operational mode. The auto-configuration mode includes:

- Step 1: configuration of the WiFi card and connection to the network;
- Step 2: configuration of the RFID tag reader (power, frequency, reading mode);
- Step 3: configuration of the inputs to support the optical line tracking sensor.

The full auto-configuration procedure must be completed with no errors in order to enter the operational mode. If the auto-configuration procedure fails, it is automatically restarted. After successful configuration, the device is ready to work and enters operational mode.

Two agents work in the operational mode: the RFID tag reader agent and the InfluxDB agent. The former is responsible for checking whether new incoming data is ready for reception from the RFID tag reader. The communication with the reader is performed via software serial. If any tag has been read by the RFID tag reader, its ID number is saved. The last-read ID is always stored in the memory. The latter agent sends the InfluxDB data every second.

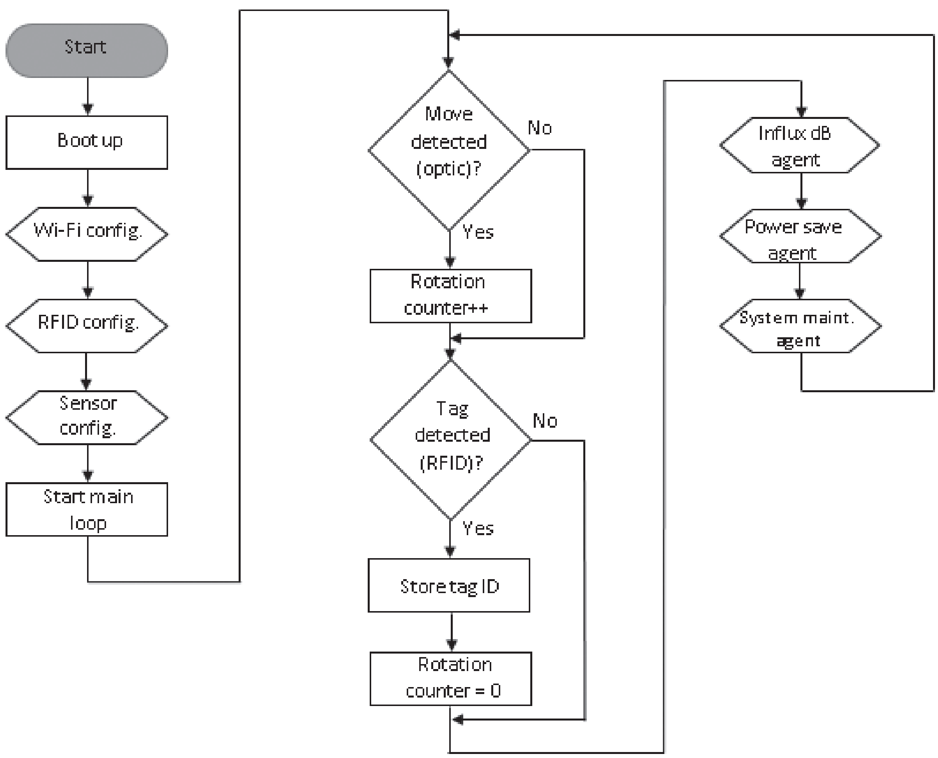

FIGURE 11 The localization data schematic flow

The data in question consists of the last-read ID number (the 32 least significant bits (LSBs) bits forming a so-called *electronic product code* or EPC) and the number of wheel half-rotations. This solution additionally serves as a form of device heartbeat. The system retrieves information about the operational (online) devices. Detecting markers on the wheel (counting of the number of wheel rotations) is a crucial issue for location accuracy.

Therefore, support for the optical sensor is implemented using interrupts. Thus, even when the device is busy (i.e., transmitting data via WLAN or reading an RFID tag), the wheel rotation will be detected without any issue. Moreover, the interrupt handling functions are placed in random access memory (RAM) to increase reliability and minimize delays. The direction of wheel rotation is indicated by the sign of the wheel counter (positive values correspond to the forward direction; negative to the reverse direction). Each time a new RFID anchor is detected, the wheel counter is reset to zero. Two watchdogs (software and hardware) are responsible for the stability of the code execution.

6 | CONCLUSIONS AND FURTHER RESEARCH

The TrackMe system presented in this paper is a proposal for a low-energy wireless localization system. The low-energy concept is derived from mechanisms used in plant infrastructure as well as on the tracked vehicle. On the infrastructure side, energy is reduced to zero since passive RFID technology (tags) was used for providing reference marks (referred to as *RFID anchors*). On the tracked vehicle side (i.e., the RFID reader embedded along with the WiFi module and a power bank), an efficient enabled/disabled algorithm was applied to minimize power consumption.

Prior to implementation in a real industrial environment, successful trials of the entire system, including the hardware and software components, were carried out in Wrocław University of Science and Technology facilities in a 110-meter-long corridor, along a path shown with arrowed lines in Figure 12.

The system operation was finally validated by its deployment in a real production hall of an automotive company plant in Poland, belonging to one of the global manufacturers. The system components, namely the RFID anchor and the optical detector (shown in Figure 13a and Figure 13b, respectively), were mounted on carts transporting production materials (Figure 13c). The RFID reader was mounted at a height of approximately 50 cm (to achieve the experimentally confirmed optimal scanning range of the RFID antenna depicted in Figure 13b), at an angle of 60 degrees with respect to the floor surface on which RFiD anchors (one of which

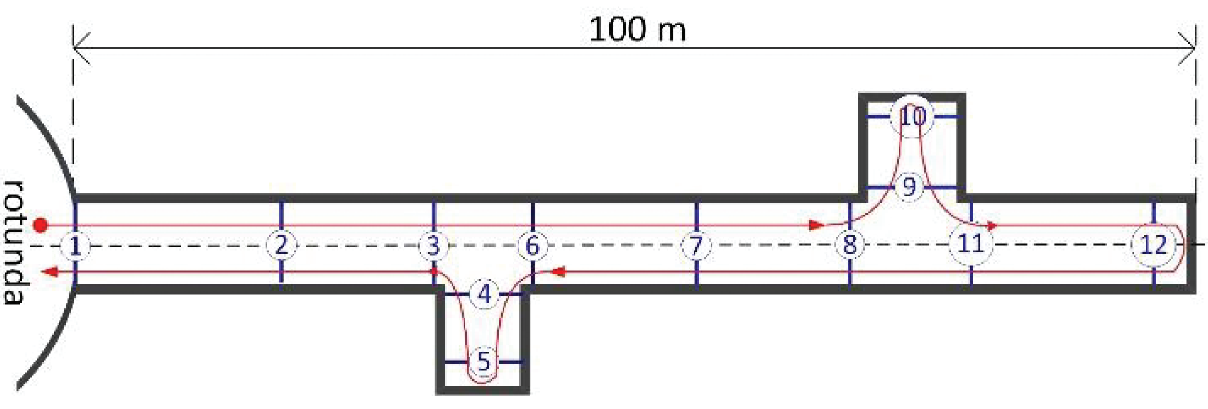

FIGURE 12 The experimental environment for drive tests

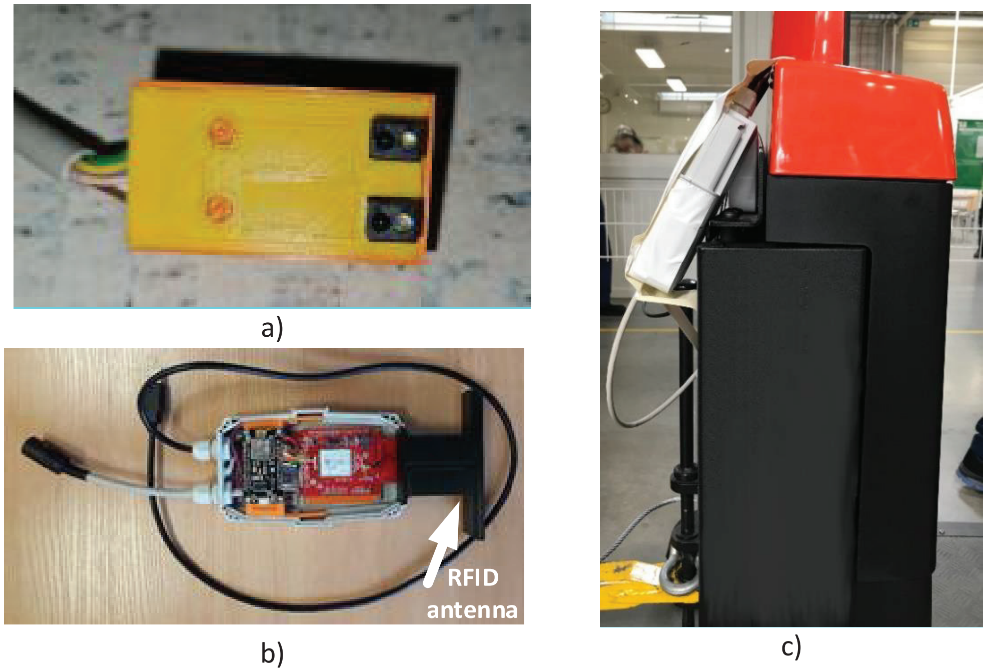

FIGURE 13 The tracking system components: a) an optical detector; b) the TrackMe module; and c) the TrackMe device mounted on a forklift

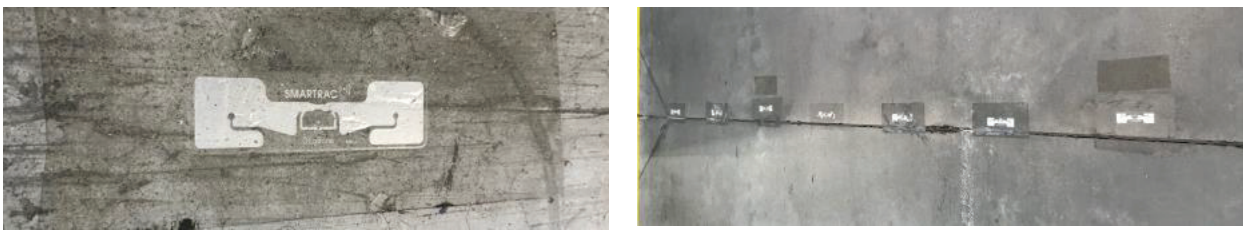

FIGURE 14 RFID anchors stuck on the concrete floor: a) a close-up on a single RFID tag; b) a full RFID anchor

is shown in Figure 14) were placed at regular distance intervals across the transportation routes of carts.

The TrackMe devices were mounted on various types of carts (i.e., manned delivery trucks, forklifts, AGVs) differing in wheel sizes, which the tracking accuracy directly depended on. Hence in the current deployment, the tracking resolution is kept at c.a. 60 cm for vehicles with the smallest wheels (40 cm in diameter) and at c.a. 87 cm for vehicles with the largest wheels (55 cm in diameter).

This resolution, however, can easily be halved by counting wheel quarter-rotations instead of the half-rotations used in the present system, which would lead to further reduction of localization resolution Δd (as defined in Section 2) from πR down to $\pi R/2$. The current Δd performance, in turn, was fitted to meet the customer's demand requiring only a sub-meter tracking precision.

Both drive test campaigns allowed the authors to arrive at a number of practical engineering recommendations scattered throughout the paper, regarding the following optimal settings:

- the TrackMe module placement on the tracked vehicle;
- proper electromagnetic shielding of the WiFi module;

- a safe operational distance between the WiFi and the UHF RFID antenna;
- deployment of RFID tags on the floor and their proper securing from the wear and tear due to movement of the vehicle wheels; and
- an energy-saving algorithm extending the power bank lifetime.

Despite succeeding in drive tests at WUST and at the automotive plant, the authors seek further enhancements to the system, mainly in the following areas:

- reducing the number of tags in the RFID anchors by testing TrackMe constructions with three 868-MHz antennas: one in the front (as is now the case) and two on both sides; this solution is meant to leave out only the central tag in the lane and two other tags located at the two lane edges where a probability of being run over by a vehicle wheel is very low;
- implementing additional sensors on board the TrackMe module for further enhancements, especially catering for two areas: providing a more reliable wake-up trigger than the currently used optical detector and adding an additional information source on the direction of motion; both areas could be accommodated by the use of an inertial sensor such as a gyroscope or an accelerometer; and
- decreasing the power consumption in the disabled state below the present 50 mA by manually deactivating unnecessary onboard electronic components, such as LEDs—the removal of which would yield ~5 mA of savings per each LED.

The project described herein has been supported by WUST K34W04D03 fund for basic research activities no. 8201003902

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How to cite this article: Staniec, K., Kowal, M., Kubal, S., & Piotrowski, P. (2022). TrackMe—A hybrid radio-optical system for assets localization in Industry 4.0 plants. *NAVIGATION, 69*(2). https://doi.org/10.33012/navi.524