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RESEARCH ARTICLE

Dynamic Wireless Power Transfer System for Indoor AGV With a Distance-Measurement-Based Position Detection Technique

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ABSTRACT Inductive dynamic wireless power transfer (WPT) for moving objects, such as automated guided vehicles (AGVs), has become of special interest. For efficient and leakage-flux-reduced WPT for an AGV, only one transmitting coil (or a small array of transmitting coils) should be energized simultaneously; therefore, the position of the receiving coil should be detected precisely. Conventional AGV position detection techniques are often based on position detection sensors (magnetic or optical) placed near or inside each transmitting coil. However, this approach is expensive, relatively unreliable and it has high level of complexity. Therefore, in this study, a less expensive, more reliable and less complex technique for position detection of low-speed and moderate-speed AGVs (speed <1.5 m/s) is proposed and verified experimentally using a scaled-down AGV prototype. The technique is based on the ultrasonic distance measurement of a moving AGV to energize the correct transmitting coil. As shown in the comparative measurements, the performance of the dynamic WPT system with the proposed detection technique for low-to-moderate-speed AGVs is similar to that of the dynamic WPT system with conventional position detection techniques. However, the cost and level of complexity of the position detection system are moderately lower and the proposed position detection system is immune to optical radiation and magnetic fields. To extend applications of the ultrasonic techniques to high-speed AGVs, another AGV position detection technique based on the combined application of the maximum transmitting coil current detection and ultrasound-based AGV motion direction detection was also proposed.

INDEX TERMS Wireless power transfer, sensors, position detection, automated guided vehicles, transmitting coils, distance measurement.

I. INTRODUCTION

With an ever-increasing level of automation in modern warehouses and manufacturing facilities, automated guided vehicles (AGVs) have become important components of almost all such facilities [1]. AGVs are often utilized for unmanned transportation of goods from one place to another within a warehouse or manufacturing facility. Traditionally, indoor AGVs are slow-moving electrical vehicles with speeds below 2 m/s [2], [3].

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An AGV has an electric motor, power converter, sensors, and some electronic devices to control the motor and, process data from the sensors. They all require electrical energy for normal operation. Energy can be obtained from a battery incorporated in an AGV. Despite of the fact that this solution for powering AGVs is straightforward, it also has some important disadvantages, because batteries need to be charged over time, they increase the volume and weight of the AGV, and they have a limited lifetime. Moreover, owing to poor battery management systems, lithium batteries can explode and cause fires [4]. Therefore, dynamic wireless power transfer (WPT) to AGVs and other types of electrical vehicles has been of significant interest over the last two decades because this approach offers the possibility of reducing the size of batteries or even eliminating them [5], [6], [7]. Because AGVs should be constantly in operation, dynamic WPT yields a significant increase in productivity within a warehouse [6].

Dynamic WPT can be performed using magnetic fields (inductive coupling) or electric fields (capacitive coupling). Resonant-inductive dynamic WPT is the most useful technique for short transmission distances owing to its wide range of power levels and relatively high efficiency. To transfer electric power wirelessly while the AGV is in motion, a long transmitting wire loop or a long array of multiple transmitting discrete inductive coils can be used [8], [9]. If the latter is used, then the electromagnetic interference and stand-by loss are significantly lower, and the dynamic WPT system efficiency is higher than that of a dynamic WPT system with a long transmitting wire loop [5], [10]. Owing to these advantages, dynamic resonant-inductive WPT systems with a long array of transmitting coils are much more often utilized for AGVs than dynamic WPT systems with a long-loop primary coupler.

For efficient and radiated-emission-reduced dynamic resonant-inductive WPT for electric vehicles, only the transmitting coils (or single transmitting coil) with the highest inductive coupling coefficient with the receiving coil should be activated. The activation of the correct transmitting coil (or some adjacent transmitting coils) can be achieved using different approaches, such as using a single inverter with auxiliary switches [8], [11], [12], [13], multiple inverters without switches [12], [13], [14], or single inverter without auxiliary switches [7], [15].

In the first approach, AGV position detection is performed using position sensors, such as optical sensors [6], magnetoresistive sensors [16], ultrasonic sensors [11], sensors based on one or more detection coils created within each transmitting coil [5], or radio-frequency identification device tags [17], [18]. The main disadvantage of this approach is that the overall cost of the WPT system is relatively high, because the position detection sensors are placed near or inside each transmitting coil (see Figure 1a). Although it was not shown in the literature, AGV position detection to activate the correct transmitting coil can be performed using data from the AGV positioning system. However, due to considerable latency times of modern radio-communication protocols, this approach may be feasible only for low-speed AGVs.

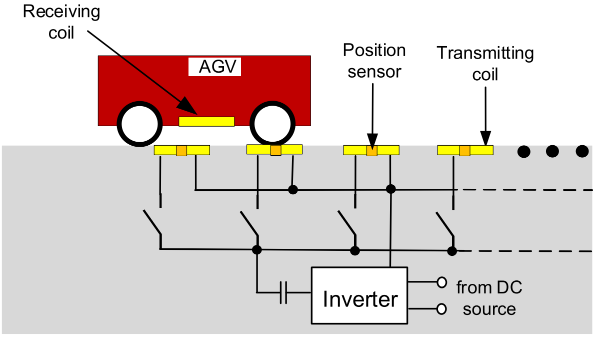
If the second activation approach is used, AGV position detection is performed by measuring one of the parameters characterizing the transmitting resonant circuit, such as the phase angle between the resonant circuit current and voltage [14] (see Figure 1b). Because one inverter (and at least one compensation capacitor) is necessary for each transmitting coil or some adjacent coils, the number of power components and cost of the dynamic resonant-inductive system are noticeably higher than those of the dynamic WPT system using the first activation approach. However, the efficiency of a dynamic WPT system using this approach is moderately higher than that of a dynamic WPT system using the first activation approach [12], [13].

In the third activation approach, a single inverter without auxiliary switches is used for a long array of transmitting coils [7], [15]. In this case AGV position detection sensors are not necessary. The advantage of this approach is the lower cost of the dynamic resonant-inductive WPT system compared to that of the dynamic WPT systems with the two aforementioned activation approaches. However, this approach has certain disadvantages. For example, as shown in [7], the overall efficiency of the dynamic WPT system is relatively low compared to the efficiency of dynamic WPT systems with the first two activation approaches. Moreover, the disadvantages of the dynamic resonant-inductive WPT system with automatic position detection and transmitting side activation with a compensation capacitor proposed in [15] are that, owing to the specific structure of the compensation capacitors, only small AGV deviations from the straight line are allowed. Additionally, because of the variable frequency of operation, it is difficult to meet the requirements of WPT standards because the allowable frequency range is rather limited.

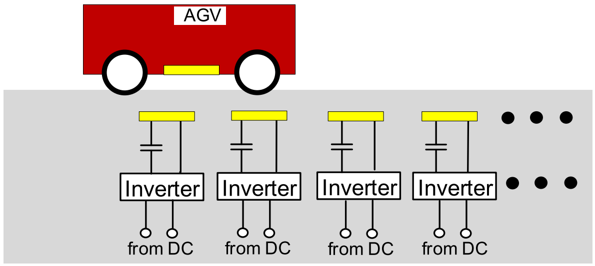
Dynamic resonant-inductive WPT systems with the first transmitting-side activation approach and sensor-based position detection are attractive because of rather high efficiency and moderate costs. However, because at least one position detection sensor is required for each transmitting coil, a large number of position detection sensors are necessary leading to increased complexity of AGV position detection, decreased reliability and increased cost of the WPT system. Additionally, if magnetic sensors are used as position detection sensors, they can operate incorrectly because of leakage magnetic fields emitted from adjacent transmitting coils. If optical sensors are used for position detection, ambient optical radiation (e.g. light from lamps) can interfere with them [8].

Let us assume that the AGV track is 100 m long and six transmitting coils per meter are necessary. Therefore at least 600 position detection sensors are necessary. This large number of sensors must be connected to the microcontrollers and voltage regulators. The high number of sensors and the large number and length of wires required to connect the sensors to the microcontrollers and voltage regulators increase the cost and complexity of the position detection system. Therefore, in this study, we propose a novel AGV position detection approach for energizing the correct transmitting coil (Figure 2). It is based on measuring the distance to a moving AGV using ultrasound. The main advantage of the proposed approach is that it is moderately cheaper and less complex for AGV position detection, because it has significantly lower number of inexpensive position detection sensors, considerably shorter length and number of connection wires, and because its microcontrollers have approximately 40 % fewer number of digital inputs/outputs. Moreover, unlike classical position detection systems based on either optical or magnetic position detection sensors, the proposed position detection system is immune to optical radiation and leakage magnetic fields. The proposed approach was experimentally verified using a scaled-down AGV prototype.

To extend applications of the ultrasonic techniques to high-speed AGVs, another AGV position detection technique based on the combined application of the maximum transmitting coil current detection and ultrasound-based AGV motion direction detection was also proposed.



(a)



(b)

FIGURE 1. **Dynamic resonant-inductive WPT systems with the conventional transmitting-side activation and AGV position detection approaches: (a) a single inverter with auxiliary switches and sensor-based AGV position detection; (b) multiple inverters without switches and AGV position detection by measuring one of the parameters of the transmitting resonant circuit.**

II. CONSIDERATIONS FOR THE CHOICE OF A TYPE OF A DISTANCE METER

Three main factors determine the choice of a distance meter for the position detection of a moving AGV to energize the correct transmitting coil. These factors are the distance measurement accuracy, reading update rate, and cost. Considering the typical dimensions of the transmitting coils and the typical speed of AGVs, we believe that the accuracy of the distance measurement should be <1 cm and the reading update rate should be at least 100 Hz. Therefore, to energize the correct transmitting coil without significant delays for AGVs moving at a speed of <1 m/s, we believe that at least 100 measurements per second with an accuracy of <1 cm are sufficient. A low distance reading update rate and poor accuracy may lead to incorrect operation of the dynamic WPT system, and consequently, may result in disruptions in the movement of the AGV and a considerable decrease in power transfer efficiency. Obviously, there is a trade-off between measurement speed, accuracy, and cost. The cost of a distance meter increases as the reading update rate increases and accuracy improves.

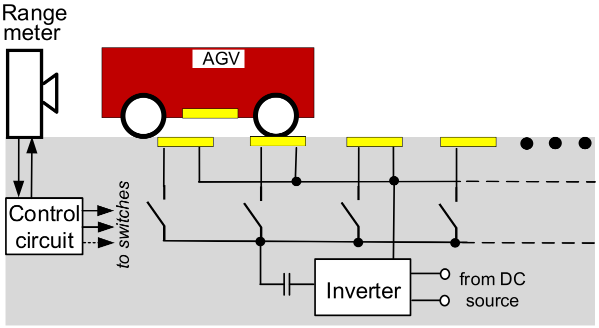


FIGURE 2. **A dynamic resonant-inductive WPT system with the proposed AGV position detection approach.**

There are three types of distance meters: laser, microwave, or ultrasonic distance meters. Laser and microwave distance meters can be used for short to long distances (up to 500 m or even higher). Ultrasound distance meters are suitable for relatively short distances (usually 6 – 10 m); however, they are less expensive than laser and microwave distance meters. By conducting market research, we found that relatively inexpensive (<150 EUR) laser distance meters are not suitable for typical dynamic WPT systems for AGVs because they either have a low reading update rate (<20 Hz) or relatively poor accuracy (a few cm – a few tens of cm). Laser distance meters with high accuracy (a few millimeters) and high reading update rate (>100 Hz) are very expensive (>2000 EUR) and thus unsuitable for dynamic WPT systems. High-accuracy and fast-update-rate microwave distance meters are also expensive.

By conducting market research, we found that one of the cheapest and most popular ultrasonic (US) distance-measuring devices, the HC SR-04, has an accuracy of 3 mm and a maximum measurement distance of 4 m. Some stores charge approximately 1.1 EUR per piece. In calculating the ultrasound round-trip time, we concluded that a reading update rate of 100 Hz can be achieved if the distance d between the ultrasonic sensor and AGV is <1.6 m. After making repeated measurements of different distances

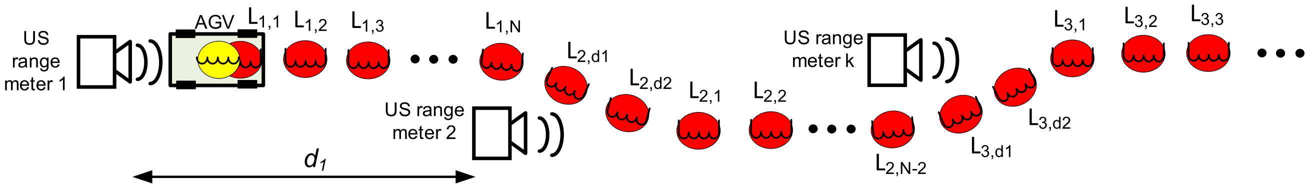


FIGURE 3. A simplified diagram showing location of the transmitting coils and the US short-range meters in the dynamic WPT system with the proposed position detection technique.

(up to $d = 1.5$ m) with HC SR-04, we concluded that the readings were relatively accurate and precise, because most of the readings stayed within d_{true}-0.7 … d_{true}+0.7 cm (where d_{true} is the true value of the distance measured using a measuring tape). In our measurements, the distance between the ultrasonic sensor and surface of the AGV track was 20 cm, and the size of the ultrasound-reflective part of the AGV was 30 × 30 cm. To reduce the measuring angle (and thus the size of the ultrasound-reflective part of the AGV) we used 1.5 cm-long plastic cylinders attached to cases of both piezo elements of the HC SR-04. Plastic cones with longer lengths should be used to obtain an even smaller measurement angle and increase the measurement range.

III. DESCRIPTION OF THE PROPOSED POSITION DETECTION TECHNIQUE

We chose the ultrasonic distance meter HC SR-04 for position detection of the AGV by placing the necessary distance meters along the AGV track, as shown in Figure 3. In the dynamic WPT system with the proposed position detection technique, adjacent ultrasonic distance meters are placed with d_1 distance between them and there are N transmitting coils within each d_1. $L_{1,1} = L_{1,2} = \ldots = L_{k,n}$. Because it is impossible to use a single ultrasonic range meter for a long track, the AGV path is not a straight line (Figure 3), and therefore, when the AGV is near US transducer k, it should move from one straight path to another. Coils $L_{k,d1}$ and $L_{k,d2}$ (k=2, 3, 4 …) are necessary to energize the AGV near US range meter k, when the AGV moves from one straight path to another. If the coils are not used, energy transmission to the AGV may be interrupted for a considerable amount of time and there is a high chance that the AGV will not move further. The transmitting coils $L_{k,d1}$ and $L_{k,d2}$ are connected in series and their total inductance is equal to $L_{k,n}$. When the AGV moves from the left to the right, if the measured distance $> d_1$, then $L_{k,N-2}$ ($k \geq 2$) becomes inactive, but $L_{k+1,d1}$ and $L_{k+1,d2}$ become active. When the distance measured by the next ultrasonic range meter is equal to a certain threshold value, $L_{k+1,d1}$ and $L_{k+1,d2}$ become inactive, but $L_{k+1,1}$ is activated.

The distance d_1 between the adjacent ultrasonic distance meters depends on the maximum speed v_{AGV} of the AGV and the maximum allowable change in the measured distance Δd_{max} during the maximum measuring time $t_{\max}$ (which is the reciprocal of the update rate f_{update}). Therefore, we can conclude that the readings update rate should be

$$f_{update} \geq v_{\text{AGV}} / \Delta d_{max}, \tag{1}$$

and the distance between the adjacent ultrasonic distance meters should be

$$d_1 \leq v_{sound} / (2 f_{update}), \tag{2}$$

where v_{sound} is the ultrasound velocity in air (343.2 m/s at 20°C [19]).

From (1) and (2) it follows that the lower the maximum speed of the AGV, the greater the distance between adjacent ultrasonic range meters, and therefore, the lower the cost of the position detection system.

Considering typical dimensions of transmitting coils of dynamic WPT systems, Δd_{max} should be ≤ 1 cm. Therefore, it follows from (1) that if, for example, the maximum speed of the AGV is 1 m/s, the reading update rate should be at least 100 Hz, but d_1 should be lower than 1.7 m.

If we assume that the maximum speed of the dynamic WPT system for the AGV is 1 m/s, the adjacent ultrasonic distance meters should have 1.5 m distance d_1 between them.

A simplified schematic diagram of the dynamic resonant-inductive WPT system with the proposed AGV position detection technique based on ultrasonic distance measurements to activate the correct transmitting coil is shown in Figure 4. It is assumed that the WPT system is connected to a 48-V DC grid and is based on an array of multiple transmitting coils $L_{k,n}$ with the coils' activating switches and their drivers as well as inverters and compensation capacitors. For the energy losses due to long wires connecting the transmitting coils with the inverters and the coils' activating switches to remain low, the inverters should be placed every 3 m along the AGV track (Figure 4). High-durability relays or bi-directional switches based on two metal-oxide-semiconductor field-effect transistors (MOSFETs) connected in an anti-series manner can be used as the activating switches of the transmitting coils.

The proposed AGV position detection system is based on K range meters and ceil(K/2) microcontrollers. Microcontrollers are used to control the activating switches of the transmitting coils and decide which transmitting coil should be activated according to the data obtained from the ultrasonic distance meters. Multiple microcontrollers should be used instead of a single microcontroller, because they usually have a limited number of digital inputs/outputs and because if the

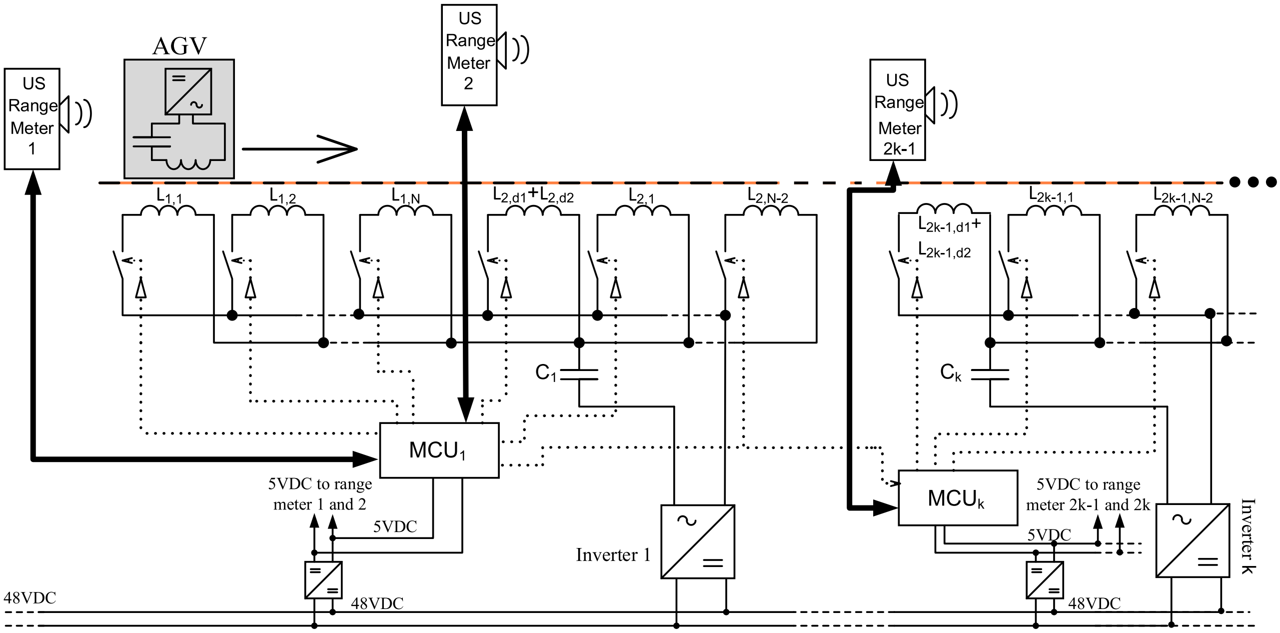


FIGURE 4. A simplified schematic diagram of the dynamic resonant-inductive WPT system with the proposed AGV position detection technique to activate the correct transmitting coil.

AGV track is long, then long wires connecting one microcontroller to the drivers activating the transmitting coils are necessary. To convert 48 V to a voltage (e.g. 5 V) necessary for the normal operation of microcontroller units (MCUs) and US range meters, multiple DC/DC voltage regulators are necessary (Figure 4).

The ultrasonic range meters can provide the microcontrollers MCU_k either measured distance d (between the ultrasonic range meter and AGV) data or measured ultrasound round-trip time Δt_{meas} (proportional to d) data. Based on the data received from the US range meters, the microcontrollers determine which transmitting coil must be activated. The output data of the ultrasonic range meters (HC SR-04) correspond to the ultrasound round-trip time. If the microcontrollers receive data regarding the measured distance between the US range meter k and the AGV, then the n-th transmitting coil $L_{k,n}$ is activated if

$$d_{\min} - d_3 + (2n-3)(d_{\text{coil}} + d_2)/2 \leq d < d_{\min} - d_3 + (2n-1)(d_{\text{coil}} + d_2)/2, \tag{3}$$

where $d_{\min}$ is the distance between the US range meter k and the transmitting coil $L_{k,1}$; d_{coil} is the transmitting coil ferrite pad dimension; d_2 is the distance between adjacent transmitting coils; d_3 is the distance between the front side of the AGV and the front side of the receiving coil ferrite pad (see Figure 5). It should be noted that $d_{\min}$-d_3-$(d_{\text{coil}} + d_2)/2$ should be higher than the minimum distance that can be measured by a range meter with high accuracy (e.g., for the HC SR-04 range meter it is 2 cm [20]). Let's consider an example: $d_{\min} = 15$ cm, $d_3 = 5$ cm, $d_{\text{coil}} = 10$ cm, $d_2 = 6$ cm, then from (3) it follows that, for example, the transmitting coil $L_{1,2}$ will be active if 18 cm $\leq d <$ 34 cm. Note that $d_{\min}$ between US range meter k (k≥2) and $L_{k,1}$(k≥2) is $d_2/2+2(d_{\text{coil}} + d_2)$, but $d_{\min}$ between US range meter 1 and $L_{1,1}$ is $d_3 + (d_{\text{coil}} + d_2)/2+2$. As previously mentioned, when the AGV moves from left to right, if the measured distance exceeds the maximum threshold value $d_{\max}$, the previous transmitting coil becomes inactive; however, $L_{k,d1}$ and $L_{k,d2}$ become active. When the distance measured by the US range meter k (k≥2) is equal to the minimum threshold value $d_2/2+2(d_{\text{coil}} + d_2)$, then $L_{k,d1}$ and $L_{k,d2}$ become inactive, but $L_{k,1}$ is activated.

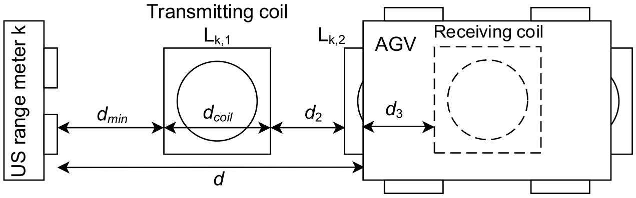
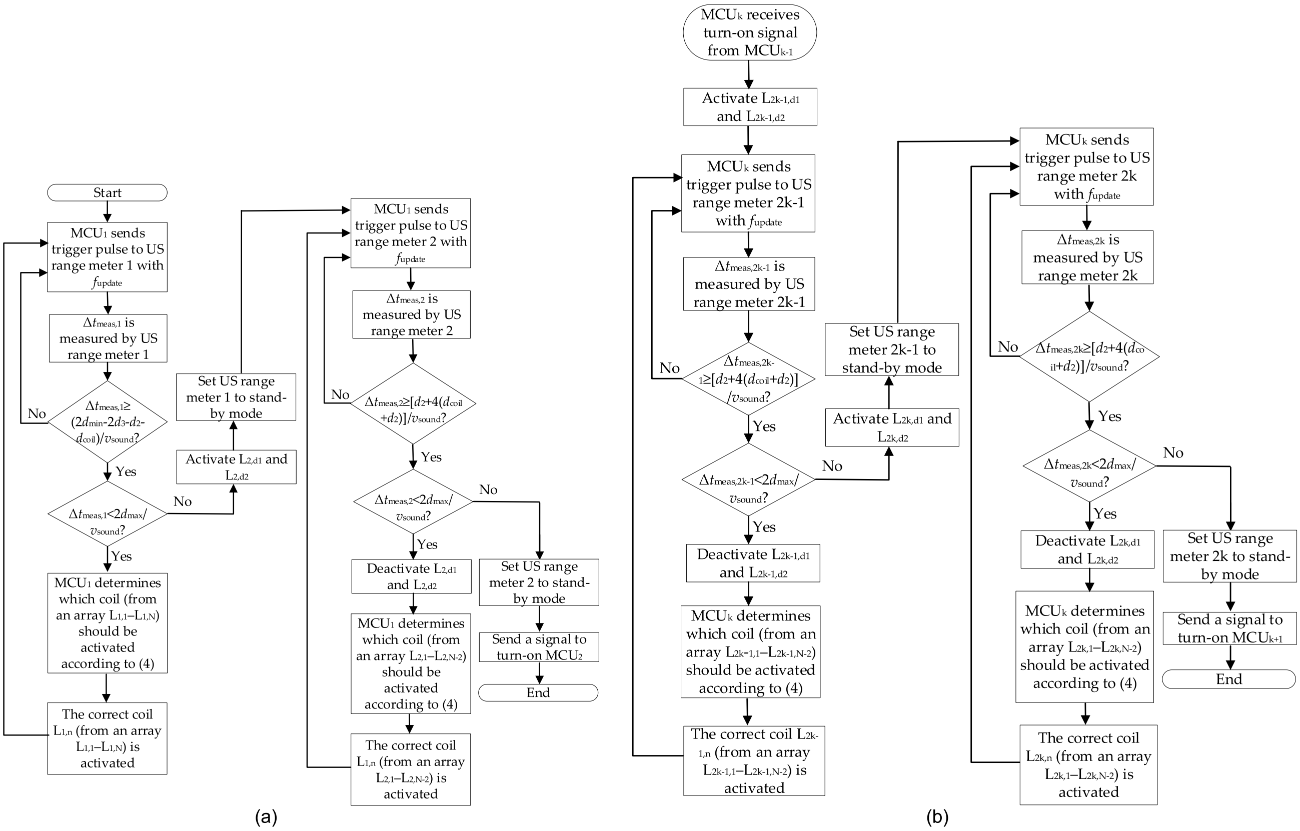


FIGURE 5. An image showing the location of the ultrasonic range meter and the transmitting coils to better understand definitions of the parameters in (3).

If the microcontrollers receive the measured ultrasound round-trip time, the n-th transmitting coil $L_{k,n}$ is activated if

$$2[d_{\min} - d_3 + (2n-3)(d_{\text{coil}} + d_2)/2]/v_{sound} \leq \Delta t_{meas,n} < 2[d_{\min} - d_3 + (2n-1)(d_{\text{coil}} + d_2)/2]/v_{sound}. \tag{4}$$

To explain the operating principle of the dynamic resonant-inductive WPT system with the proposed AGV position detection technique based on distance measurements,



(a) (b)

FIGURE 6. Flowcharts of the proposed AGV position detection and activation of the transmitting coils: (a) done by MCU_1 and US range meters 1 and 2; (b) done by MCU_k and US range meters 2k-1 and 2k (if $k \geq 2$). Note the flowcharts are useful only when the AGV moves in one direction, but it can be used (with some modifications) when the AGV moves in the opposite direction.

flowcharts of the AGV position detection and transmitting-coil activation are shown in Figures 6(a) and 6(b). The proposed AGV position detection system allows the AGV to move in both directions.

The dynamic WPT system with the proposed position detection technique has two obvious limitations:

1. It will not operate correctly if there is an object (e.g., a human) between the ultrasonic range meter and the AGV.
2. It will not operate correctly if two or more AGVs are between US range meters k and k+1 or if two or more AGVs are above transmitting coils that share the same compensation capacitor.

However, the dynamic WPT system with the proposed position detection technique can still be used for multiple AGVs moving along the same track if there is a sufficient distance between two AGVs, such that they are not located simultaneously above transmitting coils that share the same compensation capacitor. In other words, the minimum allowable distance between the AGVs moving along the same track should be greater than the length of an array of transmitting coils sharing the same compensation capacitor. For example, if an array of transmitting coils that share the same compensation capacitor is 3 m long, the minimum allowable distance between AGVs moving along the same track should be >3 m.

Because we focus our attention on the proposed AGV position detection technique, determining the optimum number of transmitting coils, the optimum spacing between them and their optimum geometrical parameters is beyond the scope of this study.

IV. EXPERIMENTS

A. DESCRIPTION OF THE EXPERIMENTAL SETUP

To verify the feasibility of the resonant-inductive dynamic WPT system with the proposed technique for AGV position detection based on ultrasonic distance measurements, experimental prototypes of the dynamic WPT system and a small electrical vehicle resembling an AGV were designed and physically built. An image of them is shown in Figure 7. Note the prototypes were modified versions of those designed, built, and used in [8]. The modifications were as follows:

1. An ultrasound-reflective plastic sheet was added to the electrical vehicle resembling the AGV from one side (see Figure 7).
2. US range meter HC SR-04 was added to the position detection system.

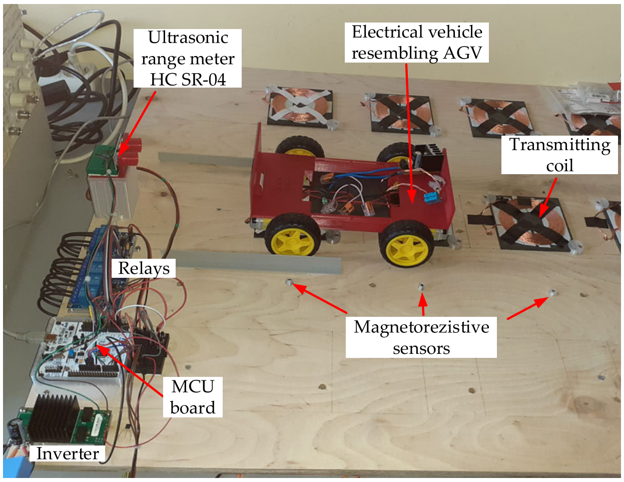


FIGURE 7. An image of the experimental prototypes of the electrical vehicle resembling an AGV and the dynamic WPT system with either the proposed position detection technique based on the ultrasonic distance measurement or the conventional position detection approach based on the magnetoresistive sensors placed near each transmitting coil.

3. The microcontroller code was modified significantly to implement the position detection of the electric vehicle also with the proposed technique based on ultrasonic distance measurements.
4. The optical sensors were disconnected from the MCU board, whereas the magnetoresistive sensors remained connected.
5. Buttons were added to the prototype to choose between the proposed position detection technique and the conventional position detection technique based on magnetoresistive sensors.

The test bench (Figure 7) allowed us to compare the performances of the dynamic WPT system with the proposed and conventional AGV position detection approaches. In the conventional position detection approach, magnetoresistive sensors are placed near each transmitting coil. Each magnetoresistive sensor is connected by three wires to a low-power voltage regulator and a microcontroller. Relays with suitable drivers are used as active switches. The secondary side is simple and similar to that in [8]. It consists of two compensation capacitors, a receiving coil, a rectifier followed by filtering capacitors, and four small low-voltage electric motors. The main parameters of the power stage of the dynamic WPT system prototype are the same as in [8] and are presented in Table 1. The readings update rate of the ultrasonic range meter was 67 Hz during the experiments.

Because of space limitations in our laboratory, the AGV track length is 1 m. However, as previously described, the proposed technique for the AGV position can be used for a much longer track length. It should also be noted that because we focused our attention on AGV position detection and correct transmitting coil activation, the principle of selecting the spacing between the transmitting coils was not considered in this study.

TABLE 1. The main parameters of a prototype of the WPT system [8].

Parameter	Value	Unit of Measurement
Inductance of the transmitting coils	26	µH
Inductance of the receiving coil	26	µH
Switching frequency of the inverter	147	kHz
DC input voltage of the inverter	12.4 – 16	V
Tolerance on the inductances	±5	%
Total nominal capacitance of the transmitting-side compensation	2 × 22	nF
Total nominal capacitance of the receiving-side compensation	2 × 22	nF
Distance between the transmitting and the receiving coils' ferrite pads	2.5	cm
Dimensions of the ferrite pad	10×10	cm
Distance between the centers of the transmitting coils	16	cm
AGV track length	1	m
Total number of transmitting coils	6	-

B. EXPERIMENTAL RESULTS AND DISCUSSION

Before conducting the main experiments, the ultrasonic position detection system was tested in terms of static accuracy. According to (3), a transition from the activated transmitting coil L_{n-1} to activated transmitting coil L_n should occur exactly when the center line of the receiving coil is located at the distance $(d_2 + d_{coil})/2=8$ cm from the center of the coil L_{n-1} (when the vehicle moves from the left to the right according to Figure 8). When slowly moving the vehicle resembling an AGV, we determined that the stable transition from the activated coil L_{n-1} to activated coil L_n occurred when the distance b between the center line of the receiving coil and center line of the transmitting coil L_{n-1} was $8\pm x$ cm, where x value was ≤ 0.5 cm for all transmitting coils. Based on the results, we concluded that the static accuracy (not worse than ± 0.5 cm) of the prototype positioning system is acceptable considering the dimensions of the coils and distances between them.

As previously mentioned, limited reading update rate leads to a delay in transition from the activated transmitting coil L_{n-1} to the activated transmitting coil L_n, and therefore, contributes to the total distance measurement error. For the selected reading update rate of 67 Hz and maximum allowable change in the measured distance of 1.13 cm during the maximum measuring time $1/f_{update}$, the maximum speed of the vehicle according to (1) should be ≤ 0.76 m/s and d_1 should be <2.56 m [see (2)].

To calculate the total error of the ultrasonic position detection system when the vehicle moved with different speeds (0.35 – 0.76 m/s), we conducted the following modifications of the experimental prototype:

1. We activated the ultrasonic position detection.
2. We disconnected data outputs of the magnetoresistive sensors from the microcontroller and applied 5 V voltage to each sensor.
3. We attached a bar with magnets to the side of the vehicle and adjusted a position of the bar to get change

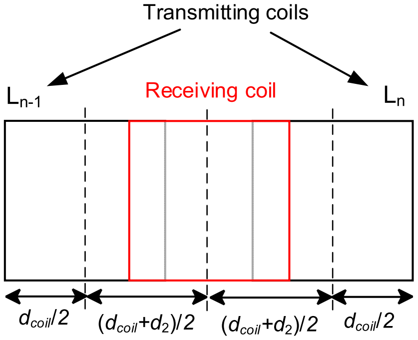


FIGURE 8. Ideal location of the receiving coil with respect to the adjacent transmitting coils.

of output state of the magnetoresistive sensor n from high to low exactly when the center line of the receiving coil is located at the distance of 8 cm from the center of the coil L_{n-1}.

The total error of the ultrasonic position detection system was calculated as follows:

$$\Delta d = v_{\mathrm{AGV}} \cdot \Delta t, \tag{5}$$

where v_{AGV} is the speed of the vehicle (measured by using an oscilloscope); the transition delay Δt is the time interval between the time instant at which the magnetoresistive sensor n output changes its state and time instant at which the microcontroller output n (connected to the input of the relay driver n) changes its state (to activate L_n). To measure Δt, one of the channels of the two-channel oscilloscope was connected to the microcontroller output n (connected to the input of the relay driver n), but the second channel was connected to the magnetoresistive sensor n output. To calculate maximum Δd, we measured Δt five times when the receiving coil was between coil 2 and coil 3 (in this case the oscilloscope channel 1 was connected to the input of the relay driver 3 and channel 2 was connected to the magnetoresistive sensor 3 output), coil 3 and 4, coil 4 and 5, coil 5 and 6. After collecting Δt measurement results for the different positions of the receiving coil and for different speeds of the vehicle, we have found out using (5) that the maximum position detection error was 1.5 cm which is much lower than the dimensions of the coils.

During the main experiments the electrical vehicle resembling an AGV moved continuously with an average speed of 0.35 – 0.76 m/s (depending on DC input voltage of the inverter) when either the proposed position detection technique or conventional position detection technique was used. The measured waveforms of the output voltage, output current and input current of the experimental resonant-inductive dynamic WPT system using the proposed position detection technique based on ultrasonic distance measurements are depicted in Figure 9 (for speed of 0.35 m/s). Similar waveforms of voltages and currents were obtained when conventional position detection methods based on magnetoresistive sensors were employed. To compare the efficiency of the dynamic WPT system with the proposed technique for position detection with that of the dynamic WPT system with the conventional position detection technique, we calculated the efficiency from the measured input and output voltages and currents for two cases: within the time interval t_3-t_2 (when the transmitting and receiving coils are relatively well aligned) and within t_4-t_1 (when the electrical vehicle travelled the distance $d_{\mathrm{coil}} + d_2$). The efficiency η_1 within time interval t_4-t_1 was calculated as follows:

$$\eta_1 = \frac{\sum_{m=1}^{M1} I_{out}(m)V_{out}(m)}{\sum_{m=1}^{M1} I_{in}(m)V_{in}(m)}, \tag{6}$$

where $I_{\mathrm{out}}(m)$, $V_{\mathrm{out}}(m)$, $I_{\mathrm{in}}(m)$ and $V_{\mathrm{in}}(m)$ are the measured discrete values of the output current, output voltage, input current and input voltage, respectively; $M1$ is the number of output current samples within time interval t_4-t_1. The efficiency η_2 within time interval t_3-t_2 was calculated as follows:

$$\eta_2 = \frac{\sum_{m=1}^{M2} I_{out}(m)V_{out}(m)}{\sum_{m=1}^{M2} I_{in}(m)V_{in}(m)}, \tag{7}$$

where $M2$ is the number of output current samples within t_3-t_2.

Despite of the fact that there is a moderate delay in a transition from the activated coil L_{n-1} to activated coil L_n and the accuracy of the receiving coil position detection using the ultrasonic range meter is lower than that of the conventional method, measured efficiency values of the WPT system with the proposed and conventional position detection techniques are similar for different AGV speeds (Table 2). An explanation for this conclusion is that the dynamic WPT system with the proposed position detection approach is immune to leakage magnetic fields emitted from adjacent transmitting coils and the mutual inductance between the receiving and the transmitting coils weakly depends on the receiving coil center distance from the transmitting coil center line when the longitudinal misalignment of the coils is between 7 and 9 cm (see also Figure 10(a)).

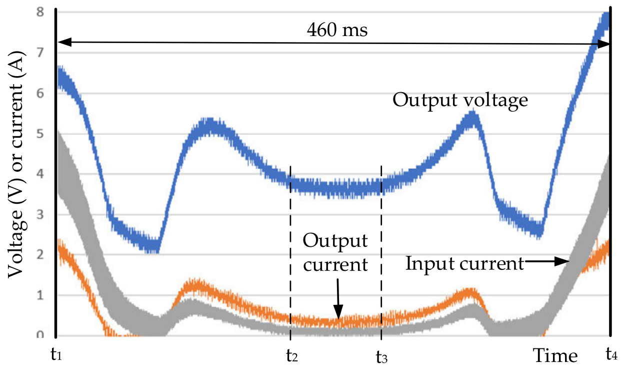


FIGURE 9. Measured waveforms of the output voltage, output current,and input current of the WPT system with the proposed position detection technique based on ultrasonic distance measurements (the switching frequency of the inverter was 147 kHz; an average speed of the vehicle was 0.35 m/s).

TABLE 2. **The measured efficiencies of the dynamic WPT system with the conventional position detection method (when magnetoresistive sensors are placed near each transmitting coil) and with the proposed position detection method based on the ultrasonic distance measurements (the switching frequency is 147 kHz).**

Type of AGV Position Detection Technique	η_1 (v_{AGV}= 45 cm/s)	η_1 (v_{AGV}= 76 cm/s)	η_2 (v_{AGV}= 45 cm/s)	η_2 (v_{AGV}= 76 cm/s)
Proposed method (with ultrasonic distance measurements)	36.8%	36.1%	88.8%	88.1%
Conventional method (with the magnetoresistive sensors)	34.9%	37%	88.4%	87.8%

V. COMPARISON OF THE AGV POSITION DETECTION TECHNIQUE BASED ON ULTRASONIC DISTANCE MEASUREMENTS WITH THE CONVENTIONAL POSITION DETECTION TECHNIQUE

In this section, we compare the performance and cost of the proposed and conventional position detection techniques. As the conventional technique, we consider only those based on magnetoresistive sensors because an optical position detection system based on infrared receivers and transmitters is more expensive than that based on magnetoresistive sensors.

To compare the cost of the position detection systems based on either ultrasonic distance measurement or magnetoresistive sensors, we calculated the total cost including the cost of microcontrollers, HC SR-04 distance meters, magnetoresistive sensors, connection wires, printed circuit boards required for the microcontrollers and magnetoresistive sensors, and small plastic cylinders and stands for HC SR-04. We used the electronic parts search engine, Octopart, to determine the lowest prices of the components. When calculating the total cost of the position detection system with either ultrasonic distance measurements or magnetoresistive sensors, we assumed that there were six coils per meter of the AGV track, one magnetoresistive sensor was placed near each transmitting coil, the maximum speed of the AGV was 1 m/s, AGV track length is 100 m, and HC SR-04 was placed every 1.5 m. In calculating the cost, we also considered that the position detection system based on the magnetoresistive sensors requires microcontrollers with a 40% higher number of digital inputs/outputs than the proposed position detection system. The calculation results revealed that the cost of the position detection system based on the ultrasonic distance measurements is by approximately 20% less than that of the position detection systems based on magnetoresistive sensors. As mentioned in Section III, the lower the maximum speed of the AGV, the greater the acceptable distance between adjacent ultrasonic range meters, and therefore, the lower the cost of the position detection system. Therefore, calculations show that the cost of the position detection system based on the ultrasonic distance measurements is by approximately 40% less than that of the position detection systems based on magnetoresistive sensors if the maximum speed of the AGV is 0.5 m/s. A lower maximum AGV speed results in a greater reduction in the cost of the positioning system. However, if the maximum speed of the AGV is 2 m/s, the cost of the position detection system based on ultrasonic distance measurements may be even higher than that based on magnetoresistive sensors. The comparison results are presented in Table 3.

TABLE 3. **Comparison of AGV position detection techniques.**

	Conventional method (with the magnetoresistive sensors)	Proposed method (with ultrasonic distance measurements)
Efficiency of WPT systems	Similar to the proposed method	Similar to the conventional method
Cost of position detection system (if max AGV speed $\leq$ 1m/s)	Moderately higher than that of the proposed method	At least 20% less than that of the conventional method
Accuracy of the position detection (if max AGV speed $\leq$ 1m/s)	Moderately better than that of the proposed method	Moderately worse than that of the conventional method
Level of complexity of WPT system	High	Moderate
Other	- Radiated magnetic fields may result in disruption of normal operation of the sensors and WPT system + Can be used for low and high-speed AGVs	+ Immune to radiated magnetic fields and optical radiation - It is feasible only for low and moderate-speed AGVs (v_{AGV}<1.5 m/s) - WPT system will not operate correctly if there is an object between the ultrasonic range meter and AGV

VI. IMPROVED POSITION DETECTION METHOD FOR BETTER ACCURACY AT HIGHER AGV SPEEDS

As previously mentioned, the proposed AGV position detection method based on ultrasonic distance measurement due to limited reading update rate is suitable only for low-to-medium-speed AGVs, and it is sensitive to obstructions caused by objects that may appear between the moving AGV and the ultrasonic range meter. Therefore, an improved AGV position detection method is proposed in this study. The improved method is based on the position detection using the transmitting coil maximum current detection and ultrasonic detection of the AGV motion direction. Because it is impossible to know direction of the AGV motion from the transmitting coil current, the ultrasonic range meters are used to determine it. Moreover, the US range meters are necessary to know initial coordinates of the AGV to activate the correct transmitting coil before the AGV movement.

To better understand the receiving coil position detection based on the maximum transmitting coil detection, let us consider an expression for the transmitting coil current peak value [10]:

$$I_{1p} = U_{1p} \Big/ \left| r_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) + \frac{\omega^2 M^2}{R_l + r_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right)} \right|, \tag{8}$$

where U_{1p} is the peak value of the transmitting coil current fundamental harmonic; L_1 is the inductance of the transmitting coil; L_2 is the inductance of the receiving coil; r_1 and r_2 are the parasitic resistances in the primary and secondary resonant tanks, respectively; C_1 and C_2 are capacitances of the primary and the secondary compensation capacitors, respectively; R_l is the load resistance; M is the mutual inductance. From (8) it follows that for a given value of M, R_l, C_1, C_2, r_1 and r_2, the maximum transmitting coil current can be achieved at the transmitting and receiving resonant tank resonant frequency (if $\omega L_1 = \frac{1}{\omega C_1} = \omega L_2 = \frac{1}{\omega C_2}$). Because L_1 depends on the longitudinal misalignment b of the coils (Figure 10(b)), and M at large b is low and weakly depends on b (in our case, 7 cm $< b <$ 9 cm), to achieve maximum primary resonant tank current exactly if the center line of the receiving coil is located at the distance $(d_2 + d_{\mathrm{coil}})/2 =$ 8 cm from the center of the transmitting coil, the switching frequency of the inverter should be chosen to be equal to the resonant frequency of the primary resonant tank:

$$f_{sw} = \frac{1}{2\pi\sqrt{L_{1b} C_1}},$$

where L_{1b} is the inductance of the transmitting coil when the longitudinal misalignment of the transmitting coil is $(d_2 + d_{\mathrm{coil}})/2$ (in our case 8 cm). After conducting some experiments, we have concluded that even at small lateral misalignments ($<$1 cm) of the receiving coil, the receiving coil detection above the transition point can be done with relatively high accuracy using the maximum transmitting coil current detection.

A block diagram of the receiving coil detection system based on the maximum transmitting coil current detection is shown in Figure 11. It consists of the transmitting coil current sensor, amplifier, envelope detector, maximum current detector, pulse counter and demultiplexer (Demux). Because envelopes of the transmitting coil current or input current of the inverter can have two more local maxima, but with much lower values than the main local maxima (Figure 9), the proposed receiving coil detection system incorporates a comparator with a definite voltage threshold V_{th} value which should be chosen so that the max current detector operates only if the measured current envelope values are higher than some current threshold value (in our case 1 …3 A). If maximum current is detected, the max current detector sends a pulse to the input of the pulse counter. When the pulse counter receives the pulse, it changes the input address code of the demultiplexer by one and a transition from the activated coil $L_{k,n-1}$ to the activated coil $L_{k,n}$ occurs.

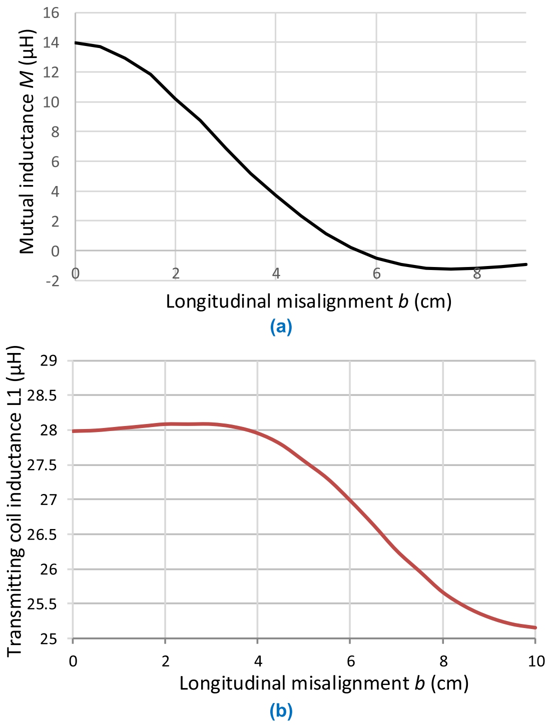


FIGURE 10. **Measured mutual inductance (a) and the transmitting coil inductance (b) versus longitudinal misalignment of the receiving and transmitting coils used in the experimental setup.**

Despite the fact that the proposed improved approach can also be used for the receiving coil position detection of high-speed AGVs, complexity of the position detection system based on the proposed combined approach is higher than that of the proposed ultrasonic position detection system. The proposed improved position detection approach based on max transmitting current detection is much less sensitive to obstructions than the proposed ultrasonic position detection approach.

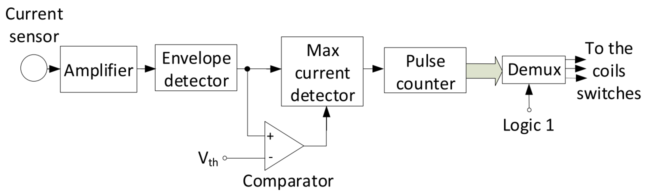


FIGURE 11. **A block diagram of the proposed receiving coil detection system.**

VII. CONCLUSION

The study proposes a novel concept for AGV position detection. For the first time, it was shown that distance meters can be simply integrated into resonant-inductive dynamic WPT systems for detecting the position of an AGV to activate the correct transmitting coil. Important attention should be paid to the accuracy and measurements update rates of distance meters. Because laser- and microwave-based distance meters with high update rate and accuracy are expensive, it is proposed to use inexpensive ultrasonic range meters. However, they need to be placed every 1–3 m along the AGV track. The lower the maximum speed of AGV, the greater the distance between adjacent ultrasonic range meters, and therefore, the lower the cost of the position detection system.

Comparative measurements show that the efficiency of the dynamic WPT system with the proposed detection technique is similar to that of the dynamic WPT system with conventional position detection techniques, while the cost and level of complexity of the position detection system are moderately lower. Moreover, the proposed position detection system is immune to optical radiation and magnetic fields. The disadvantage of the ultrasound-based AGV position detection technique is that it is feasible only for low- and moderate-speed AGVs (AGV speed below 1.5 m/s) and the dynamic WPT system will not operate correctly if there is an object between the ultrasonic range meter and the AGV.

To eliminate the disadvantages of the proposed ultrasound-based AGV position detection technique, another technique based on the combined application of the maximum transmitting coil current detection and ultrasound-based AGV motion direction detection was proposed. However, the advantages of the proposed combined method come with the increased complexity of the AGV position and motion direction detection system.

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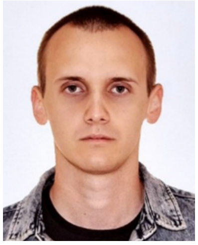

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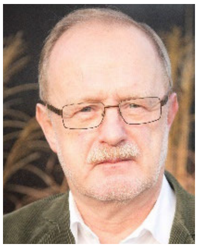

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