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DESIGN OF A NOVEL DUAL-LOOP GATE ANTENNA FOR RADIO FREQUENCY IDENTIFICATION (RFID) SYSTEMS AT LOW FREQUENCY BAND

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Abstract—In this paper, a dual-loop gate antenna is designed to generate the magnetic field distribution in various directions. It is applied to Radio Frequency Identification (RFID) systems for animal identification operating at the low frequency (LF) band of 125 kHz and 134.2 kHz. The percentage of volume of magnetic field intensity is introduced and used as a figure of merit in the design. The optimum antenna parameters are also designed by the genetic algorithm (GA) in conjunction with the Numerical Electromagnetic Code (NEC). The prototype antenna was fabricated and tested to confirm the antenna performance in the LF-RFID system for animal identification. It is found that the dual-loop gate antenna can be efficiently used in the LF-RFID system.

1. INTRODUCTION

Radio Frequency Identification (RFID) systems become very popular in many applications, such as industrial automation and supply chain management since it can provide fast and automatic operation. Practical RFID systems employ different operating frequencies such as Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF) and microwave band [1, 2]. The LF-RFID system is suitable for

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animal identification and anti-theft systems where tags used in these applications are possibly arranged in various orientations. This system employs the principle of inductive coupling to communicate between a reader and passive tags. In the LF-RFID system, there are two operating frequencies; i.e., 125 kHz for ISO card tags and 134.2 kHz for bolus tags, ear tags and glass tags. The conventional rectangular- or circular-loop antennas are usually employed as reader antennas, but they cannot provide sufficient magnetic field intensities in some desired locations to activate tags [3–6]. Thus, a novel design of reader antennas is required to obtain better communication performance between a reader and tags. There are various loop antenna configurations presented in the literature [7–10]. Most techniques can improve the magnetic field distribution at the expense of structural complexity such as "figure of eight" shape loop antennas with the switching circuit or sequencing circuit [7]. The trapezoidal loop structure [8] and the trapezoidal dual-loop structure [9] are used in walk-through gate arrangement. In addition, the "Vee" loop antenna was proposed to improve the performance of the rectangular loop antenna [10].

In this paper, two novel dual-loop antennas in a walk-through gate arrangement are proposed. These antennas are connected to an RFID reader. The associated antenna parameters are optimized by the genetic algorithm (GA) [11–19] in conjunction with the Numerical Electromagnetic Code (NEC) [20] based on the Method of Moments. The percentage of volume of magnetic field intensity is introduced and employed as a figure of merit of reader antennas. It is found that this proposed antenna possesses low cost, simple structure and high performance of communications with various tag orientations for animal identification and anti-theft systems.

This paper is organized as follows. Section 2 discusses the proposed antenna structure to overcome the limitation of the conventional loop antennas. The analysis and design of the antenna structure are provided in Section 3. Section 4 presents measured results of the antenna performance. Finally, conclusions are given in Section 5.

2. ANTENNA STRUCTURE

The LF-RFID system for animal identification and anti-theft systems usually employ reader antennas in a walk-through gate arrangement to obtain longer communication range between a reader and tags. Usually, there are two types of magnetic field excitation; i.e., in-phase and 180° out-of-phase [1, 2]. In this paper, a novel loop antenna configuration in a walk-through gate arrangement is proposed to improve the distribution of magnetic field intensity in the operating region of interest and resulting in better communication performance between a reader and tags. Two loop antennas are combined to form the dual-loop configuration as shown in Fig. 1, and two parallel dual-loop antennas are installed as a walk-through gate arrangement as shown in Fig. 2. This configuration is of interest because it can generate the magnetic fields for various directions in the operating region of interest with a simple antenna structure. In Fig. 1, the tilted wires can improve the distribution of magnetic field intensities in x- and z-directions. Note that the currents in each loop passing through the tilted wires in the same direction. For illustration, the width and height of each dual-loop antenna are 60 cm and 90 cm respectively, which are suitable for the human and animals with medium size; e.g., sheep and goat. In Fig. 1 and Fig. 2, g is the gap width between two loop antennas, and d is the distance between two dual-loop antennas. For illustration, the distance d is equal to 100 cm, which is sufficient for medium-size and large-size animals. To obtain the optimum performance, the antenna structure will be optimized by GA with in-phase and 180° out-of-phase excitations that will be shown in the next section.

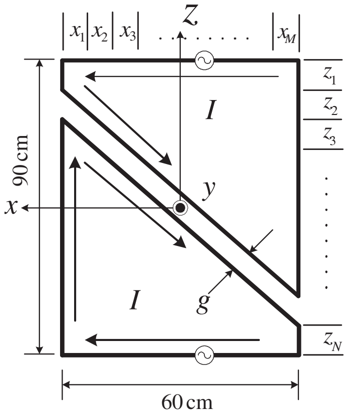


Figure 1. The dual-loop antenna and the discretizations along x and z axes for computing the percentage of line.

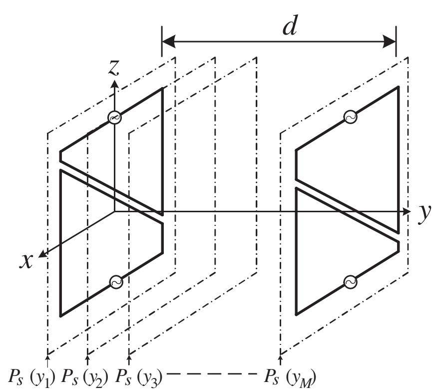


Figure 2. Two dual-loop antennas in a walk-through gate arrangement and the calculation of the percentage of volume.

3. STRUCTURAL ANALYSIS AND DESIGN

In the design of two dual-loop antennas in a walk-through gate arrangement in Fig. 2, there are several design parameters affecting the antenna performance. Thus, it is very difficult to search for optimum parameters in the design. For this optimization problem, the GA approach conducting a global search for the optimum solution becomes attractive [11–19]. In the design of two dual-loop antennas, the goal is to determine the appropriate structure satisfying the set of performance criteria; i.e., the maximum percentages of volume in x-y- and z-directions in this case, as shown in (1):

$$\text{Objective Function } (F) = [P_{v,H_x}, P_{v,H_y}, P_{v,H_z}], \tag{1}$$

where P_{v,H_x}, P_{v,H_y} and P_{v,H_z} are the percentages of volume in the x-, y- and z-directions, respectively. The percentage of volume is used as a figure of merit of antennas; i.e., the higher the percentage of volume, the better the communication performance.

To determine the percentage of volume, the percentage of line (P_l) is first computed by considering a tag moving through the gate along a straight line from the entrance to the exit. If at least one point along the line (parallel to the x-axis in Fig. 1 and Fig. 2) possesses the magnetic field intensity $H(x, y, z) \geq H_t$, the percentage of that line is equal to 100%, where H_t is the activated magnetic field strength of tags. In other words, the tag can communicate successfully with the RFID reader along that line. However, if every point along the line has $H(x, y, z) < H_t$, the percentage of line is equal to 0%. In this case, it means that the communication along that line is failed. In the simulation, it is assumed that H_t is equal to 175 mA/m for ISO card tags operating at 125 kHz (for initial design), which can be determined from the measurement under the condition of maximum read range in conjunction with using simulation results. Once P_l is known, the percentage of surface at the distance $y_m(P_s(y_m))$ can be calculated as

$$P_s(y_m) = \frac{\sum_{n=1}^{N} P_l(z_n)}{N}, \tag{2}$$

where $P_l(z_n)$ is the percentage of line at the distance z_n and N is the total number of considered lines along the z axis. The discretizations along x and z axes are shown in Fig. 1. Once the percentage of surface is known, the percentage of volume (P_v) can be readily calculated as

$$P_v = \frac{\sum_{m=1}^{M} P_s(y_m)}{M}, \tag{3}$$

where M is the total number of considered surfaces parallel to the x-z plane between two gates separated by the distance d as shown in Fig. 2. It should be pointed out that N and M must be appropriately chosen to obtain accurate P_v. By definition, $P_s(y_m)$ and P_v are always less than or equal to 100%. In addition, the considered volume should at least cover the common region of interest between two gate antennas. In this paper, the considered volume is the same as the volume occupied by the gate antennas; i.e., from −30 cm to 30 cm along the x axis, from 0 cm to 100 cm along the y-axis, and from −45 cm to 45 cm along the z-axis. For this configuration, it is found that the suitable number of N and M are 45 and 20, respectively.

There are several configurations and dimensions of dual-loop antennas. In this paper, the structure for each side of the gate antenna is separated into three models as shown in Fig. 3 under the consideration of all possible orientations of the slanting wires. These wires are employed to generate the magnetic field in the x- and z-directions because the Radio Frequency Identification (RFID) system at Low Frequency (LF) band has been applied to identify animals in the agricultural farms such as cattle. The RFID tags for this application have usually been installed at ears or in stomach of some animals such that the orientation of tags is difficult to fix for transferring data with an RFID reader. The conventional rectangular- or circular-loop antennas are usually employed as reader antennas, but they cannot provide sufficient magnetic field intensities in some desired locations to activate tags such as in x- and z-directions. After appropriate combination of each model in Fig. 3, there are only six unique models for walk-through gate installation as shown in Fig. 4. In addition, there are two cases of magnetic field excitations to be considered. The first case is that Antennas 1 and 2 (see Fig. 4) are fed with in-phase currents, and the other is that they are fed with 180° out-of-phase currents.

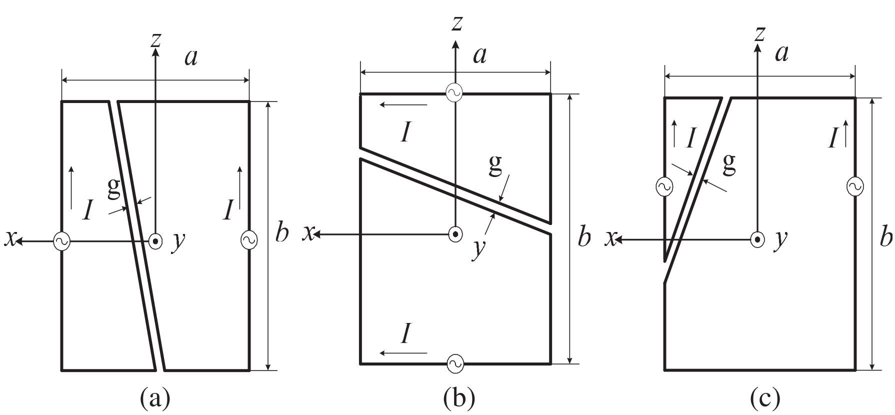
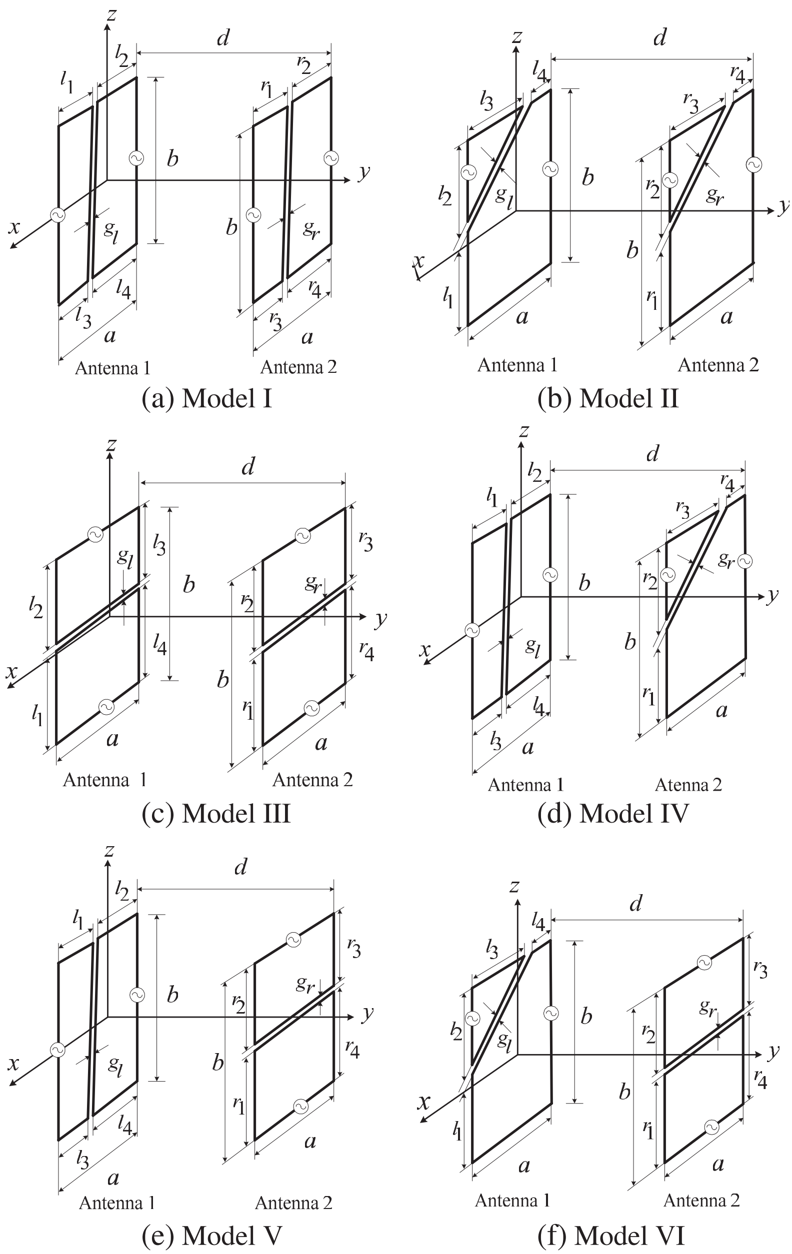


Figure 3. Three models of dual-loop antennas.



(a) Model I (b) Model II

(c) Model III (d) Model IV

(e) Model V (f) Model VI

Figure 4. Six models of two dual-loop antennas in a walk-through gate arrangement.

The simple genetic algorithm (SGA) and multi-objective optimization solutions consist of four operators; i.e., selection wheel, crossover, mutation and elitism [18, 19]. Fig. 5 shows a general flow diagram of the SGA used in this paper which antenna parameter of six models is optimized by SGA in conjunction with NEC program [21]. The SGA begins the search with a large population of randomly generated individuals that are solutions to a problem. This randomness produces a diverse population of possible solutions representing a broad cross section of the entire solution space. For the problem at hand, each individual in the population represents the six models of antenna structure with two cases of magnetic field excitations as shown in Fig. 4. The characteristic of each structure is evaluated using the NEC program [21], and then assigned a fitness based on how closely the designed antenna structure meets the desired performance properties. Note that new populations are produced and evaluated for many generations until the optimum population converges, or some other stopping criteria are met.

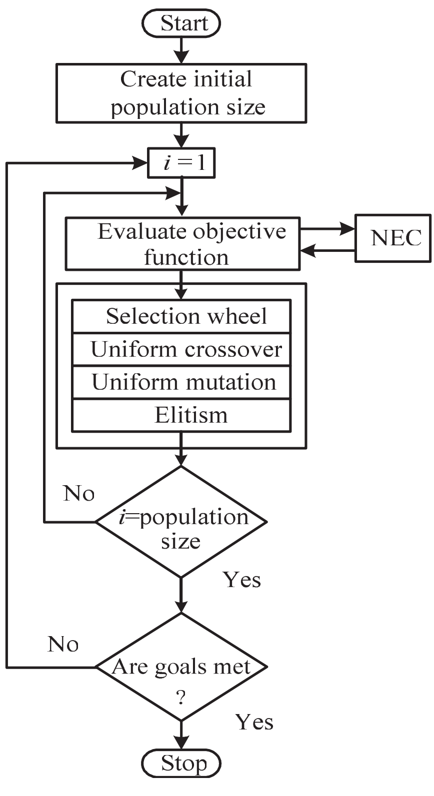


Figure 5. The flow diagram of the simple genetic algorithm.

In this study, the crossover of 80%, the mutation of 5% and the elitism with 5 best populations are employed to optimize the structure of two dual-loop antennas including their excitations. After optimization, the optimum antenna structure is found as shown in Fig. 6 with the 180° out-of-phase excitation of each gate antenna. It is observed that the gate antenna of Model IV in Fig. 4 yields the best communication performance for this considered problem. The simulated percentages of volume in the x-, y- and z-directions can be calculated using (3) and found to be 93.82%, 91.32% and 70.78% respectively as shown in Fig. 7. Note that a tag is moved along the

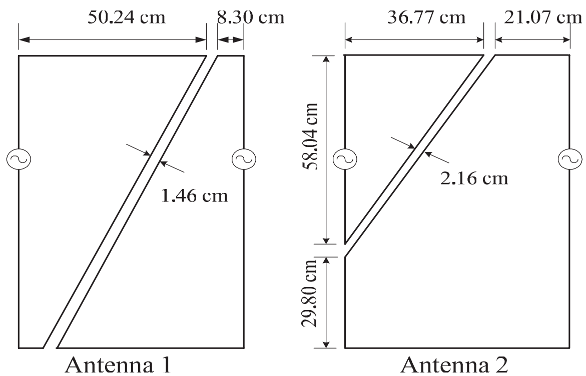


Figure 6. The actual dimension of the optimum two dual-loop antennas for a walk-through gate arrangement.

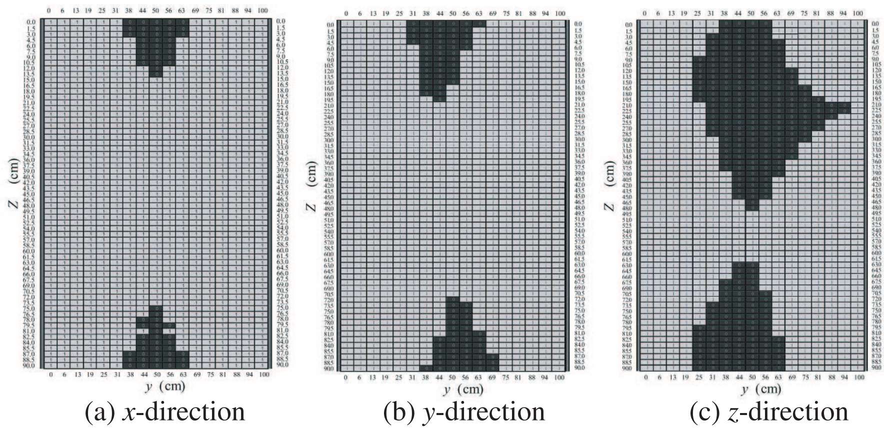
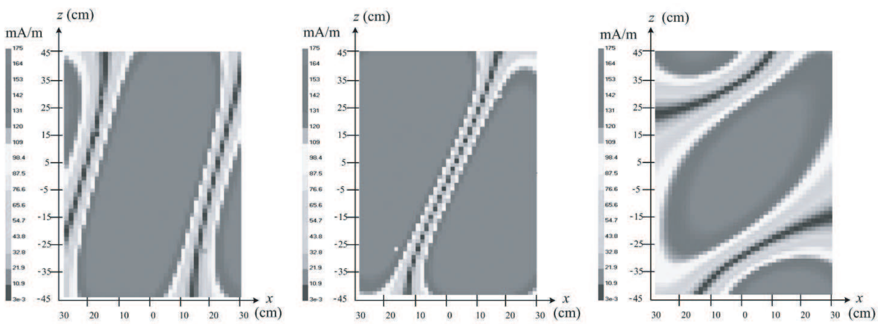


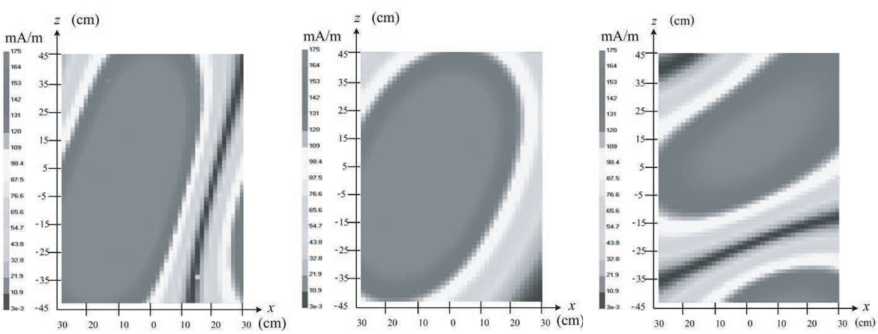
Figure 7. The simulated communication performance between RFID reader and a tag in the walk-through gate area of the optimum gate antenna.

straight line parallel to the x axis from the entrance to the exit of the optimum gate antenna. The gray slot with the number "1" in Fig. 7 represents the area that the tested tag can successfully communicate with the RFID reader, whereas the black slot with the number "0" represents the area that the communication between the tag and the reader is not successful. It is noted that this LF-RFID antenna type utilizes near field magnetic induction coupling between transmitting and receiving antenna coils. The field produced by the small dipole loop antenna compared with the wave length is not a propagating wave, but rather an attenuating wave. The field strength falls off with r^{-3} (where r = distance from the antenna). This near field behavior (r^{-3}) is a main limiting factor of the read range in RFID applications. Therefore, the magnetic field distribution in near field is



(a) H_x (b) H_y (c) H_z

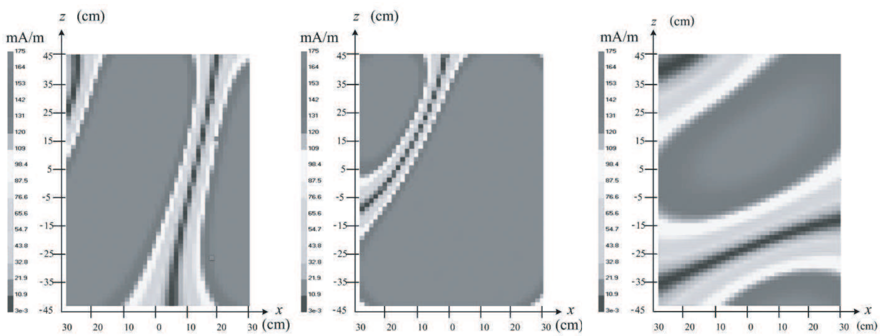
Figure 8. The simulated magnetic field distribution in the x-z plane for each principal direction at the distance $y = 25$ cm.



(a) H_x (b) H_y (c) H_z

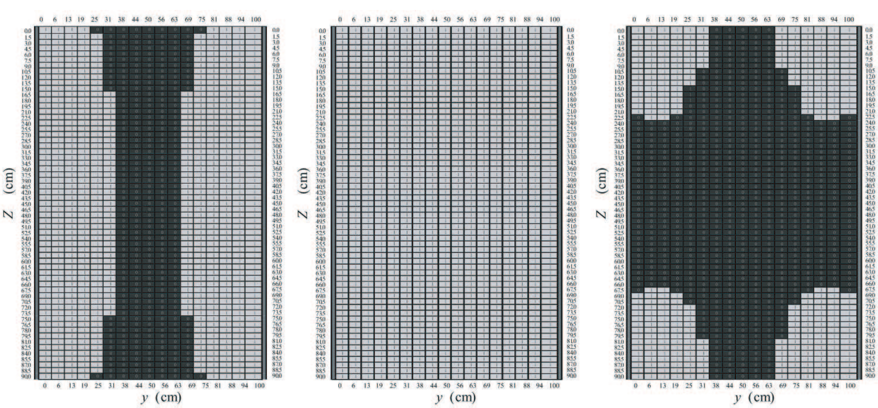
Figure 9. The simulated magnetic field distribution in the x-z plane for each principal direction at the distance $y = 50$ cm.

used to evaluate the antenna performance instead of radiation pattern in far field of conventional antenna operating at higher frequency [3]. The program NEC [21] is used to simulate magnetic field intensities for each principal direction (H_x, H_y and H_z) in the x-z plane at $y = 25$ cm, $y = 50$ cm and $y = 75$ cm of the optimum gate antenna as shown in Figs. 8–10, respectively. In the simulation, the current source (I) is set to be 1 A identically for every antenna. From Fig. 8, it is found that the simulated magnetic field intensities in the x-z plane for each principal direction are distributed more uniformly compared to those of the rectangular-loop gate antenna.



(a) H_x (b) H_y (c) H_z

Figure 10. The simulated magnetic field distribution in the x-z plane for each principal direction at the distance $y = 75$ cm.



(a) x-direction (b) y-direction (c) z-direction

Figure 11. The simulated communication performance between an RFID reader and a tag in the walk-through gate area of the rectangular-loop gate antenna.

For comparison, Fig. 11 illustrates the simulated results for the case of the rectangular-loop gate antenna of the same antenna size as the optimum gate antenna. It is found that the simulated percentages of volume in the x-, y- and z-directions are equal to 66%, 100% and 32%, respectively. It is apparent that the optimum dual-loop gate antenna designed by the SGA has better performance on average than the rectangular-loop one Note that the simulated percentage of volume in the z-direction of the optimum antenna is significantly improved compared to that of the rectangular-loop one at the expense of slightly reduction of the simulated percentage of volume in the y-direction.

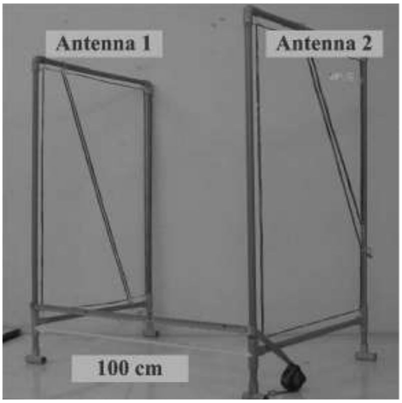


Figure 12. The photograph of the prototype gate antenna on an insulated structure.

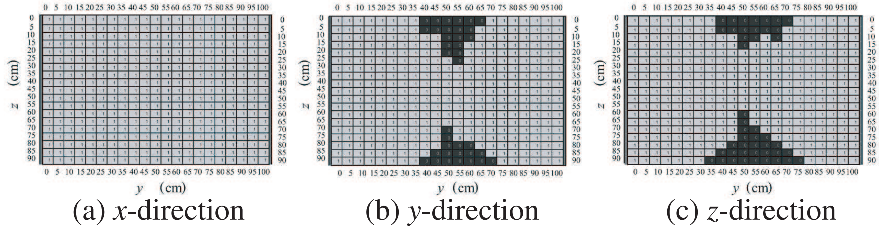
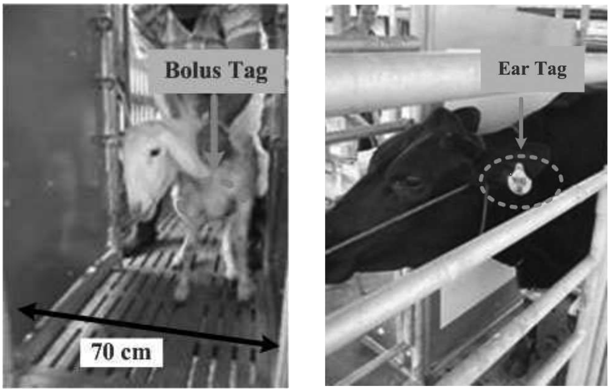


Figure 13. The measured communication performance between an RFID reader and the ISO card tag in the walk-through gate area of the optimum gate antenna.

4. MEASURED RESULTS

The measurement set up was carried out using the optimum dual-loop gate antenna as shown in Fig. 12. The prototype antenna was constructed by using the wire No. 24 AWG (American Wire Gauge) with 17 turns. At two ends of the wire, they are connected with BNC connectors as the feeding ports. The measured total inductance of the gate antenna must be in the range of 500–510 µH, which is suitable for the RFID reader (IET PL-163U model) [22]. The tag under test is the ISO card tag operating at 125 kHz. The left-hand side antenna is defined as Antenna 1, and the right-hand one is Antenna 2 as shown in Fig. 12. Fig. 13 shows the measured percentages of volume of the ISO card tag along the straight line between two dual-loop antennas in three principal directions. In Fig. 13, only tags oriented in the x-direction possess the percentage of volume of 100%. However, the percentages of volume in the y- and z-directions are equal to 93.08% and 91.12%, respectively. In practice, the test of the optimum antenna with animal identification is performed and more interested The original size of prototype antenna (medium size) is the optimized structure for sheep using bolus and ear tags, and the other size was extended from the original one by 1.5 times (large size) for cow with the distance $d = 70$ cm because the bolus tag needs stronger activation field strength than ISO card tag We tested the prototype antennas of medium and large sizes with animal identification system at the veterinarian training farm of Chulalongkorn University in Thailand.



(a) Sheep (with the medium gate antenna covered by plastwood structure) (b) Cow (with the large gate antenna covered by plastwood structure)

Figure 14. Photograph of the animals under test.

We tested with 5 sheep and 5 cows where each animal walked through the antennas 2 or 3 times. The prototype antennas can read all data from RFID tag inside sheep and cows which are 100% read rate. It is found that the two prototype antennas can be efficiently used in the LF-RFID system for animal identification.

5. CONCLUSION

The novel dual-loop gate antenna can efficiently provide more uniform distributions of magnetic field intensity in various directions. The genetic algorithm in conjunction with the NEC is employed to determine the optimum structure of the dual-loop gate antenna. Both simulated and measured results show efficient communication performance. It is found that the measured percentages of volume of the medium gate antenna at $d = 100\,\mathrm{cm}$ with the ISO card tag in the x-, y- and z-directions are equal 100%, 93.08% and 91.12% respectively, which are sufficiently good in practice. In addition, this proposed gate antenna is tested in the LF-RFID system for animal identification. It is found that the gate antenna can be efficiently used in the system.

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