Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Wireless Charging Docking Method for Multi-Sensor Integrated Logistics Robot in Substation

To cite this article: Shuyan Pan *et al* 2023 *J. Phys.: Conf. Ser.* **2584** 012130

Wireless Charging Docking Method for Multi-Sensor Integrated Logistics Robot in Substation

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Abstract. To avoid wasting time and manpower during the wireless charging docking process of logistics robots of different sizes and models in substations, which may affect the operational efficiency of the robots, this paper proposes a wireless charging docking method for multi-sensor integrated logistics robots in substations. First, multiple data signals, such as infrared sensors, pressure sensors, and ultrasonic sensors, are fused within the coarse positioning interval to obtain the length and width data of the robot. The robot is then controlled to travel along the X-axis towards the pre-set displacement sensor while maintaining its position relative to the wireless charging transmitter coil. In the fine positioning interval, the distance between the displacement sensor and the wireless charging transmitter coil is fixed. A coarse-precision positioning transformation method is used to decelerate the robot as it travels along the X-axis towards the pre-set displacement sensor, and the robot is parked at the wireless charging transmitter coil. Additionally, two sets of laser sensors are used to compare the lateral distance, which is half the difference between the charging station width and the robot width. This assists the robot in aligning along the Y-axis with the wireless charging transmitter coil and completing the wireless charging docking process. The experimental results show that the wireless charging system has superior docking time and stability compared to traditional docking methods. It is also compatible with multiple logistics robots of different sizes for wireless charging, with a docking error of less than 0.3%. This effectively improves the charging efficiency of robots in substations.

1. Introduction

Substations are an indispensable part of the power system. With the development of technology, various intelligent robots have replaced manual labor for efficient management and maintenance of substations [1]. However, robots usually require manual charging docking operations, and different types of robots have different charging methods, which often waste time and manpower and affect the operational efficiency of substations. In order to improve the intelligence of robot operations, reduce the labor intensity and operation time of maintenance personnel, and improve the overall work efficiency of multiple robots in substations, it is necessary to develop a universal wireless charging system for multiple robots that can meet the energy maintenance requirements of various types of robots and ensure the efficient operation of substations.

DANA, a company from the United States, has designed and manufactured a charging docking system that can enable robots to navigate autonomously to the charging dock and complete the charging docking when their battery level is below a threshold [2]. The DOCKING SYSTEM developed by Torino University in Italy can assist robots in achieving precise positioning charging docking through fixed seats, fixed adhesive plates, anti-collision bars, bottom insertion plates, and other mechanisms [3]. Microsoft has designed a self-moving device charging docking process [4], which uses a wedge-shaped charging head and a Hall sensor for docking and has 4 degrees of freedom buffering to make the connection more stable. Robert et al. [5] have developed a non-contact charging design based on inductive coupling, which pre-sets the charging area and enables non-contact charging through AC electromagnetic coupling of the charging base. In China, Zhou [6] has designed a flexible docking method for AGV vehicles and ground charging stations using two-dimensional code positioning technology and infrared communication technology, which has a high success rate and stability. Zeng et al. [7] proposed a new charging alignment method using infrared regression reflection and ultrasonic ranging, which achieves simpler and lower-cost charging alignment.

The existing charging docking system in substations has the following prominent problems. First, charging docking mostly relies on robot rough positioning and manual docking, with low intelligence and automation [8]. Second, it mostly uses wired charging docking, which has poor contact or robustness problems [9]. Third, the different types of moving robots in the substation require corresponding chargers and charging docking methods, leading to poor universality and versatility [10]. In summary, the current charging docking system has limitations in terms of low intelligence, poor robustness of charging docking methods, and inability to adapt to the charging of most robots in substations, which hinders the promotion and application of the charging docking system for robots in substations.

This article addresses the above problems by first installing a wireless charging receiving coil at the center of the robot's bottom and then setting up visual identification markers to guide the robot into the wireless charging station. The robot then sequentially passes through a rough positioning information measurement module and a precise positioning and charging docking module. The rough positioning information measurement module is used to obtain the length and width information of the robot while assisting the robot in adjusting its pose. The precise positioning and charging docking module are used to guide the robot into the wireless charging station and to assist the robot in X and Y-axis positioning to complete the charging docking. The length and width information of robots of different sizes and types is calculated to enable the robot to complete the charging docking accurately, thus meeting the general requirements of the charging station.

2. Wireless charging system for robots in substations

2.1. Analysis of requirements for robot charging system

Multiple intelligent robots in the substation are important equipment for efficient management and maintenance instead of manual labor. However, robots usually require manual charging and docking operations, and different types of robots have different charging methods, which often causes a waste of time and labor, affecting the efficiency of the substation. Therefore, it is necessary to develop a universal wireless charging system to meet the maintenance needs of various types of robot energy and ensure the efficient operation of the substation.

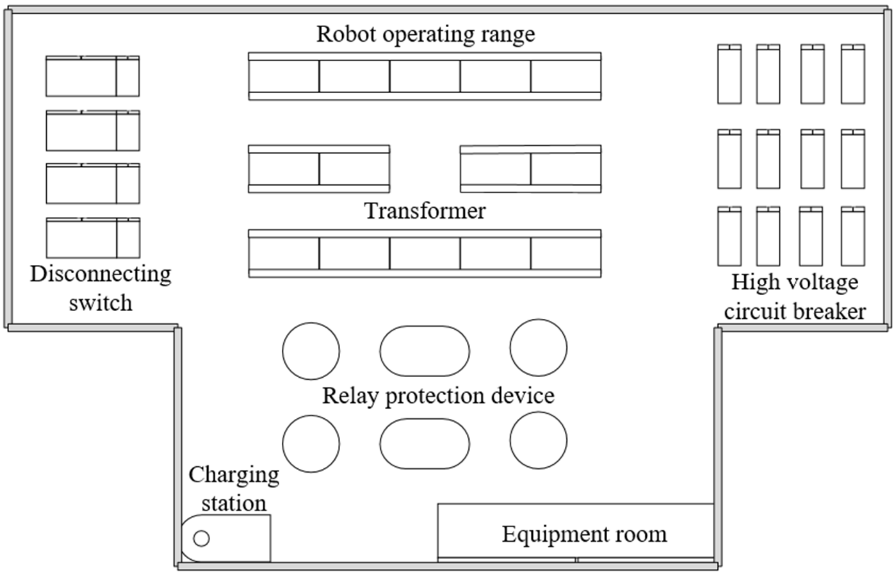


Figure 1. Schematic diagram of robot operating environment in substation

2.2. Wireless Charging System

This article proposes a wireless charging and docking method for substations based on sensor information fusion. The wireless charging station consists of two rails with multiple infrared sensors, ultrasonic sensors, and laser sensors, and a main control box at the end of the rails. The robot is guided into the wireless charging station by a visual identification mark on the main control box. The sensor fusion system composed of multiple sensors on the rails is used to measure the robot's size information, assist the robot in adjusting its forward direction, and obtain the center position of the robot. Finally, the bottom center of the robot's pre-installed wireless charging receiver coil is aligned with the pre-set wireless charging transmission coil to perform energy replenishment. Figure 2 shows the schematic diagram of the wireless charging system configuration.

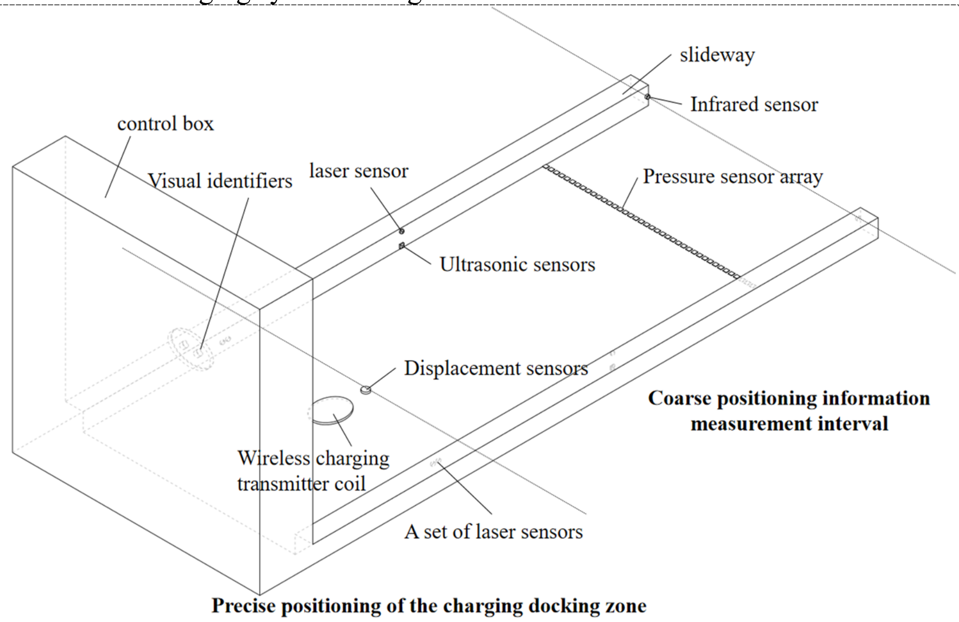


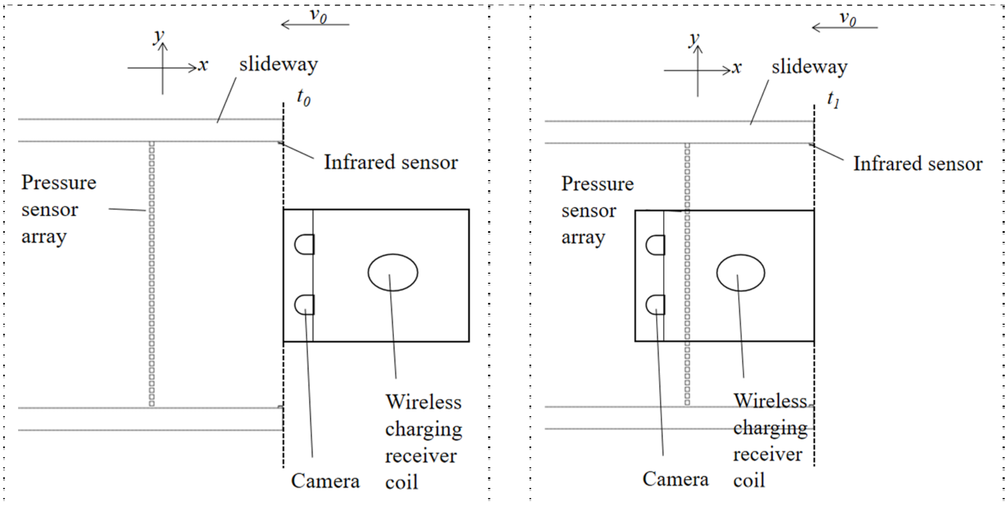
Figure 2. Schematic diagram of wireless charging system configuration

3. Robot wireless charging docking method based on sensor information fusion.

3.1. Coarse positioning measurement algorithm based on sensor information fusion.

Before entering the parallel guide rail, the robot roughly determines the forward direction near the central axis of the parallel guide rail through the visual identification mark and the robot camera. The control center issues instructions to the robot to advance at a predetermined constant speed v_0. When the front end of the robot just passes the first infrared sensor in the pair, an electrical signal is generated, and the time is recorded as t_0, as shown in Figure 3(a). When the robot completely passes the first infrared sensor in the pair, the electrical signal disappears, and the time is recorded as t_1, as shown in Figure 3(b). Thus, the length of the robot is calculated.

$$x_1 = v_0 * (t_1 - t_0)$$



(a) t_0: Detected by the infrared sensor | (b) t_1: Passes the infrared sensors

Figure 3. Initial measurement of robot length

where x_1 is the length of the robot; v_0 is the pre-set constant speed when the robot passes through the infrared sensor; t_1 is the time when the robot completely passes through the first through-beam infrared sensor; t_0 is the time when the front end of the robot just passes through the first through-beam infrared sensor.

The pressure sensor array consists of 100 pressure sensors with a length and width of 1 cm and a spacing of 0.5 cm. The sensors are numbered from right to left as a_0, a_1...a_{100}. When the robot's wheels contact the pressure sensor array, two pressure signal values will be generated from the left and right wheels. We let the number of the pressure sensor that the right wheel contacts be an ($0<n<50$), and the triggering time be t_n. We let the number of the pressure sensor that the left wheel contacts be am ($51<m<100$) and the triggering time be t_m.

If $t_n=t_m$, as shown in Figure 4, the direction of the robot's forward movement is towards the centreline of the parallel guide rail along the visual marker. Therefore, the width of the robot can be calculated as follows:

$$y_1 = (a_m - a_n) * 1 + (a_m - a_{n-1}) * 0.5.$$

Journal of Physics: Conference Series **2584** (2023) 012130 doi:10.1088/1742-6596/2584/1/012130

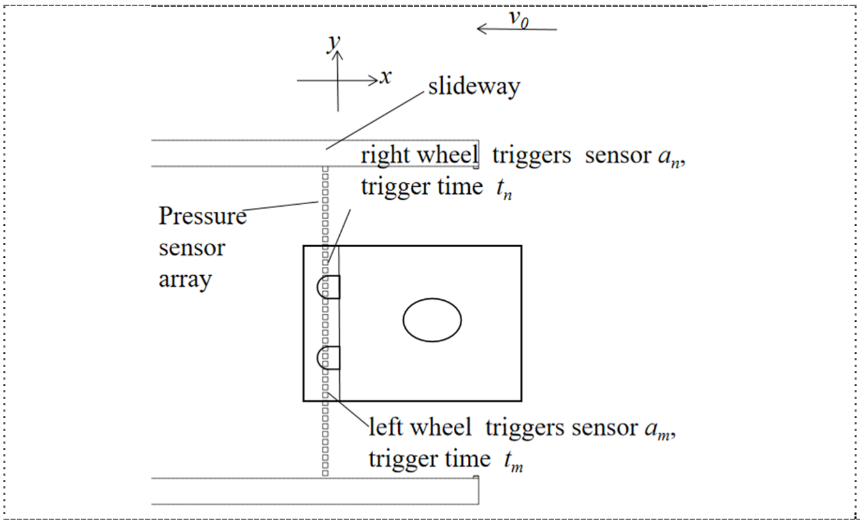
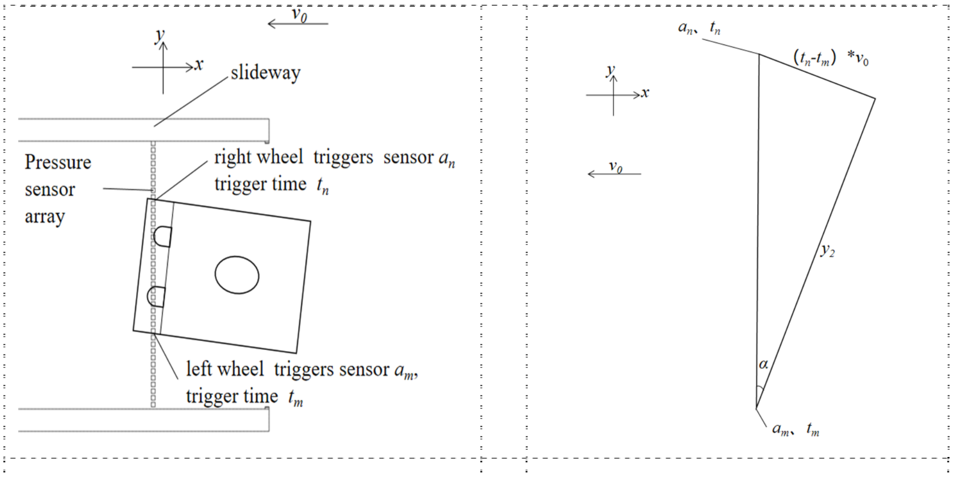


Figure 4. Robot trigger pressure sensor array

If $t_n>t_m$, as shown in Figure 5(a), the left wheel triggers the pressure sensor before the right wheel, indicating that the forward direction of the robot has not been adjusted to the optimal state. This information is fed back to the control center to adjust the robot's left offset angle α, and then calculate the width of the robot as y_2. The specific calculation abstracts the actual problem into a mathematical model, as shown in Figure 5(b), and the expression is as follows.

$$\alpha = \arcsin\left[\frac{(t_n - t_m)v_0}{(a_m - a_n) * 1 + (a_m - a_{n-1}) * 0.5}\right]$$

$$y_2 = [(a_m - a_n) * 1 + (a_m - a_{n-1}) * 0.5] * \cos\alpha$$



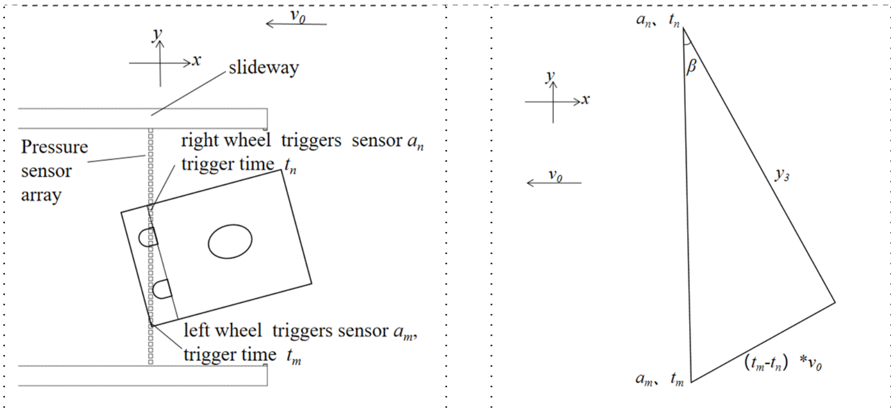
(a) Trigger diagram (b) Abstract graph

Figure 5. The left wheel triggers the pressure sensor before the right wheel

If $t_m>t_n$, as shown in Figure 6(a), the right wheel triggers the pressure sensor before the left wheel, indicating that the forward direction of the robot has not been adjusted to the optimal state. This information is fed back to the control center to adjust the robot's left offset angle β, and then calculate the width of the robot as y_3. The specific calculation abstracts the actual problem into a mathematical model, as shown in Figure 6(b), and the expression is as follows.

$$\beta = \arcsin\left[\frac{(t_m - t_n)v_0}{(a_m - a_n) * 1 + (a_m - a_{n-1}) * 0.5}\right]$$

$$y_2 = [(a_m - a_n) * 1 + (a_m - a_{n-1}) * 0.5] * \cos\beta$$



(a) Trigger diagram (b) Abstract graph

Figure 6. The right wheel triggers the pressure sensor before the left wheel

3.2. Robot dimension information checking and coarse-precision location interval conversion optimization algorithm

The length and width information of the robot is checked. The specific process is as follows.

When the robot passes through the target ultrasonic ranging sensor and the second infrared sensor at a pre-set speed, the robot is located on the central axis parallel to the parallel guide rail by adjusting its position and pose. The distance between the parallel guide rail and both sides of the robot measured by the opposite ultrasonic sensor is obtained, and the width of the robot is calculated. The length of the robot was calculated by recording the time when the front end of the robot truncated the infrared signal from the second infrared sensor and the recovery time of the infrared signal. The length and width information of the robot obtained is checked with the length and width information obtained in advance.

In the specific implementation, the review process is as follows. After the robot passes through the pressure sensor array, the robot posture adjustment is completed. Then, the ultrasonic ranging sensor and the second infrared sensor will pass through the firing. The distance measured by the ultrasonic ranging sensor from the boundary of the left and right guide rails to the side of the robot is L_a and L_b. Considering that the ultrasonic sensor has a certain range advantage, the values of L_a and L_b can be dynamically adjusted in real time, as shown in Figure 7.

When L_a>L_b, the robot is deflected to the right so that L_a=L_b;

When L_b>L_a, the robot is deflected to the left so that L_a=L_b;

When L_a=L_b, calculate the final robot width y= $y_{station}$-2L_a, where $y_{station}$ is the distance between parallel guide rails measured by ultrasonic sensor.

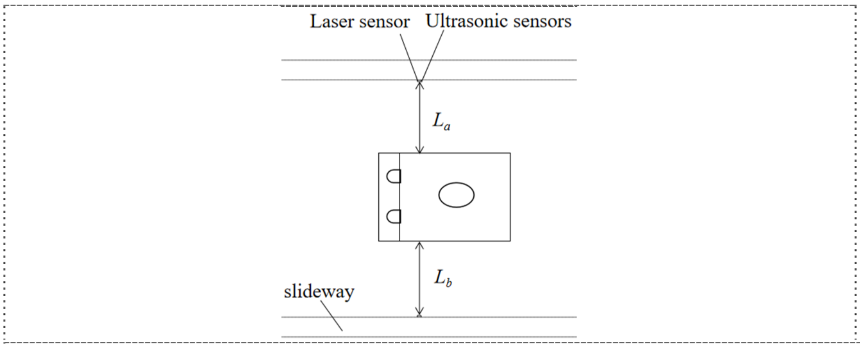
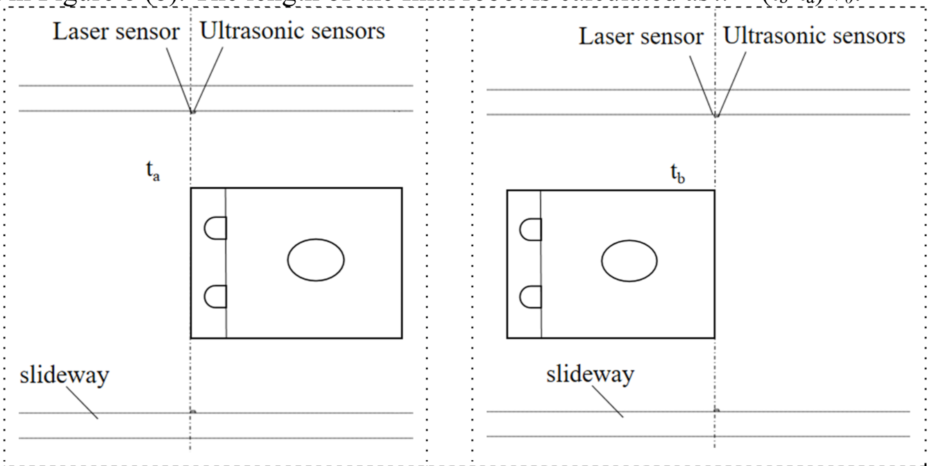


Figure 7. Robot width check

When the front end of the robot truncates the infrared signal emitted by the second infrared sensor, the time t_a is recorded, as shown in Figure 8 (a). When the tail end of the robot passes through the second infrared sensor that fires, the truncated infrared signal recovers again, and the recording time is t_b, as shown in Figure 8 (b). The length of the final robot is calculated as $x = (t_b\text{-}t_a)\ v_0$.



(a)Robot is detected by sensors (b)Robot passed sensors

Figure 8. Robot length check

After adjusting the measurement interval of the robot through rough positioning information, the length x and width y of the robot are obtained. Then, the center position of the robot chassis is obtained. As shown in Figure 9, when the front end of the robot passes the displacement sensor, the control center sends deceleration instructions to the robot. The distance between the displacement sensor and the center of the wireless charging transmitting coil is x_0, so the deceleration displacement of the robot is $x_0 + x/2$. After time passes, the wireless charging receiving coil in the center of the robot site slows down and stops above the wireless charging transmitting coil, so the stopping speed v_t is 0.

$x_0 + \frac{x}{2} = \frac{(v_t^2 - v_0^2)}{2a_s}\ and\ v_t = 0, a_s = \frac{-v_0^2}{2x_0+x}$, where a_s is the acceleration when the robot decelerates.

It is also known from the acceleration formula that $a_s = \frac{v_t - v_0}{t_s}, then\ t_s = \frac{2x_0+x}{v_0}$; when the front end of the robot passes through the displacement sensor, the control center sends an instruction to make the robot slow down, stop within t_s seconds, and reach the top of the wireless charging transmitting coil. At this time, the wireless charging alignment in the direction of the X-axis can be ensured.

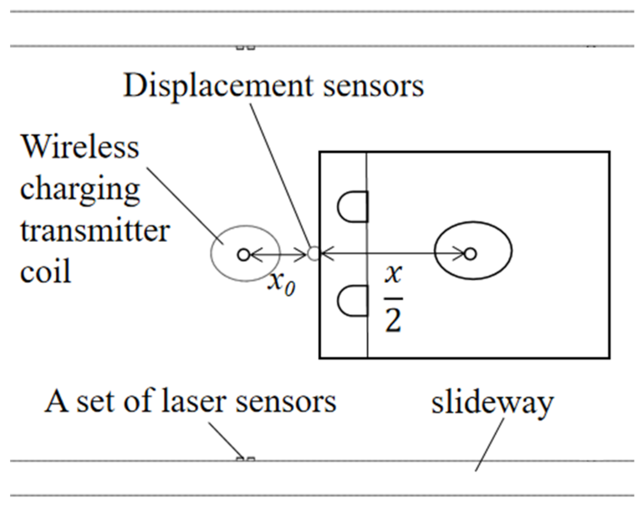


Figure 9. Coarse-precision positioning transformation method

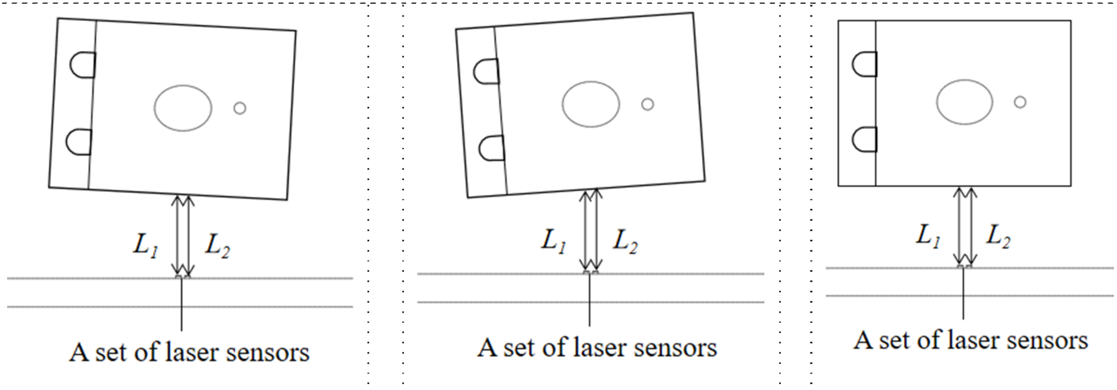
A set of laser sensors are used to detect the accuracy of the robot after parking. A set of laser sensors are used to measure the distance between the left and right guide rail boundary and the robot boundary, respectively, L_1 and L_2.

If $L_1>L_2$, it means that the robot needs to adjust to the left and adjust to $L_1=L_2$, as shown in Figure 10(a).

If $L_1<L_2$, it means that the robot needs to adjust to the right and adjust to $L_1=L_2$, as shown in Figure 10(b).

If $L_1=L_2$, as shown in Figure 10(c), no adjustment is needed, and $y_{station}=2L_1+y$ is satisfied. In this case, the alignment of wireless charging along the Y-axis can be ensured.

When the wireless charging transmitting and receiving coils are aligned on the X and Y axes, it can realize the wireless charging of different sizes and different types of machines in the substation.



(a) (b) (c)

Figure 10. Wireless charging docking optimization method

3.3. Implementation steps of robot wireless charging docking method in substation

The docking method of substation wireless charging is divided into four steps. Figure 11 shows the implementation steps of the substation wireless charging system.

(1) Detection of visual marker positioning is mainly responsible for guiding and adjusting the robot along the center line of the wireless charging system before entering the charging system, according to the relative position relationship between the visual marker on the main control box and the robot body camera;

(2) The measurement interval of coarse positioning information is mainly collected by the first infrared sensor and pressure sensor array for robot size information;

(3) The size data of the robot is checked through the ultrasonic sensor and the second infrared sensor. The maximum stopping distance of the robot is set when the displacement sensor is triggered, and the data is transmitted to the main control box.

(4) Precise positioning charging docking interval is responsible for the final wireless charging docking. The distance between the robot and the guide rail boundary is mainly measured by a group of laser sensors fired at each other so that the wireless charging receiving coil at the bottom center of the robot is accurately positioned to the wireless charging transmitting coil, thus completing the wireless charging docking operation.

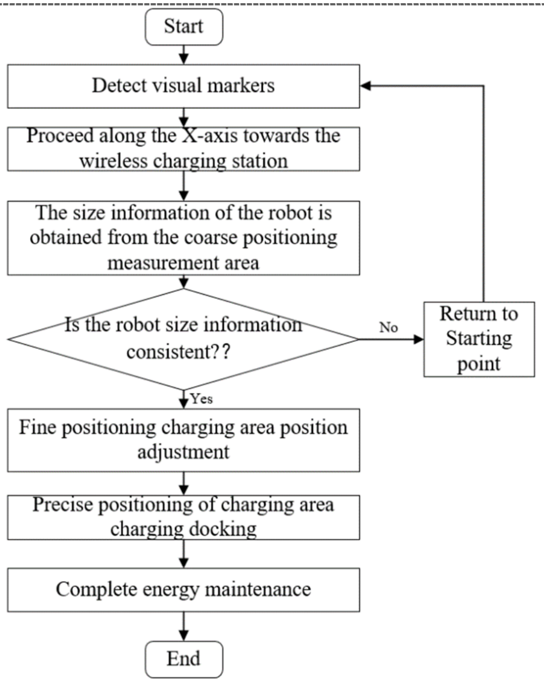


Figure 11. Substation wireless charging system implementation steps

4. Experiment and analysis

In order to test the charging efficiency of the wireless charging system, this paper uses the inspection robot in the substation to conduct the wireless charging docking experiment and compares it with the traditional charging mode to verify the high efficiency of the wireless charging system. In the experiment, the inspection robot enters the charging station from right to left according to the position of the charging station, as shown in Figure 1. The docking modes within the charging station are set as plug-in, adsorption, and wireless, and five times of charging docking are carried out, respectively. The time required for each successful docking under different charging modes is recorded.

Table 1 below shows the comparative test results between wireless charging docking and traditional charging docking. After several tests, the average time for the robot to complete charging docking is the shortest when wireless charging docking is adopted. The variance shows that the stability of wireless charging docking is better than that of traditional charging docking.

Table 1. Test results of wireless charging docking with traditional plug-in charging and adsorption charging docking

Charging methods	Each docking time /s					Mathematical e xpectation	Variance
Plug-in	90	88	93	95	99	93	14.8
Absorption	86	89	91	85	89	88	3.8
Wireless	75	75	77	76	77	76	0.8

In order to test the universality of the wireless charging system in this paper, the inspection robot, the handling robot, and the charged water washing robot in the substation are taken as examples to conduct the wireless charging docking experiment. Experimental Settings: inspection robot (actual parameter: 1220 mm*905 mm), handling robot (actual parameter: 1350 mm*1100 mm), and charged water washing robot (actual parameter: 1550 mm*1260 mm) enter the charging station from right to left for several times according to the position of the charging station in Figure 1. The measured length and width of the final robot and the time to complete wireless charging docking are recorded. The error between the size and the actual robot is calculated. Due to the characteristics of wireless charging, the error is allowed to be within 0.3%.

Table 2. Wireless charging docking data of different kinds of robots

Charging robots	Measure length /mm	Measure width /mm	Docking time /s	Length error	Width error
Inspection	1218	905	75	0.164%	0
Handling	1351	1099	77	0.074%	0.091%
Washing	1547	1258	82	0.193%	0.159%

The experimental results of the two groups show that the mathematical expectation and variance of the wireless charging docking method in this paper are both smaller than that of the traditional plug-in charging docking method and the adsorption charging docking method, and the gap is larger. Traditional charging docking methods tend to have relatively simple docking objects. Wireless charging systems can simultaneously accommodate different types of robots to complete charging docking operations, and the measured robot length and width size errors are small. Therefore, the wireless charging system based on sensor information fusion can effectively and stably complete the charging docking task for the robot in the substation.

5. Conclusion

Aiming at the situation that there are many kinds of robots in substations, which leads to low charging efficiency or inconvenient manual operation, this paper studies and draws a conclusion:

(1) Aiming at a variety of robots in the substation, a set of methods based on multi-sensor real-time measurement of robot size is proposed to guide the robots to complete wireless charging docking.

(2) The robot is introduced into the central axis position of the wireless charging system in rough positioning, and the length and width information of the robot is calculated by infrared sensors and pressure sensors. The size of the robot is checked by the infrared sensor and ultrasonic ranging sensor. The coarse-precise positioning interval is converted, and the precise positioning position is calculated. A set of laser sensors make precise positioning adjustment to complete the final charging docking.

The experimental results show that the error of the final robot size information is within 0.3%. This paper proves the superiority and effectiveness of wireless charging systems and wireless charging docking methods.

Acknowledgments

This work was supported by a grant from the Youth Project of the National Natural Science Foundation of China, No.51907055

This work was supported by a grant from the Key Project of the Education Department of Hubei Province, No. D20221404

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