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A Special Review of Foreign Object Detection for Electric Vehicle Wireless Charging

Hongrui Zhang*

JSNU-SPbPU Institute of Engineering, Jiangsu Normal University, Xuzhou 221116, Jiangsu, China

**Corresponding author: Hongrui Zhang.*

Abstract

Electric vehicle (EV) wireless power transfer (WPT) technology provides a new technical approach for automated vehicle charging because of its advantage of contactless energy transmission. However, during wireless charging, a metal object (MO) may produce additional eddy-current loss and a local temperature rise through electromagnetic induction, and a living object (LO) entering the charging area may also create an electromagnetic exposure safety risk. Therefore, foreign object detection (FOD) is an important technology for ensuring the safe operation of an EV-WPT system. Although existing studies have proposed various detection methods and investigated detection algorithms and coil structures, detection performance may still be affected by factors such as power-transfer interference, receiver misalignment, and complex electromagnetic environments. The detection mechanisms, classification bases, and performance evaluation methods of different technical routes also require further systematic review. To address these issues, this paper reviews FOD technology for EV-WPT systems. Starting from the main sensing paths and physical response mechanisms, the working principles, technical characteristics, and interrelationships of different detection methods are summarized and compared. The analysis shows that different detection methods have their own characteristics in terms of sensing information, detection capability, hardware complexity, and environmental adaptability. A single method may have limitations when handling complex operating conditions and the detection requirements of multiple foreign objects. Multimodal information fusion, sensorless frequency tracking, and the coordinated design of magnetic fields and detection structures provide different technical approaches for improving detection performance and system adaptability. On this basis, this paper further discusses potential research directions, including the decoupling of power disturbance, the coordinated design of intelligent algorithms and detection systems, and standardized performance verification, to provide a reference for selecting FOD schemes, evaluating their performance, and conducting subsequent research.

Keywords

wireless charging, electric vehicle, metal object detection, living object detection

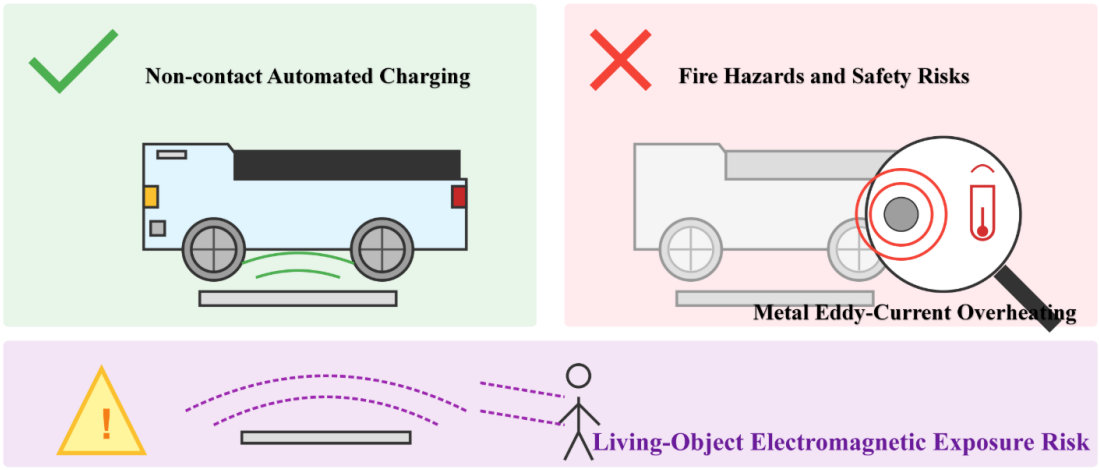
1. Introduction

Foreign object detection (FOD) is an important safety function of electric vehicle (EV) wireless power transfer (WPT) systems [1]. When metal objects (MOs), such as coins, keys, and screws, enter the charging area between the transmitting and receiving coils, the alternating magnetic field produces eddy currents inside the metal and causes loss and heating, which may create a safety hazard in severe cases. When a living object

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(LO) enters the charging area, its electromagnetic exposure risk must be considered [1, 2]. Therefore, FOD must not only detect MOs but also account for the safety protection of living targets and reduce the risks of missed and false detections as much as possible. Relevant standards specify requirements for the safety of wireless charging systems and for foreign object detection. Their exact scopes of application and determination conditions shall be based on the official texts of the corresponding standards. The main safety risks caused by MOs and LOs in an electric vehicle wireless charging system are shown in Figure 1.

Figure 1: Comparison of the convenience of an electric vehicle wireless charging system with the safety risks of metal eddy-current overheating and living-object electromagnetic exposure



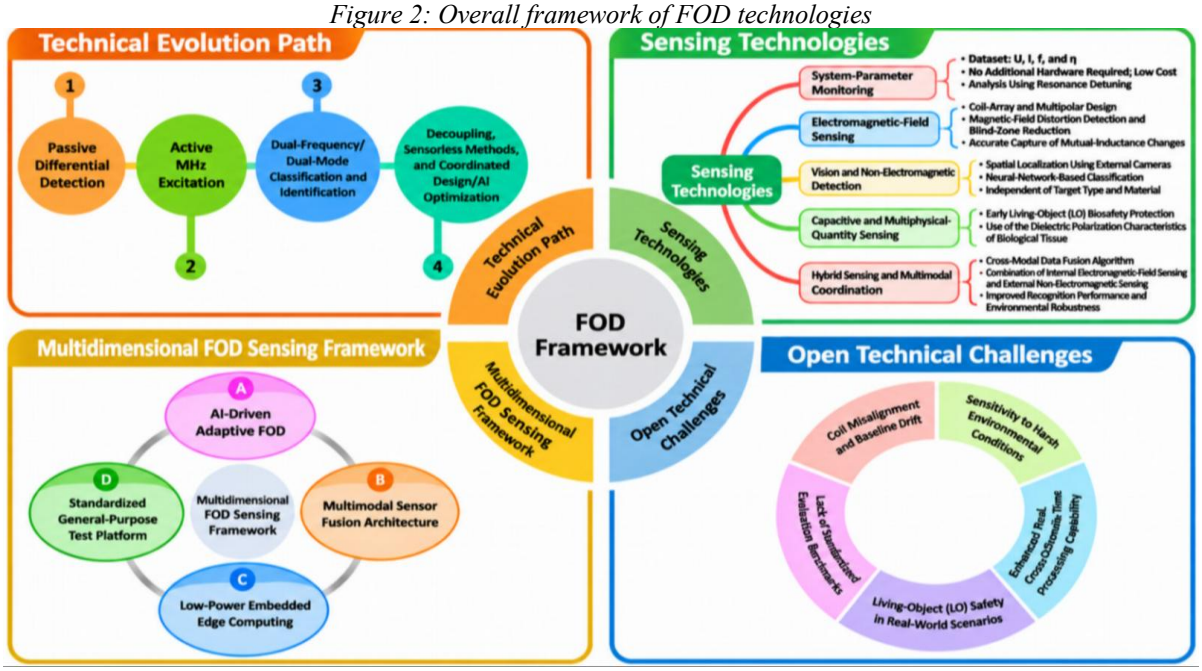
In response to the above requirements, various FOD methods have been proposed in China and other countries. According to the main sensing mechanisms and information sources, this paper classifies the related studies into five categories: detection-coil methods, sensorless system-parameter monitoring methods, non-electromagnetic external sensing methods, machine-learning and signal-processing enhancement methods, and multimodal fusion and imaging methods. Detection coils and related electromagnetic sensing methods usually determine the presence of a foreign object from changes in induced voltage, self-inductance, mutual inductance, impedance, quality factor, or resonance characteristics. Existing studies have used structures such as double-D (DD) coils, three-dimensional helical coils, and strip multipolar coils to improve the spatial coverage and detection sensitivity of the detection area [3, 4, 5]. Optimization schemes have also been proposed for the detection sensitivity and blind-zone problems of DD coils [6, 7], and another study used laminated coils for foreign object detection [8]. Regarding detection strategies, related studies have addressed excitation-frequency optimization, dual-frequency detection, and material identification [9, 10, 11]. Other work has investigated dual-mode, self-resonant, and improved detection-circuit schemes [12, 13, 14]. Other studies have also focused on bipolar checkerboard detection structures and the design of quadrupolar detection coils [15, 16]. In addition, self-excitation oscillation has been used for foreign object detection [17]. Sensorless system-parameter monitoring methods use existing observable quantities of the system, such as efficiency, current peaks, or frequency, for foreign object detection [18, 19]. In addition, the charging-pad coil itself has been used as a sensing element. By extracting the amplitude and phase characteristics of the coil current during the sensing stage, this method senses the vehicle position, receiving-coil alignment state, and conductive foreign objects [20]. A foreign object detection and classification method for a capacitive wireless power transfer system has also been investigated [21]. Non-electromagnetic external sensing methods, such as vision and motion-feature methods, use visual or motion information to obtain target features [22-24]. Machine-learning methods have been used for foreign object detection and feature analysis [25, 26], whereas classical signal-processing methods can be used to filter detection signals [27]. In addition, a study attempted to coordinate the optimization of the magnetic-field distribution and detection structure to improve detection conditions [28]. Multimodal fusion and imaging methods further use different types of physical information or multichannel spatial information to obtain richer foreign-object categories and spatial features. For example, an integrated electromagnetic and capacitive dual-modality sensor array can be used for foreign object detection and image reconstruction [29], while a double-winding structure based on time-division multiplexing combines metal object detection with living object detection [30].

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Existing literature has systematically summarized and analyzed the basic principles and technical routes of FOD from the perspectives of electricity, thermal effects, vision, and multimodal fusion [1, 2, 31]. For example, Lu et al. summarized foreign object detection problems and related methods in wireless power transfer systems [1], while Alam et al. conducted a comprehensive analysis from the perspectives of electricity, magnetic fields, thermal effects, capacitance, ultrasound, vision, and hybrid detection [31]. As detection-coil structures, dual-frequency detection, system-parameter monitoring, array imaging, and data-driven methods continue to develop, the coordination among sensing structures, detection signals, and algorithms requires further synthesis. In particular, research directions such as power-decoupled detection, sensorless frequency tracking, the combination of magnetic induction tomography with machine learning, and the coordinated design of detection structures and algorithms have expanded the research scope of existing FOD technology. These advances also indicate that the performance results reported in different papers must be understood in relation to their foreign-object types, positions, power levels, detection thresholds, and experimental platforms. Numerical values obtained under different conditions should not be ranked directly.

Accordingly, this paper systematically reviews FOD technology for electric vehicle wireless charging based on the main sensing mechanisms and information sources and establishes the above five-category technical framework. On this basis, this paper discusses the detection principles, sensing structures, main detection parameters, and signal-processing methods of each type of method. The analysis focuses on common issues such as spatial detection blind zones, excitation frequency and material response, MO/LO discrimination, and robustness under misalignment and load variation. The experimental conditions and results reported in the literature are also used to compare the applicable characteristics and limitations of different methods and to summarize development directions such as power decoupling, sensorless frequency tracking, coordinated optimization of hardware and algorithms, and multimodal sensing. The remainder of this paper is organized as follows. Section 2 discusses the interaction mechanisms between foreign objects and electromagnetic fields and the safety requirements. Section 3 reviews detection-coil methods. Section 4 discusses sensorless and non-electromagnetic external sensing methods. Section 5 discusses machine learning, signal processing, coordinated design, and multimodal fusion and imaging methods. Section 6 summarizes common issues and future directions. Section 7 presents the conclusions. To systematically organize existing studies, this paper classifies the relevant FOD methods into five categories based on the sensing mechanisms and detection implementation methods. The overall classification framework is shown in Figure 2.

Figure 2: Overall framework of FOD technologies



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2. Interaction Mechanisms Between Foreign Objects and Electromagnetic Fields and Safety Requirements

Electric vehicle wireless power transfer (EV-WPT) systems mainly rely on a high-frequency alternating magnetic field between the transmitting and receiving coils for energy coupling. When a foreign object enters the open-air gap between the two coils, its physical interaction with the electromagnetic field not only changes the local field distribution but also causes deviations in the overall electrical parameters of the system. Because the dielectric and conductive properties of MOs and LOs are completely different, clarifying their different physical response mechanisms is the theoretical basis for subsequently developing and evaluating various FOD technologies.

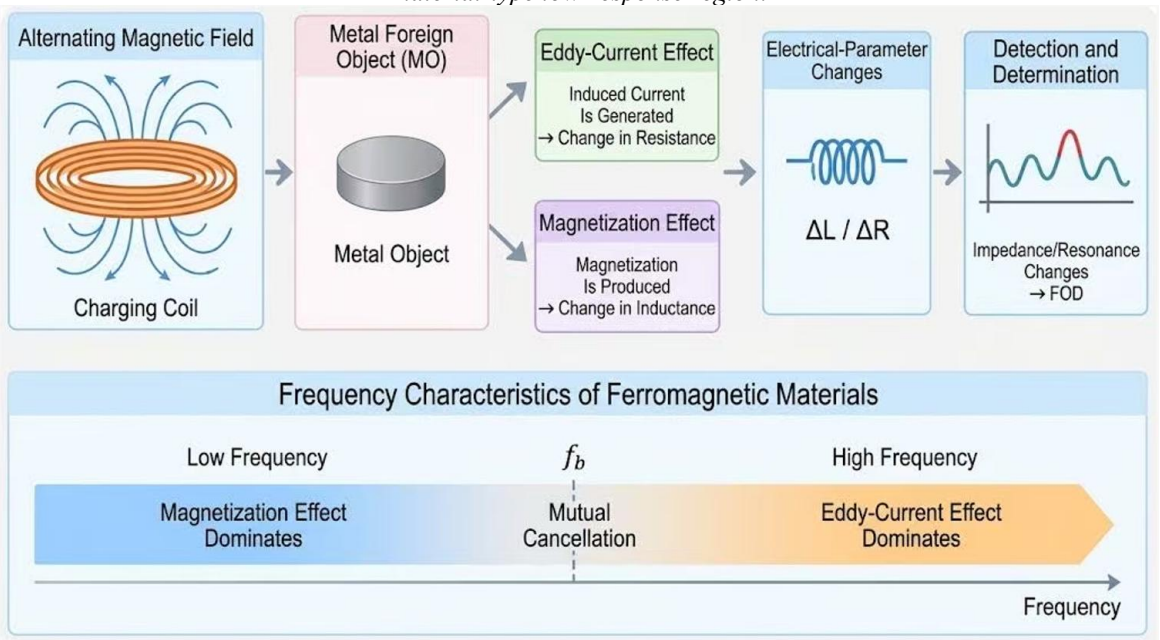
2.1 Interaction Between Metal Objects and High-Frequency Magnetic Fields

The influence of an MO on a wireless charging system is mainly related to eddy-current loss and magnetization effects. A conductive metal produces eddy currents in an alternating magnetic field. Eddy-current loss may increase the temperature of the foreign object and change the equivalent parameters of the detection coil or power coil through electromagnetic back-reaction. Ferromagnetic materials also exhibit a significant magnetization response. Therefore, a foreign object may change parameters such as the inductance, resistance, impedance, resonant frequency, or quality factor of the detection coil [10, 11].

For ferromagnetic materials, existing studies have indicated that a low-response region caused by the mutual cancellation of different electromagnetic effects may occur near a particular excitation frequency. Reference [11] discussed complementary high- and low-frequency detection strategies for this phenomenon. This paper refers to this low-response phenomenon, which is jointly determined by material parameters and excitation frequency, as a “frequency-domain material blind zone” and distinguishes it from a “spatial-domain structural blind zone” caused by the geometry of the detection coil and the spatial magnetic-field distribution.

Existing studies have shown that the electromagnetic parameters of a foreign-object material affect detection sensitivity and that a low-response region may form under particular combinations of material, excitation frequency, and detection structure [9]. Its physical origin is completely different from that of the “spatial-domain structural blind zone” (i.e., spatial blind zone) caused by dead zones in the coil geometry and magnetic-field distribution, which is discussed in Section 3. The former must be eliminated by optimization in the excitation-frequency dimension, whereas the latter must be resolved by improving the spatial topology of the detection coil. The electromagnetic response of an MO and the frequency-domain material-type low-response region that may occur under particular conditions are shown in Figure 3.

Figure 3: Schematic diagram of the electromagnetic response of an MO and the formation of a frequency-domain material-type low-response region.



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After a foreign object enters an alternating magnetic-field region, its electromagnetic response changes the observable parameters of the detection coil or system. For ferromagnetic materials, the eddy-current and magnetization responses may exhibit different characteristics as frequency changes. Under particular conditions, these responses may cancel each other and reduce the detection signal. It must be emphasized that the specific blind-zone frequency depends on the material, size, coil structure, and detection-circuit parameters. A specific frequency reported in one study cannot be directly generalized to all systems.

2.2 Interaction Between Living Objects and Electromagnetic Fields

The human body and other biological tissues have electrical conductivity and dielectric properties that differ from those of metals. When a living target enters the detection area, its tissue may change the electrical state of the detection network through dielectric polarization, parasitic capacitive coupling, and dielectric loss. Based on these response differences, capacitive detection and combined inductive-capacitive detection can provide observable information for living object detection (LOD) and can complement electromagnetic sensing methods that mainly target metal object detection (MOD) [32, 33, 21, 30].

The specific influence of a living target on a measured quantity depends on the sensor structure, compensation network, excitation frequency, relative position of the target and electrode or coil, and equivalent tissue parameters. Therefore, phenomena such as an increase or decrease in resonant frequency or a change in quality factor observed in a particular study should be interpreted only under that study's detection structure and test conditions and should not be treated as fixed criteria for all LOD schemes.

A distinction must also be made between "living object detection" and "human electromagnetic exposure safety assessment." LOD concerns whether a system can identify a living target in the detection area and trigger the corresponding control. Electromagnetic exposure assessment concerns whether the applicable safety requirements are satisfied when a person is in a specific electromagnetic-field environment. The result of the former cannot replace field-strength measurement, exposure assessment, or compliance verification for the latter.

2.3 Influence of Foreign Objects on System Parameters

In addition to causing local electromagnetic-field distortion, a foreign object directly affects the overall observable quantities at the WPT system level. The power absorption and field distortion caused by an MO lead to reduced transmission efficiency, fluctuations in the primary-coil input current, equivalent-impedance deviation, and resonant-frequency drift [18-20].

Sensorless FOD technology uses abnormal changes in these overall parameters to infer the presence of a foreign object indirectly. Its main advantage is that no additional dedicated detection array is required, which greatly reduces hardware cost. However, this mechanism faces a major challenge: receiving-side misalignment, nonlinear changes in battery load, and input-voltage fluctuations during the actual operation of an EV-WPT system can cause very similar parameter deviations. Therefore, a detection scheme based on system parameters must establish robust criteria that can effectively decouple foreign-object disturbance from normal operating fluctuations.

2.4 Safety Standards and Detection Requirements

The safe operation of an electric vehicle wireless charging system involves the local temperature rise caused by MOs and the electromagnetic exposure risk faced by living targets. Standards such as SAE J2954, IEC 61980, ISO 19363, and GB/T 38775 provide a basis for the safety design and technical evaluation of wireless charging systems. The scopes of application and test requirements differ among these standards, and the specific provisions shall be based on the official text of the corresponding standard.

In terms of detection targets, FOD mainly includes metal object detection (MOD) and living object detection (LOD). The former mainly concerns the changes in electromagnetic characteristics and thermal safety risks caused by MOs, whereas the latter focuses on identifying living targets and assessing the related safety risks. Actual detection must also consider detection sensitivity, area-coverage capability, and the influence of receiving-side misalignment and load variation on the detection results.

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In summary, standard requirements and the experimental performance of specific detection methods should be treated separately. To avoid treating experimental conditions from a study as standard provisions, Table 1 summarizes the relationship between relevant standards and FOD. When specific test objects, dimensions, and temperature limits are involved, the official text of the corresponding standard shall prevail.

Table 1: Comparison of safety standards.

Standard	Main content involved	Relationship with FOD
SAE J2954	Technical requirements related to electric vehicle wireless charging	Provides a reference basis for the safety design and performance evaluation of wireless charging systems
IEC 61980	Requirements related to electric vehicle wireless power transfer systems	Provides a normative basis for the safety design and technical evaluation of wireless charging systems
ISO 19363	Requirements related to electric vehicle wireless power transfer systems	Provides a basis for the technical requirements and safety evaluation of related systems
GB/T 38775	Chinese national standards related to electric vehicle wireless charging	Provides a basis for the technical requirements and evaluation of wireless charging systems in China

It should be noted that the scopes of application and specific test limits differ among standards. Therefore, when evaluating the sensitivity, area-coverage capability, and stability under complex operating conditions of a specific detection method, the actual experimental conditions must be considered together with the official text of the relevant standard.

2.5 Comparison of the Principles and Performance of Different FOD Methods

Existing FOD methods differ significantly in detection mechanism, detectable foreign-object type, detection distance, misalignment tolerance, and system complexity. To facilitate a horizontal comparison of different technical routes, Table 2 summarizes the detection principle, applicable foreign objects, typical detection area, misalignment tolerance, pre-charging detection capability, and main advantages and disadvantages.

Table 2: Comparison of the principles and applicable characteristics of the main FOD technical routes.

Technical route	Main sensing quantity and core principle	MO/LO detection	Pre-charging detection	Key performance	Main advantages	Main limitations	Key references
Passive detection coil (blind-zone elimination type)	Induced voltage/differential signal; reuses the 85 kHz power magnetic field to reduce detection blind zones	MO: suitable; LO: generally weak or requires combination with another method	Generally limited by the power field	Reduces detection blind zones through detection-coil structure design	Relatively simple structure and easy integration with the power system	Depends on the power field; spatial blind zones and power-field disturbance still require attention	[3-8, 15, 35]
Passive detection coil (power-decoupled type)	Differential signal; orthogonal structure or four-quadrant flux-coupling ratio (4Q-FCR) normalized criterion	MO: suitable; LO: generally weak or requires combination with another method	Generally limited by the power field	Reduces the influence of power coupling through structural design or normalized criteria	Can reduce the influence of power-field coupling	Coil spatial layout and hardware calibration are relatively complex	[34, 36]
Active excitation - frequency optimization	Impedance / inductance / resonance / amplitude and phase; independent MHz excitation with	MO: suitable; LO: possible in some schemes	Available	Sensitivity of 92.89% at 6.22 MHz	Allows independent excitation and provides relatively rich features	Specific calibration is required for the target foreign-object type	[9, 37]

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Technical route	Main sensing quantity and core principle	MO/LO detection	Pre-charging detection	Key performance	Main advantages	Main limitations	Key references
	frequency optimized for the material						
Active excitation - dual-frequency complementarity	Impedance/resonance; low-frequency magnetization measurement and high-frequency eddy-current measurement to compensate for the low-response frequency of ferromagnetic materials	MO: suitable; LO: depends on the specific scheme	Available	Uses response differences among frequency bands to assist MO identification	Uses complementary responses among different frequency bands	Dual-frequency and dual-excitation hardware architecture is relatively complex	[10, 11]
Active excitation - integrated MO/LO detection	Impedance/amplitude and phase/Q; time-division multiplexing (TDM) + frequency-swept resonance (FSR), Q, or sweep-frequency slope for joint discrimination	MO/LO: both detectable	Available	Uses detection signals or quality-factor changes for foreign object detection and classification	Allows independent excitation and supports MO/LO classification	May misclassify extremely small foreign objects or overlapping Q values	[13, 14, 32, 33]
Active excitation - strong decoupling	Mutual-inductance change; a quadrupolar alternating-polarity structure reduces coupling between the detection and power coils	MO: suitable; LO: no clear validation found	Available	Reduces power-channel interference through the detection-coil structure and magnetic-coupling characteristics	Can reduce the influence of the power coil on the detection signal	Requires high manufacturing accuracy and spatial alignment accuracy	[15, 16, 34]
Sensorless method	Current / efficiency / impedance / frequency; monitors native electrical parameters of the system and combines current-peak detection with frequency tracking	MO: suitable; LO: depends on the features	Depends on the system	Uses changes in system current, efficiency, or resonant frequency for foreign object monitoring	Requires little additional hardware	Relatively low sensitivity and susceptible to sudden load changes and misalignment disturbance	[18, 19]
Non-electromagnetic external sensing	Vision / radar / thermal / ultrasonic sensing; visual anomaly detection, motion features, and support vector machine (SVM) classification	MO: can cover some nonmetallic objects; LO: some methods are suitable	Available	Can provide environmental sensing information independent of the main power parameters	Does not depend on power-field observation	Susceptible to lighting, severe weather, and underbody occlusion	[22-24, 39]
Machine-learning and signal-processing enhancement	Features/time-series data; machine learning (ML) is used for classification and design optimization in combination with magnetic induction tomography (MIT), ensemble learning, and α-β filtering	Depends on the input sensor	Depends on the sensor	Machine-learning classification and signal processing can enhance detection	Can be used for classification, filtering, and optimization	Data dependence, generalization, and edge-deployment issues	[25-27]
Coordinated design optimization	Magnetic field/detection signal; joint design of magnetic-field uniformity and detection sensitivity	MO/LO: amplitude-phase discrimination can be combined	Available	Uniformity increased by 54%; baseline remains robust within 10 cm of misalignment	Improves detection conditions at the source and can be coordinated	Requires reconstruction of the main transmitting coil and joint hardware-software design	[28, 38]

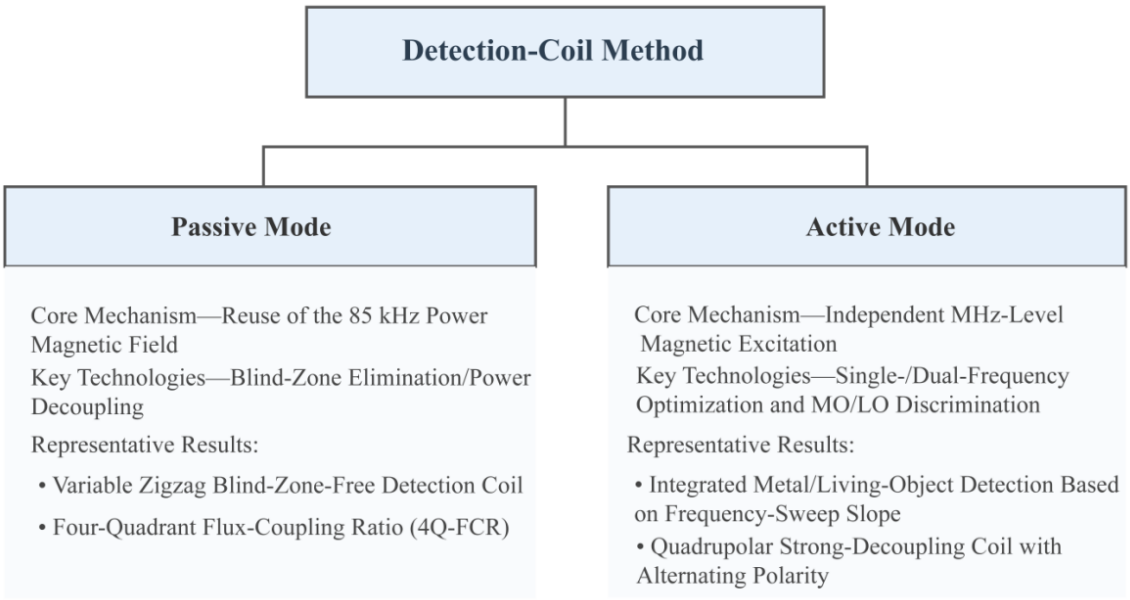
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Technical route	Main sensing quantity and core principle	MO/LO detection	Pre-charging detection	Key performance	Main advantages	Main limitations	Key references
					with algorithms		
Multimodal fusion and imaging	Multiple physical quantities/spatial array; electromagnetic and capacitive time-division multiplexing or magnetic induction tomography imaging	MO/LO: both can be covered	Depends on the sensing structure	Fuses multisource sensing information for foreign object detection, classification, or localization	Provides rich information and can support localization and classification	High hardware cost and complex synchronization and multimodal fusion	[29, 30, 32, 33]

3. Detection-Coil Methods

A detection-coil method places a dedicated detection structure near the power coil and senses a foreign object through changes in observable quantities such as induced voltage, self-inductance, mutual inductance, impedance, or resonance. Existing studies include passive schemes that use the power field for sensing and active schemes that use independent excitation signals. The main technical branches of detection-coil methods and their basic detection approaches are shown in Figure 4.

Figure 4: Main technical branches of detection-coil methods



3.1 Passive Detection Coils

A passive detection coil directly uses the power magnetic field generated during operation of the wireless charging system for sensing. When no foreign object is present, the detection coil can form a relatively stable baseline through reverse series connection, a symmetrical structure, or a differential structure. When an MO enters the detection area, the local magnetic field and the equivalent parameters of the detection coil change, and the presence of the foreign object is determined from changes in the differential voltage or other electrical parameters [3-7, 34-36]. Because this approach does not require additional independent high-frequency excitation, its structure is relatively simple and it has good potential for system integration. However, the detection process usually depends on the power field, and the detection features are therefore affected by the power-transfer state and spatial magnetic-field distribution.

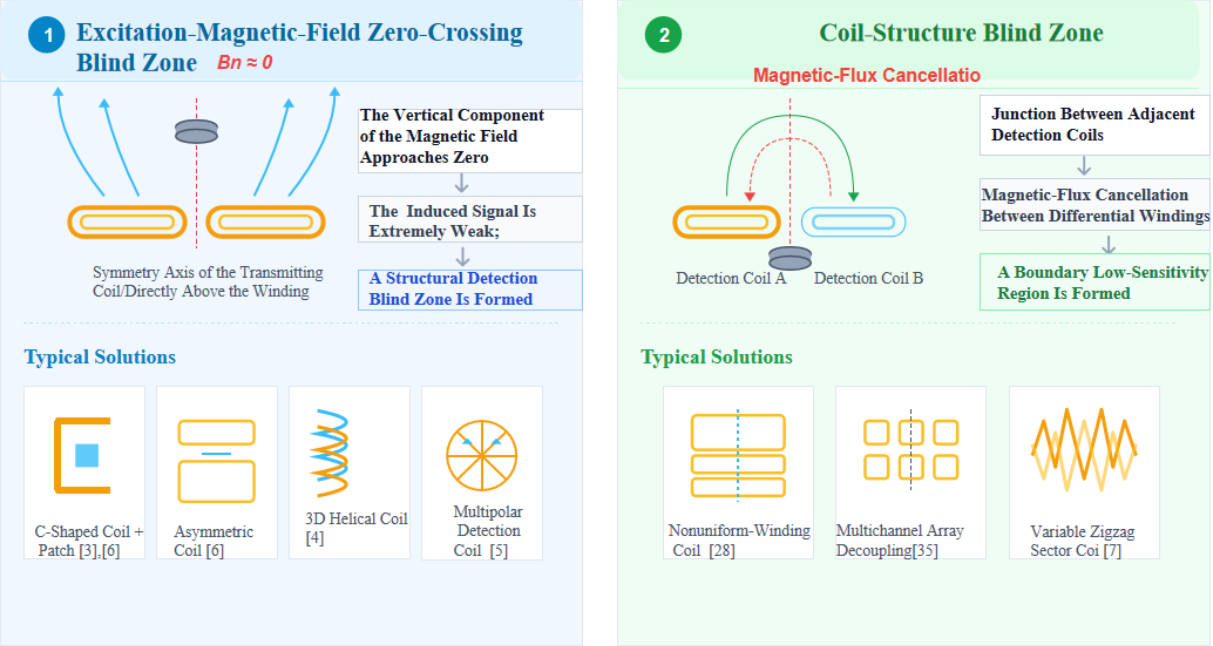
1) Spatial-domain structural blind zones

Passive detection may be affected by the spatial magnetic-field distribution and detection-coil topology, creating local low-sensitivity regions. References [3-7] improved spatial coverage through C-shaped/patch

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structures, asymmetric coils, three-dimensional helical coils, multipolar detection coils, and variable-structure coils, respectively. It should be noted that the specific sensitivity, test positions, and thresholds belong to the experimental conditions of the individual studies. This paper cites only their original results and does not rank them across studies. The two types of spatial-domain structural blind zones that may occur in passive detection coils are shown in Figure 5.

Figure 5: Two types of spatial-domain structural blind zones faced by passive detection coils



2) Power decoupling

Changes in the input, voltage, load, and misalignment of the power link may change the baseline of the detection signal. Reference [36] used an orthogonal arrangement of the detection and power coils to reduce coupling. Reference [34] further discussed detection under power disturbance using normalized observable quantities and adaptive criteria. The common purpose of these methods is to reduce the influence of the power-transfer state on the FOD criterion, but the specific degree of decoupling should be evaluated under the respective experimental conditions.

3.2 Actively Excited Detection Coils

An actively excited detection coil uses an independent excitation signal so that the detection process is relatively separated from the main power field in frequency or time sequence. Changes in electromagnetic parameters caused by an MO may be represented by changes in coil inductance, impedance, output voltage, or resonant frequency. Compared with a passive scheme, an important characteristic is that pre-charging detection can be performed under certain conditions, but additional excitation and detection circuits are required. Figure 6 shows the basic process by which an actively excited detection coil obtains a foreign-object response through an excitation signal and the principle of detection using resonance detuning or impedance changes.

1) Single-frequency excitation and frequency optimization

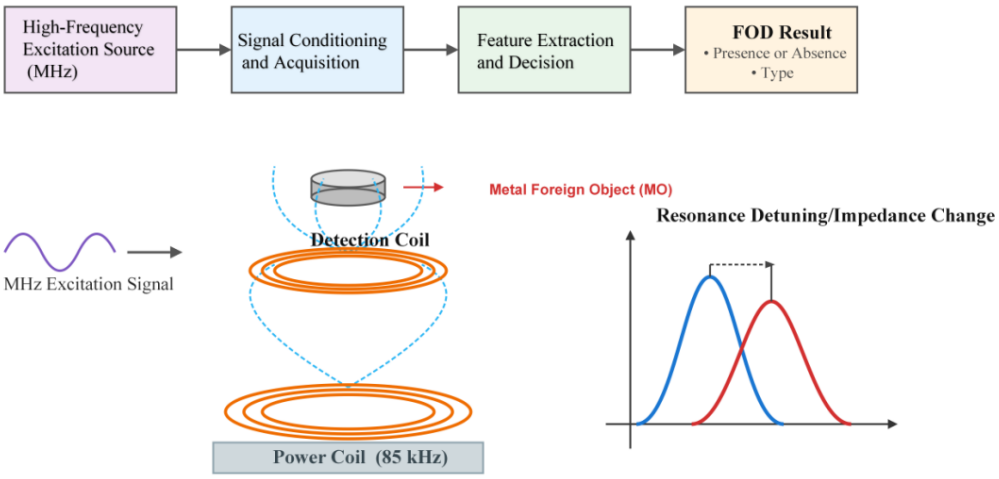
Reference [9] investigated the influence of excitation frequency on the sensitivity of MO detection and reported optimized results for a specific coin and coil structure under specific experimental conditions. Reference [8] used a laminated coil and high-frequency excitation for detection. These results show that excitation frequency is an important parameter in detection-coil design, but a specific optimal frequency cannot be generalized without considering the foreign-object material and size, coil structure, and detection circuit.

2) Dual-frequency detection and material identification

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Reference [10] used dual-frequency excitation to investigate the responses of different materials. Reference [11] further used high- and low-frequency detection features to identify material types. It should be clarified that ferrite is not a metal, but because its magnetization effect still interacts with a magnetic field, it should be treated separately as a nonmetallic interferent in FOD.

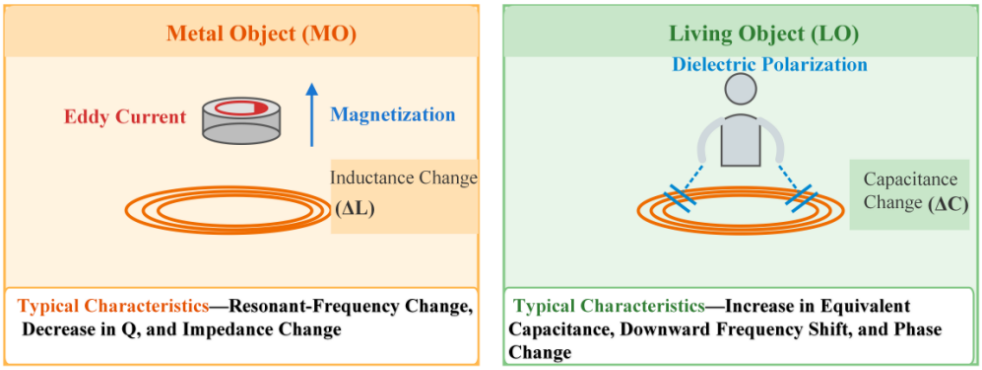
Figure 6: Signal-processing flow of an actively excited detection coil and the principles of resonance-detuning/impedance-change detection



3) Dual-mode architecture

Reference [12] used a dual-mode structure of "presence detection + confirmation and identification" to obtain complementary features through different operating modes. Reference [32] further investigated the discrimination between metal and living foreign objects. Because the sign conventions and equivalent models of different detection circuits may differ, this paper uses only the directions of frequency, amplitude, or phase changes explicitly reported in the literature and does not generalize them as universal rules for all FOD circuits. Figure 7 compares the main physical effects, related parameter changes, and typical signal characteristics of MOs and LOs.

Figure 7: Comparison of the physical effects, dominant parameter changes, and typical signal characteristics of MOs and Los



Feature/Classification	MO (Metal Object)	LO (Living Object)
Main Effect	Eddy Current + Magnetization	Dielectric Polarization
Dominant Parameter Change	nductance (ΔL) and Resistance (ΔR)	Capacitance (ΔC)
Typical Signal Characteristics	Frequency Increase/Decrease in Q	Downward Frequency Shift/Phase Change
Common Detection Methods	Inductive Method, Dual-Frequency Method, and Q-Factor Method	Capacitive Method, Dual-Mode Architecture, and Phase Method

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4) Self-resonant and decoupled structures

Reference [13] investigated a self-resonant detection coil for detecting metal and living objects. Reference [16] investigated a quadrupolar excitation-sensing detection coil to reduce the coupling between the detection and power coils. The coupling coefficients, detection dimensions, and misalignment ranges reported in the related papers are results from their respective experimental platforms, and the original test conditions should be retained when these results are used.

5) Detection circuits and signal processing

Reference [14] investigated an improved voltage-decision circuit. Reference [17] used changes in the frequency and amplitude of a self-excitation oscillation signal for detection. Reference [37] used interlayer parasitic capacitance to implement inductance-capacitance (LC) parallel resonance without a tuning capacitor and used a microcontroller unit + direct digital synthesis (MCU+DDS) to adaptively search for the excitation frequency and counter parameter drift.

3.3 Evaluation of Detection Sensitivity and Detection-Coil Design

In evaluating detection-coil methods, detection sensitivity depends not only on the magnitude of the electrical-parameter changes caused by a foreign object but also on the spatial distribution of the detection coil, the material and size of the foreign object, its position, the excitation frequency, power-field coupling, and the detection circuit. Therefore, "sensitivity" in different studies cannot be treated simply as the same indicator for horizontal ranking. In particular, studies use different foreign-object types and sizes, detection positions, power levels, decision thresholds, and definitions of sensitivity. This paper treats the quantitative results in the literature as reported results under their respective experimental conditions and focuses on the design variables that affect sensitivity.

1) Quality factor and circuit-parameter changes

The quality factor Q represents the loss and energy-storage characteristics of a detection coil and its resonant branch and can therefore serve as one circuit representation of foreign-object disturbance. Sun et al. proposed a shared MO/LO detection method based on the quality factor Q of a detection coil and combined it with voltage-phase changes to distinguish foreign-object types. On their 3.3 kW experimental platform, the quality factor of the detection coil was 67.9 when no foreign object was present. After an aluminum sheet, iron sheet, and beef sample were placed at specific experimental positions, Q decreased by 50.5%, 80.8%, and 69.9%, respectively. These results show that Q responds significantly to different types of foreign objects and that phase features can provide further information for MO/LO classification. However, these percentages correspond to the specific coil structure, foreign-object samples, and experimental conditions of that study and cannot be used directly as a uniform sensitivity indicator for all FOD systems [33].

2) Detection-coil structure and spatial sensitivity

The geometry of a detection coil directly determines its spatial magnetic-field distribution and the coupling strength of foreign-object disturbance. Existing studies have improved detection-area coverage through DD coils, multilayer coils, three-dimensional helical coils, and strip multipolar detection coils and have optimized their structures to address low-response regions that may occur in conventional detection schemes [3-8]. Therefore, detection-coil design should not examine only the response magnitude at one optimum position. It should also consider the minimum response within the entire effective detection area, responses at edges or corners, and response fluctuations caused by changes in foreign-object position. From an evaluation perspective, "blind-zone-free" should not be understood simply as completely identical sensitivity at all positions. A more reasonable evaluation method is to specify the detection area, foreign-object size, and decision threshold and report the detection results or minimum response at different positions, thereby determining whether the detection coil has a low-sensitivity region of practical significance. This approach also avoids directly ranking local optimum results obtained for different coil structures under different experimental conditions.

3) Influence of excitation frequency on detection sensitivity

For an actively excited detection coil, the excitation frequency simultaneously affects coil impedance, resonance characteristics, parasitic parameters, and the electromagnetic response produced by a foreign object.

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Frequency is therefore an important design variable affecting sensitivity. Sun et al. investigated frequency optimization and compared detection performance at different excitation frequencies on a 3.3 kW experimental platform. For a one-yuan coin, the detection sensitivities at the center and corner positions of the detection coil reached 92.89% and 40.16%, respectively, under 6.22 MHz excitation. Compared with 1 MHz excitation, these values increased by 22.13% and 23.19%, respectively. The study also reported that the highest overall detection sensitivity reached 97.56% [9].

These results show that increasing the excitation frequency does not necessarily produce a continuous increase in sensitivity. The actual optimum frequency must be selected according to the parameters of the detection coil and the target foreign object. Therefore, a paper should avoid directly stating a "best frequency" applicable to all FOD systems and should instead describe the optimum frequency as an optimization result under specific coil, foreign-object, and experimental conditions.

4) Dual-frequency excitation and differences in material response

At a single excitation frequency, differences in the electrical conductivity, magnetic permeability, and frequency-dependent electromagnetic response of materials may produce different detection signals. To address this issue, Xia et al. investigated MO detection using dual-frequency sinusoidal pulse-width modulation (SPWM) excitation and improved detection robustness by using complementary responses at different frequencies [10]. Zhao et al. further used high- and low-frequency detection features to identify metal types and discussed the low-response phenomenon caused by the combined action of material parameters and excitation frequency [11]. The significance of this type of method is not simply the addition of another detection frequency. Instead, response differences at different frequencies provide complementary information and reduce the risk of a low response during single-frequency detection.

It should be emphasized that Reference [11] discussed a frequency-dependent low-response phenomenon under specific materials, coil structures, and experimental conditions. Therefore, this paper describes it as a "frequency-domain material low response" and does not generalize it as a universally fixed "frequency blind zone." This wording distinguishes it from a spatial low-sensitivity region caused by the spatial field distribution of a coil and avoids overgeneralizing a specific experimental result.

5) Coordinated design of detection-coil parameters and excitation frequency

The inductance, parasitic capacitance, and resistance of a detection coil jointly determine its impedance-frequency characteristics. The coil structure and excitation frequency are therefore a coupled design problem. Lin et al. proposed a double-layer FOD detection coil and a method for selecting its excitation frequency. Inductance-capacitance (LC) parallel-resonance characteristics were formed by configuring the coil-routing parameters, and an MCU+DDS system was used to search for a more suitable excitation frequency. Under the experimental conditions of the studied coil and a 15 mm copper disc, the detection-signal amplitude ratio was 1.038 at 3 MHz and 1.258 at 3.5 MHz, corresponding to an increase of approximately 21% [37]. This result shows that frequency optimization can amplify the detection-signal change caused by a foreign object. However, because the result depends on the specific coil parameters and target foreign object, 3.5 MHz cannot be considered a universally optimal operating frequency.

6) Sensitivity evaluation should shift from a single-point indicator to a joint spatial-operating-condition evaluation

Based on the above studies, FOD detection sensitivity is better evaluated through a joint framework of "spatial coverage + target foreign object + system operating condition + decision criterion." For subsequent literature comparisons, at least the following information should be recorded: 1) the material and size of the target foreign object; 2) the position of the foreign object in the detection area; 3) the structure and dimensions of the detection coil; 4) the excitation frequency and whether it has been optimized; 5) the wireless charging power, load, and misalignment conditions; 6) the specific definition of sensitivity and the decision threshold; 7) whether MOs and LOs can be distinguished; and 8) the spatial range and sample size used in the experimental validation. Reference [38] further showed, through detection-sensitivity modeling and improvement, that sensitivity evaluation must consider the specific detection structure and operating conditions and should not be compared separately from the experimental conditions.

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Therefore, this paper does not arrange single sensitivity values from different studies into a unified ranking. Instead, the studies are summarized in terms of "detection principle - key parameters - experimental conditions - reported results - main limitations." This evaluation method retains the quantitative results in existing studies and avoids inappropriate performance conclusions caused by differences in experimental conditions.

4. Sensorless and Non-Electromagnetic External Sensing Methods

4.1 Sensorless Methods

A sensorless method indirectly determines the presence of a foreign object by monitoring existing electrical parameters of the wireless charging system. Reference [18] investigated changes in efficiency. Reference [20] used the current-amplitude/phase characteristics of the charging coil for state determination. Reference [19] proposed a current-peak + resonant-frequency tracking scheme. A nonlinear negative-resistance circuit keeps the resonant tank fully resonant and automatically tracks frequency. The equivalent series resistance of an MO reduces the current peak, whereas the arrival of the secondary coil causes a resonant-frequency shift. Combining these two criteria distinguishes foreign-object detection from in-position detection. The scheme complies with GB/T 38775 and can detect coin-sized MOs. Reference [21] investigated a capacitive power transfer (CPT) system. Its impedance characteristics are not equivalent to those of magnetically coupled WPT. Therefore, this paper treats it only as related work on a "sensorless method + classifier" and does not directly use its performance for comparison with magnetically coupled WPT.

A common problem with sensorless methods is that system-state changes and foreign-object disturbances may act on the measured parameters at the same time. For example, changes in mutual inductance, load variation, and the entry of a foreign object may all change current, efficiency, or impedance. Robust criteria must therefore be designed for the specific system.

4.2 Non-Electromagnetic External Sensing Methods

Vision, millimeter-wave radar, thermal, and ultrasonic methods obtain foreign-object information from outside the power field and can therefore extend detection to some nonmetallic objects. References [22] and [23] investigated FOD based on visual information. Reference [24] investigated living object detection using motion features. Thermal and ultrasonic methods can also be used as non-electromagnetic sensing routes, but their detection capability is affected by the environment, occlusion, response time, and sensor installation position.

In addition, thermal detection using infrared thermal imaging and ultrasonic detection have received extensive attention as important non-electromagnetic external sensing routes for FOD. Thermal detection identifies anomalies from Joule heating and surface-temperature gradients caused by the eddy-current effect in an MO under a high-frequency alternating magnetic field. For example, Sonnenberg et al. proposed a foreign object detection and living object protection system that combines real-time thermal-camera analysis. This method is independent of the main power system for wireless charging and provides relatively high detection accuracy [39]. Ultrasonic detection emits acoustic waves and analyzes changes in the time domain and amplitude of echoes to sense foreign objects and organisms in blind zones. It has a certain detection capability for nonmetallic living objects.

The main advantage of non-electromagnetic external sensing is that it obtains foreign-object information from outside the power field and can cover some nonmetallic objects. Its limitations include the sensitivity of vision to lighting and occlusion, the limited ability of radar to detect stationary targets, and the cost, installation, and environmental-adaptability issues introduced by external sensors. Specific performance should be evaluated according to the corresponding experimental conditions. Figure 8 compares the main advantages and limitations of visual sensing and millimeter-wave radar in non-electromagnetic external sensing.

Sensorless system-parameter monitoring methods and non-electromagnetic external sensing methods differ in sensing mechanism, information source, and technical advantages and disadvantages. Their main characteristics are shown in Figure 9.

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Figure 8: Comparison of the advantages and limitations of visual sensing and millimeter-wave radar in non-electromagnetic external sensing schemes

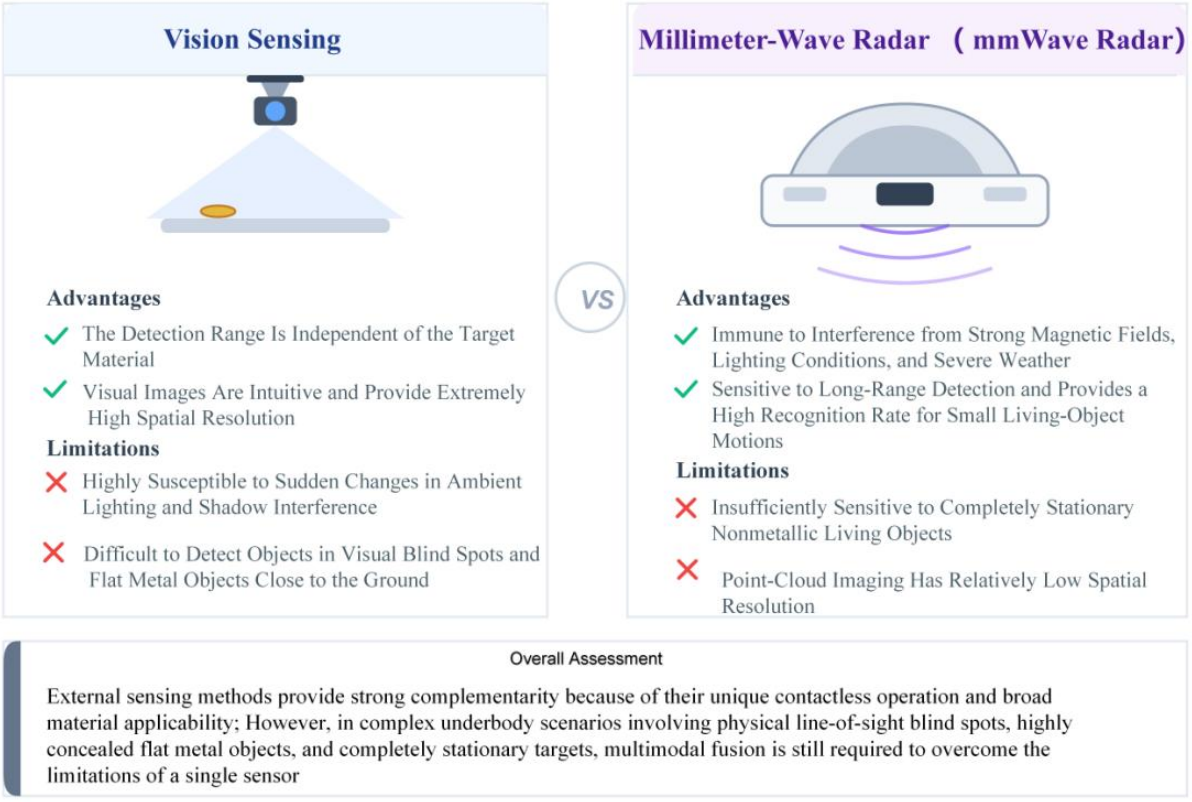
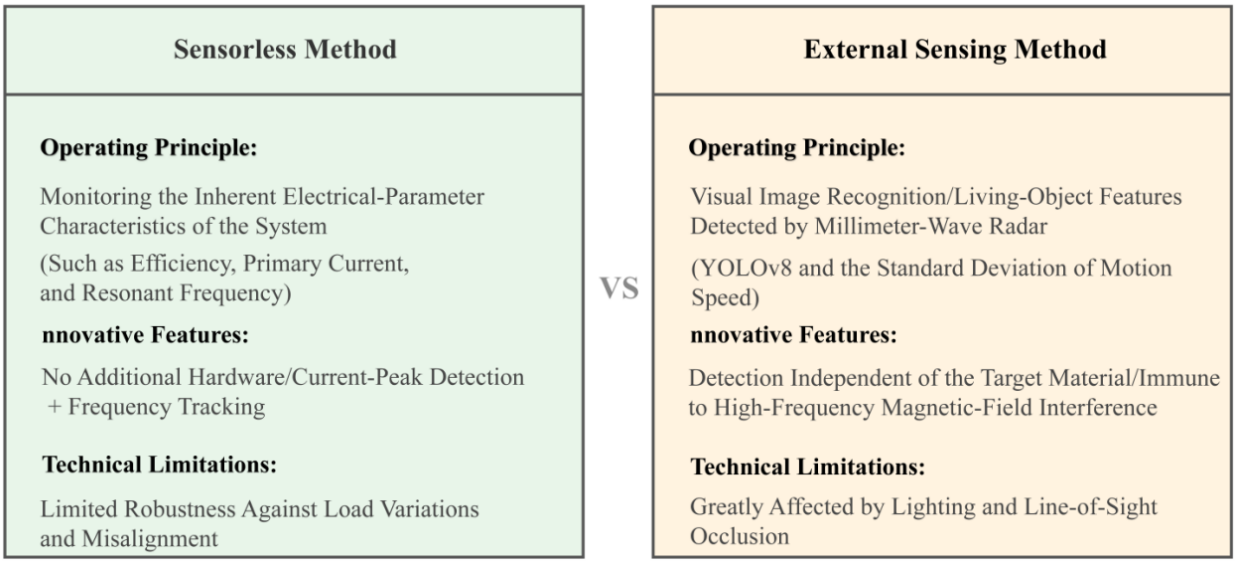


Figure 9: Comparison of the main mechanisms and technical advantages and disadvantages of sensorless system-parameter monitoring and non-electromagnetic external sensing methods

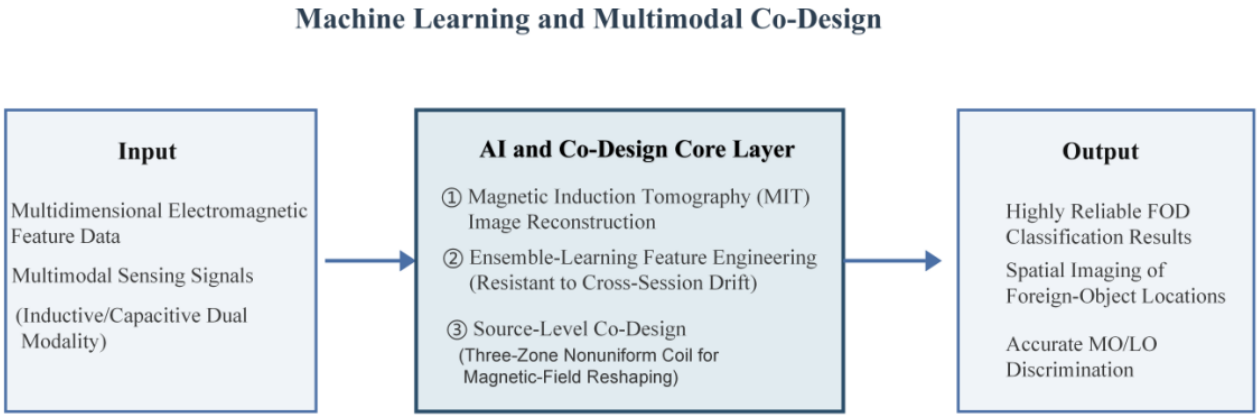


5. Machine-Learning, Signal-Processing, and Coordinated-Design Enhancement Methods, and Multimodal Imaging

Machine learning, signal processing, and multimodal information fusion can enhance an FOD system through feature extraction, target identification, and the coordination of multisource information. The overall framework is shown in Figure 10.

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Figure 10: Schematic framework of FOD algorithms based on machine learning, signal processing, and multimodal coordination



5.1 Machine-Learning, Signal-Processing, and Coordinated-Design Enhancement Methods

Machine learning and classical signal processing mainly serve as an algorithmic enhancement layer for FOD and are used for classification, filtering, feature extraction, or design optimization. Reference [25] used a 4×4 planar magnetic induction tomography (MIT) array + ensemble learning. Anti-drift feature engineering was applied to address the engineering problem of "high offline accuracy and real-time cross-session drift," and the real-time accuracy reached 98%. Reference [26] used a feedforward neural-network surrogate model instead of a full electromagnetic scan to rapidly optimize the geometric parameters of a detection coil. Reference [27] introduced α-β filtering, a fixed-gain simplified form of Kalman filtering, into amplitude-phase signal processing and achieved filtering accuracy close to that of Kalman filtering with much less computation. Reference [28] proposed a coordinated design of magnetic-field uniformity and detection. A three-zone nonuniform winding was used for the transmitting coil to flatten the magnetic field, increasing magnetic-field uniformity by 54% and reducing the channel baseline dispersion from 9.2 V to 3.36 V. A joint decision based on two-dimensional amplitude-phase features was then used for MO/LO classification and was validated on a 7.7 kW platform. This represents a new approach that "optimizes detection conditions at the source." Although machine-learning and data-driven methods significantly improve classification accuracy, their high computational complexity and hardware overhead still impose demanding real-time requirements on in-vehicle edge-computing nodes.

In summary, machine learning, signal processing, and coordinated design do not function independently in FOD. Instead, they show a layer-by-layer enhancement relationship of "signal processing - feature extraction and classification - parameter optimization - hardware-algorithm coordination." Classical signal processing has low computational requirements and is easy to implement in real time. Machine learning can further extract nonlinear features from multidimensional detection data. Coordinated design improves detection conditions at the source through the detection coil and magnetic-field distribution. Future work should not focus only on increasing model complexity or classification accuracy. It should further consider joint optimization among the sensing structure, detection signal, and algorithmic model while accounting for data requirements, real-time performance, and the cost of in-vehicle edge deployment.

5.2 Multimodal Fusion and Imaging Methods

Multimodal FOD combines different physical sensing mechanisms to obtain complementary information and improve the system's ability to detect different types of foreign objects. For joint MO and LO detection, References [32] and [13] used dual-mode and self-resonant structures, respectively, to detect the two types of targets. Reference [33] simultaneously sensed MOs and LOs by using changes in the quality factor Q of a detection coil. On a 3.3 kW platform, Q was 67.9 when no foreign object was present and decreased to 33.4, 12.9, and 20.3 after an aluminum sheet, iron sheet, and beef sample were added, respectively. This indicates that different targets can produce distinguishable electrical-parameter responses.

The fusion of different physical sensing mechanisms can further improve target-identification capability. Reference [30] used time-division multiplexing to combine inductive MOD with capacitive LOD, allowing the two detection mechanisms to share a detection-coil array and achieve joint MO and LO detection with

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limited hardware. Compared with a single detection mechanism, a multimodal method uses complementary information to reduce identification difficulty caused by overlapping target responses. However, mode switching, signal coupling, and system control must also be considered.

In addition to multiphysics fusion, array-based detection can use spatial information for imaging. Reference [25] used a 4×4 planar magnetic induction tomography (MIT) array to obtain spatial magnetic responses and combined it with ensemble learning for foreign object detection and classification. The literature reported a real-time accuracy of 98%. This type of method uses multichannel spatial information to improve foreign-object identification. However, as the array scale increases, the number of hardware channels and the requirements for data processing and calibration also increase.

Overall, multimodal fusion and imaging methods are advancing FOD from single-physical-quantity detection toward the joint sensing of multiphysics and spatial information. Future work must balance detection sensitivity, spatial coverage, real-time performance, and system complexity and should further coordinate the sensing structure and algorithm.

6. Common Issues and Future Research Directions

The studies in the collected literature show that FOD involves spatial blind-zone suppression, frequency and circuit optimization, power-field decoupling, pre-charging detection, MO/LO discrimination, and multimodal information fusion. Different routes rest on different sensing bases and applicable conditions, and cannot be simply understood as one method replacing another.

1) Power decoupling and robust criteria

Detection-coil signals are easily affected by the power-transfer state. Coil topology, normalized features, or system-level compensation should therefore be used to reduce baseline changes caused by load and misalignment.

2) Sensorless detection and frequency tracking

Using existing power-electronic parameters for FOD can reduce additional hardware, but foreign objects, misalignment, and load variation may produce similar responses. Identifiable features and joint criteria therefore require further study.

3) Coordination of design and algorithms

Some studies have begun to consider detection-coil structure, magnetic-field uniformity, signal processing, and machine learning together. Future work should pay more attention to data coverage, cross-platform generalization, and edge-computing constraints and should not evaluate an algorithm only by the recognition rate on a single experimental platform.

4) Standardized evaluation

Existing papers differ greatly in the foreign-object dimensions, materials, positions, detection thresholds, power levels, and misalignment conditions used. Establishing unified test samples, spatial sampling methods, definitions of false and missed detections, and reporting specifications is an important basis for reliable horizontal comparison

5) Dynamic conditions, multiple foreign objects, and living-object safety validation

Existing studies still need to be extended to scenarios involving multiple foreign objects, moving targets, complex environments, and dynamic misalignment. For LO detection, the relationship between experiments using substitutes and actual biological safety requirements also requires further clarification.

7. Conclusions and Outlook

This paper systematically reviews FOD technology for electric vehicle wireless charging and classifies the related methods according to their main sensing mechanisms into detection-coil methods, sensorless system-parameter monitoring, non-electromagnetic external sensing, machine-learning and signal-processing enhancement, and multimodal fusion and imaging. Detection-coil methods remain an important technical route

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in both research and engineering implementation. Their research focuses include spatial blind-zone suppression, active excitation, frequency optimization, MO/LO discrimination, and power-field decoupling. Sensorless methods emphasize using existing system parameters to reduce additional hardware. External sensing methods based on vision, radar, thermal effects, and ultrasound provide information from outside the power field. Machine learning and classical signal processing mainly perform classification, filtering, and optimization. Multimodal methods further fuse different types of physical information to obtain richer detection results.

Several issues that still require particular attention can be identified from the existing literature. Unified testing and evaluation conditions are lacking across different studies. More rigorous validation of the relationship between the experimental substitutes used in living-object detection and actual safety requirements is required. Detection robustness under multiple foreign objects, dynamic foreign objects, and complex environments still has room for improvement. Sensorless methods must further resolve the identifiability of foreign-object disturbance and system-state changes. Machine-learning methods must also address data coverage, cross-platform generalization, and edge deployment. Future FOD development should proceed from a system-level perspective, jointly design the sensing structure, power electronics, signal processing, and safety strategy, and validate reliability under actual operating conditions through standardized experimental platforms.

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Conflicts of Interest

The authors declare no conflict of interest.

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