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Review

Smart Wireless Power Transfer: A Review of Integrating AI and Sensing for Next-Generation Robotic and IoT Systems

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Abstract

Wireless Power Transfer (WPT) has emerged as a critical enabler for autonomous systems, offering an alternative to battery replacements or manual charging. However, traditional WPT systems often suffer from limited flexibility, misalignment sensitivity, and inefficiencies in dynamic environments. This paper presents a conceptual and technical overview of a smart WPT system enhanced by Artificial Intelligence (AI) and sensing technologies. Building on a retractable coil design for mid-sized mobile robots, we explore how AI models and sensor feedback can be integrated to optimize alignment, safety, and energy delivery in real-time. We propose applications in mobile robotics, industrial inspection, and smart IoT networks, while also addressing challenges such as misalignment detection, adaptive control, and system integration.

Keywords: wireless power transfer; robotics; smart charging; smart sensing; artificial intelligence

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1. Introduction

In domains like mobile robotics [1], wearable electronics [2], and hazardous inspection zones [3] where wired solutions are impractical, wireless power transfer is becoming more and more important. Mobility and uptime are restricted by traditional systems, which frequently rely on heavy tethers or static charging stations. Recent developments in retractable WPT coils make it possible to transfer energy with compact geometry over a meter-scale distance [4], which makes it perfect for incorporation into autonomous robots. But despite these mechanical advancements, alignment sensitivity and a lack of conditional adaptability continue to be obstacles to energy efficiency.

One intriguing approach to overcoming these constraints is the incorporation of advanced sensing technologies and Artificial Intelligence (AI) into WPT systems. While sensors provide real-time feedback on coil alignment, environmental factors, and power transfer efficiency, artificial intelligence (AI) can offer predictive insights, autonomous decision-making, and continuous optimization [5]. A transition from passive to active wireless power systems that adjust to the actual conditions of mobile platforms is made possible by these technologies working together [6].

An important difficulty in contemporary robotics and the Internet of Things (IoT) is energy autonomy. Power availability continues to be a constraint on the increasing intelligence and capability of robots and sensor nodes [7]. Unlocking new levels of autonomy will need the introduction of intelligent WPT systems that can self-optimize, dynamically align, and react to the operating context [8]. For example, inspection robots operating in structurally hazardous or radioactive situations cannot depend on fixed charging docks or human-assisted recharging [9]. Similarly, scalable, hands-free energy replenishment is required for agricultural sensors spread across large fields [10].

However, problems including coil misalignment, gearbox inefficiencies, and a short operating range make it difficult for WPT to be widely used in dynamic situations. Promising answers are provided by recent advancements in AI and sensing technology. It is possible to detect misalignments,

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optimize transfer parameters dynamically, and predict device behaviour by integrating intelligence into WPT systems. This results in adaptive, smart power systems that are appropriate for next-generation applications [10].

Prior research on small and retractable WPT coils for mid-sized mobile robots is expanded upon in this paper [4]. It broadens the conversation on integrating AI and sensing to instill intelligence in these systems. This study examines the basic difficulties in traditional WPT systems, the functions of machine learning and sensing, and a potential use case for these technologies in autonomous systems of the future. In order to provide a thorough understanding of how WPT will develop into a really smart technology, practical use cases, experimental findings, and potential future research areas are also covered.

2. Fundamentals of WPT and Challenges

Wireless Power Transfer (WPT) refers to the transmission of electrical energy from a power source to an electrical load without physical connectors or wires. The most common methods include inductive coupling, magnetic resonant coupling, and capacitive coupling. Among these, inductive and magnetic resonant coupling are the most widely used for mid-range applications such as robotics, electric vehicles, and implantable medical devices [11].

Magnetic resonant coupling enhances energy transfer over greater distances (up to several meters) by tuning both transmitter and receiver coils to the same resonant frequency. This enables higher efficiency and better tolerance to spatial misalignment, making it suitable for mobile robotics and industrial applications. However, the performance still heavily depends on precise alignment and coil geometry. The following sections discuss about the variations of WPT technologies with two main categories which are; near-field and far-field WPTs.

2.1. Near-Field Wireless Power Transmissions

2.1.1. Inductive Coupling

The inductive coupling (IPT) operates on the principle of magnetic field induction between two coils. When an alternating current flows through the transmitter coil, it generates a time-varying magnetic field, which induces a voltage in the receiver coil. This method is efficient at short distances (typically less than 1 cm) and is used in wireless chargers for smartphones [12] and toothbrushes [13]. For example, an alternating current in a primary coil that is connected to the source of power can produce a varying magnetic field that induces a voltage across the terminals of a secondary coil at the receiver end. A source of power energizes a primary loop or track to which pickup coils may be magnetically attached.

Fundamentally, an IPT is composed of a coil of wire in proximity between those sides; namely transmitter and receiver. Primary and secondary coils are two distinct coils in this technique. This positioning technique is mainly to capture magnetic flux. As described by Ampere's and Faraday's laws, a voltage is induced in this particular coil. Also, inductive coupling can also be classified into two categories based on the direction of the flux flow relative to the charging surface: horizontal approach and vertical approach [14]. Relatively, the setup is similar to a transformer in general although with a much lower magnetic coupling. As in transformer design, a magnetic material such as ferrite is used to direct the magnetic flux and improve the coupling between the track and any pickups [15].

As stated in the name, IPT is an electromagnetic inductive and can be classified as a non-radiative charging power transmission. A copper coil (magnetic loop antenna) is used to create an oscillating magnetic field, which can create a current in one or more receiver antennas. If adequate capacitance is added so that the loops resonate at the same frequency, the amount of induced current in the receivers increases. This is called resonant inductive or magnetic resonance. It enables power transmission at greater distances between the transmitter and receiver sides, thus increasing efficiency.

Inductive coupling has been an important and popular technology due to its simplicity, convenience and safety reasons. Many modern devices have benefited from the utilization of this technique

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especially in the manufacturing of electronic devices. Therefore, it has been successfully commercialized into respective products including electric toothbrushes, charging pads for smartphones or laptops and medical implants, such power chargers adopted a fix positioning load receiver [16] . A few systems, such as electric toothbrush charging stands, work at 50 or 60 Hz so AC mains current is applied directly to the transmitter coil, but in most systems, an electronic oscillator generates a higher frequency AC which drives the coil, because transmission efficiency improves with frequency [17]. In other applications, the frequency varies between the range of 20-40kHz for a distance around of 10 cm.

In inductive coupling, the system efficiency would be progressively decreased when transmitter and receiver coils are being separated from each other. Moreover, the issue of misalignment between these two coils would result in a drop in the system performance. The best performance could be achieved when the charging point of the device and power receiving end device are close in proximity to each other or less than the coil diameter. The range can be in centimeters and the direction of the charging must have to be aligned [18].

Inductive charging typically induces eddy currents in metal, which can create sparking and arcing hazards. To address this issue, researchers have introduced a very thin electromagnetic shield positioned beneath the charging pad and above the receiving coil [19,20]. In [21], Low et al applied this technology to eliminate external metallic contacts on an electronic device by designing a high-efficiency wireless power transfer system using a class-E transmitter. They operated at a frequency of 134 kHz and delivered 295W of power with 75.7% efficiency, incorporating forced air cooling.

In [22], Vandevoorde et al proposed a system based on inductive charging, capable of transferring 20W of power over a distance of 1 cm with an efficiency of 80%. This system is well-suited for medical applications. The same paper also presents the key differences between low-power and high-power inductive links. MIT scientists (Jadidian et al) recently unveiled a wireless charging technology called MagMIMO [23], capable of charging devices from a distance of up to 30 cm. MagMIMO can detect the location of a phone and project a focused beam of energy towards it, even when the phone is placed inside a pocket.

2.1.2. Resonant Inductive Coupling

Resonant inductive coupling is also referred to as electro-dynamic [24] coupling or strongly coupled magnetic resonance [25]. For this technique, there is considerable interest in mid-range power transfer, particularly at distances between 0.5 m and 5 m (where $d < r < 10d$). The operating frequency generally spans from 10 kHz to 200 MHz. Systems employing two, three, or four coils have been used within this range [26]. The principle of resonant frequency is preferred because it reduces leakage, thereby enabling power transfer over greater distances.

To the classical mechanical resonance, the effect of magnetic resonance is analogous, under which a string when tuned to a certain tone can be excited to vibration by a faraway sound generator if there is a match between their resonance frequencies. Each resonant circuit involves a coil of wire connected to a capacitor, or a self-resonant coil or other resonator with internal capacitance. These two are tuned to resonate at the same resonant frequency. Energy can be transmitted efficiently from a source coil to a receiver coil with a minimal loss of energy to alternating current in a primary coil (connected to a source of power) generates a varying magnetic field that induces a voltage across the terminals of a secondary coil at the receiver end.

WPT can be classified into two-coil and four-coil structures based on the presence of impedance matching coils. The extra coils in four-coil structure are typically small, featuring either fewer turns (usually 1 or 2) or a more compact size. Their primary function is to not only fine-tune impedance but also to effectively isolate the source and load from the transmitting and receiving coils, respectively [27].

Kurs et aI. [28] developed a system which enables the interactions between two different objects very strong because of the combination of inductive coupling and resonance [18]. A detailed explanation of the magnetic resonance coupling method for power transfer within this range was provided by the MIT team. In the same paper, two identical helical copper coils (diameter = 25 cm)

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were implemented to transfer power to a 60 W light bulb over a distance of 2 m (four times the coil diameter) with an efficiency of 40%, using a resonant frequency of 9.9 MHz. Furthermore, the energy will be shifted back and forth between the magnetic field surrounding the coils and the electric field around the capacitor. The feasibility of constructing a receiver coil suitable for any portable device without compromising efficiency was discussed. It was also suggested that efficiency could be enhanced through the use of silver-plated coils and improved geometries of the resonant objects.

In [29], Imura et al discussed the relationship between frequency (ranging from 11 MHz to 17 MHz) and power efficiency was investigated through electromagnetic field analysis, focusing on various air gap lengths in a magnetic coupling resonance circuit. The study also examined the correlation between maximum efficiency and air gap length. Their findings indicate that two resonant frequencies were observed for air gaps of 49 cm and 80 cm, while one resonant frequency was noted for air gaps of 170 cm and 357 cm. The number of turns is one, and the radius is 150 mm.

The use of magnetic resonant coupling to power multiple receivers is reported in [30]. Cannon et al constructed an experiment with a large source coil that generated a signal at a frequency of 8.3 MHz, while multiple resonant coil receivers were created using lumped capacitors at the terminals to match the resonant frequency. Their analysis indicated that efficiency increased as the quality factor of the resonant coupling improved. The authors noted that adjusting the lumped capacitance at the receiver coil in relation to the source and surrounding components would pose a significant challenge for future work.

In [31], an experiment is described in which a laptop battery was removed and replaced with a battery charged through a magnetic resonant coupling system by Sample et al. The system demonstrated an efficiency of 50% for power transfer over a distance of 70 cm using a frequency of 7.65 MHz. Inductive power transfer technology is also proposed for power transfer within 5 m of distance by Park et al (a team of researchers from KAIST University) [32]. This system comprises a capacitor, inverter, rectifier, and load. Experimentally obtained maximum output powers and primary-coil-to-load-power efficiencies for 3, 4, and 5 m at 20 kHz were 1403, 471, 209 W, and 29%, 16%, 8%, respectively. A dipole coil with a ferrite core, designed with a long and slender form factor was employed to facilitate easy installation along ceilings or in room corners.

There are several advantages of implementing this technique compared to an inductive coupling specifically high efficiency, negligible radiation loss and it provides greater range and directional [33]. The disadvantage of resonant coupling theory is that at close ranges when the two resonant circuits are tightly coupled, the resonant frequency of the system is no longer constant but splits into two resonant peaks [34]. When this occurs, the maximum power transfer no longer occurs at the original resonant frequency and the oscillator frequency must be tuned to the new resonance peak [35].

2.1.3. Capacitive Coupling

Capacitive coupling is commonly known as electric coupling and makes use of electric fields for the transmission of power between two electrodes; an anode and cathode, forming a capacitance for the transfer of power [36]. The first public WPT demonstration to power a "commonplace" load was capacitive coupling to tube lighting by Tesla in 1891 [37]. Tesla demonstrated the setting and tubes standing between the plates of a large capacitor. Electromagnetic induction over a distance was demonstrated shortly thereafter (again by Tesla) and proved to be more versatile for wireless power applications. Eventually, these techniques evolved into wireless communications.

In this technique, the conjugate of inductive coupling, energy is transmitted by electric fields between electrodes between electrodes [38]. The two primary types of circuits used for capacitive coupling are (1) transverse or bipolar design, in which the receiving plates must always be aligned with the charging plates, and (2) longitudinal or unipolar design. The transmitter and receiver electrodes form a capacitor, with the intervening space as the dielectric [38]. In generating an alternating current to flow in the load circuit, an alternating voltage generated by the transmitter is applied to the transmitting plate, and the oscillating electric field induces an alternating potential on the receiver plate by electrostatic induction [36]. Increasing the power to be transmitted means to increase the

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frequency [36] the square of the voltage and the capacitance between plates. The capacitance between the plates is proportional to the area of the smaller plate while inversely proportional to the separation for a short distance of power transmission [39].

The capacitive coupling has several advantages over inductive coupling. While inductive coupling relies heavily upon ferrite cores which carry more mass, in capacitive coupling, the field is largely confined between the capacitor plates, reducing interference [40]. Moreover, the misalignment problem between transmitter and receiver is less critical [41]. However, capacitive coupling has only been feasible in a few low-power applications as the very high voltages on the electrodes required to transmit significant power can cause some safety issues [41] such as causing unpleasant side effects such as toxic ozone production. Also, due to dielectric polarization, the electric fields interact strongly with most materials including the human body in contrast to the magnetic field [40].

2.2. Far-Field Wireless Power Transmissions

2.2.1. Microwaves

As for microwave WPT systems (MWPT), its transmitter uses a vacuum device to convert the electrical energy to microwaves while the receiver uses a rectifier to convert the microwaves to direct current. A vacuum device converts alternating current (AC) into microwaves, and the resulting waves are emitted using a transmitting antenna. Using a rectifying device, the receiving antenna receives and converts the microwave energy into DC power output [42]. The pros are large transmission power, small transmission loss in the atmosphere, and one-to-many transmission. Its limitations are scattering loss, jamming communication equipment, low efficiency, and a large antenna is required. Microwaves WPT is being implemented for distributed satellite platforms, solar power stations, and deep space exploration.

One of the implementations is in the space applications. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered [43]. Power beaming by microwaves has the difficulty that, for most space applications, the required aperture sizes are very large due to diffraction limiting antenna directionality. For example, the 1978 NASA study of solar power satellites required a 1-kilometre-diameter transmitting antenna and a 10-kilometre-diameter receiving rectenna for a microwave beam at 2.45 GHz [44]. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the "thinned-array curse", it is not possible to make a narrower beam by combining the beams of several smaller satellites.

In 2010, Shinohara et al reported the use of directive microwaves for remotely powering electric vehicles (EVs) [45]. It is indicated that the reasons for the poor beam efficiency in the experiment are: (1) impedance changes caused by mutual coupling between the transmitting and receiving antennas, and (2) the oblique direction of microwave power towards the receiving antennas due to the short distance. In 2013, Shinohara et al proposed a system utilizing a roadside power transmitter directed towards a rectenna receiver to rectify 10 kW of power with an 80% conversion efficiency to energise electric vehicles (EVs) [46].

In [47], Erol-Kantarci et al proposed that mobile devices could be powered using high-frequency microwaves, such as 60 GHz in cellular networks. However, the feasibility of this approach requires further experimental evaluation. Huang et al [48] discussed how the seamless integration of MPT with wireless communication has opened up a new field known as wirelessly powered communications (WPC). Various research opportunities are presented by this new area, including simultaneous information and power transfer, WPC network architectures, and methods for ensuring safe and efficient WPC.

Omnidirectional RF broadcasting can also be employed to transfer power to portable devices for non-directive applications. In [49], it is discussed that if energy is transmitted in the same manner as radio signals, it can power ultra-high-frequency RFID tags within a 10 m operating range. However, multidirectional RF power transfer technology is typically constrained by low efficiency [50]. RF beams

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with power densities ranging from 20 to 200 µW/cm² can be used to wirelessly charge sensor networks through non-directive RF charging. In [51], Hong et al implemented a transmitter with 1.79 mW power to charge a 0.683 mW receiver for an ultra-low-power sensor platform, utilising a far-field method to achieve a data rate of 500 kbps. Similar work has also been conducted on wirelessly charging sensors with batteries in [52,53].

2.2.2. Lasers

The laser WPT systems use a photoelectric device to convert the electrical energy into the laser beam. The laser output is converted into electrical energy at the receiving end after free-space transmission [54]. The advantages of this type of WPT are long transmission distance, strong directivity, small transceiver antenna aperture, and concentrated energy. When it comes to transmission of a greater distance, Collimated monochromatic wavefront propagation allows a narrow beam cross-section area.

Thus, there will be a small or close to no reduction in power when the distance increases between the transmitter and receiver. Moreover, the design for laser beam WPT devices is usually in compact sizes. The solid-state lasers could fit into small products or machines. This technique also eliminates the possibility of radio-frequency interference to the existing radio communication. In terms of power transmission and access control, only targeted receivers would receive the power as it will focus on the laser beam targeted area.

The limitations are high energy consumption, sensitivity to obstacles, and low transmission efficiency. After long-distance transmission, the laser beam is still concentrated and suitable for powering long-distance mobile devices [55]. Laser WPT is commonly used for unmanned aerial vehicles, microsatellites, space probes, and wireless sensor networks.

In 2003, team of researcher from NASA successfully flies the first laser-powered aircraft. The laser is fired from the ground to the photovoltaic cells which power the propeller of the airborne aircraft [56]. Intel announced the implementation of Light Peak optical fibre technology, which utilizes vertical-cavity surface-emitting lasers (VCSELs) for personal computers in households. This technology enables the transmission and reception of 10 billion bits of data per second [57]. A group of researchers has developed a laser using fluorescent proteins extracted from jellyfish. This type of laser is biocompatible and can be implanted into living organisms [58].

However, there are several disadvantages to using this technique. First, laser radiation is hazardous. Low power levels can blind humans and other animals without a proper safety mechanism. High power levels can be killed through localised spot heating. Also, Conversion between electricity and light is limited. Photovoltaic cells achieve a maximum of 40% to 50% efficiency [59]. Depending on the atmospheric absorption, and absorption and scattering by clouds, fog or rain, the implementation of laser power transmission will not be the best option as it can cause up to 100% losses.

2.3. Challenges and Existing Implementations

There are two different approaches to wireless power delivery: microwave wireless power transfer (MWPT) and inductive coupling power transfer (IPT). Each has advantages and disadvantages of its own. In order to accomplish long-distance power transfer, MWPT uses wide aperture antennas to transmit energy via microwaves. MWPT confronts many difficulties, especially in space applications, even though it is ideally suited for uses like charging wireless micro-sensors and medical equipment in remote locations. Rectennas are difficult to install, and the energy they harvest is usually small, between a few milliwatts and microwatts.

In order to effectively transfer power over short to intermediate distances, IPT depends on magnetic resonance between coils. IPT is more compact and useful for applications involving mobile robots, consumer electronics, and electric vehicle charging because it does not require huge antennae like MWPT requires. For mid-range applications, IPT also provides more scalability and higher power transfer efficiency. Misalignment problems and power attenuation at longer distances, however, are its limitations. In conclusion, IPT is more appropriate for situations needing higher efficiency

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and moderate-range power transmission, whereas MWPT is beneficial for long-range, low-power applications.

Regarding the near-field WPT, CPT transmits power by means of electric fields that exist between capacitor plates. IPT is ideally suited for applications that need moderate to high power, such industrial automation and electric car charging, because it often offers higher power transfer efficiency, frequently surpassing 90% under ideal circumstances. On the other hand, CPT is usually less effective because of restricted capacitance and dielectric losses, which makes it more suited for low-to-moderate power applications, such as tiny electronic devices and biomedical implants.

The sensitivity of these approaches to alignment and distance is one of their main distinctions. For IPT to function at its best, coil alignment must be exact, and efficiency decreases with increasing separation. Resonant coupling methods, however, can aid in increasing its range. However, when the distance between capacitor plates widens, CPT loses a lot of efficiency even if it is less susceptible to misalignment. IPT is more complicated to apply since it requires carefully thought-out coil arrangements and resonant circuits, while CPT is lighter, simpler, and easier to incorporate, especially in wearable and small devices.

In terms of safety and interference, IPT produces powerful magnetic fields that, while safe for human exposure, can interfere with adjacent electronic devices by causing electromagnetic interference (EMI). Although CPT produces less electromagnetic interference (EMI), it exposes people to stronger electric fields, which may be dangerous in high-power applications. All things considered, IPT is the preferable option for applications requiring greater efficiency and power handling capabilities, whereas CPT is more appropriate for low-power, lightweight situations where compact design is crucial. Specific needs including power level, efficiency, safety, and application limitations determine which of these two technologies is best.

The high energy consumption and obstacle sensitivity of laser WPT (LPT) make it unsuitable for use in this kind of project. Unlike IPT, LPT uses a laser beam to send power to a photovoltaic receiver, which transforms the laser energy into electrical power, over vast distances. Unlike IPT, which is limited to short-range applications, LPT is capable of transferring power over several kilometers, making it an attractive solution for space-based power transmission, high-altitude drones, and remote sensing applications.

LPT, however, presents a unique set of difficulties. Because of inefficiencies in optical transmission and photovoltaic conversion, laser energy conversion efficiency to electrical power is typically lower than IPT. High-power laser beams can be harmful to human eyes and the environment, thus safety is also a top priority. To avoid unintentional exposure, accurate alignment and controlled routes are necessary. Additionally, meteorological factors like dust, fog, or rain can have an impact on LPT by scattering or absorbing the laser beam, which lowers dependability and efficiency.

All things considered, IPT is the best option for applications needing great efficiency across short to intermediate distances, like industrial automation systems, mobile robots, and wireless charging of electric cars. LPT, on the other hand, works better in situations involving long-distance power transfer, particularly where conventional power delivery techniques or physical wire are not feasible. The decision between IPT and Laser WPT is influenced by a number of variables, including safety concerns, environmental issues, efficiency, and distance. Table 1 shows the summary of the WPT technologies performances.

Table 1. Summary of WPT technologies performance [60].

WPT Technology	Max. Distance	Max. Efficiency	Power Transferred
Inductive Coupling (IPT)	7 m [61]	98% [62]	20 kW [63]
Resonant Inductive Coupling (RIPT)	3 m [64]	85% [65]	25 kW [66]
Capacitive Coupling (CPT)	0.3 m [67]	90% [67]	2.4 kW [67]
Microwaves (MWPT)	1600 m [68]	62% [69]	30.4 kW [68]
Lasers (LPT)	1000 m [70]	14% [71]	8 kW [70]

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Conventional WPT systems continue to confront many difficulties in spite of technological advancements. Coil misalignment is one of the primary problems [72]. Significant reductions in coupling efficiency can result from even small changes in the spatial orientation of the transmitter and receiver. The short transmission range of energy presents another difficulty. Without resonance, the inverse-cube relationship of the magnetic field causes the power transfer to rapidly decrease with distance [73]. Furthermore, for portable and small devices, the massive coil structures that are frequently needed for better coupling are impracticable [74]. Environmental elements that can further deteriorate performance and dependability include electromagnetic interference and adjacent metallic items [75].

As seen in [4], retractable coil mechanisms and flexible geometric designs have been offered as solutions to these problems. Although these solutions are more flexible and integrate better with mobile platforms, they are still unable to react quickly to environmental changes or misalignments. Thus, it is essential to incorporate sensing and AI into WPT systems. These systems can offer the intelligence required for predictive power management and real-time modifications, enabling effective, secure, and independent energy transfer in a range of challenging situations.

3. WPT for Mobile Robots

3.1. WPT for Unmanned Ground Vehicles (UGVs)

The comparative analysis presented in Table 2 highlights the diversity and evolution of WPT technologies applied to unmanned ground vehicles (UGVs) over recent years. The key performance indicators are energy efficiency, transfer distance, and transmitted power. They are vary significantly depending on the type of WPT technology and its intended operational context.

Table 2. Comparison of Recent WPT Implementations for Unmanned Ground Vehicles (UGVs).

Year / Ref.	WPT Technology	η (%)	d (m)	P_{out} (W)
2024 [74]	Resonant Inductive Coupling	47.14	1.0	109.7
2023 [76]	Inductive Power Transfer	85.0	0.05	500
2022 [77]	Magnetic Resonance Coupling (MCR-DWPT)	90.0	0.1	500–1000
2021 [78]	Inductive Coupling	80.0	0.02	200
2020 [79]	Capacitive Coupling	70.0	0.02	100
2020 [80]	Resonant Inductive Coupling	95.0	0.03	300
2019 [81]	Microwave Power Transfer	60.0	5.0	200

Out of all the techniques examined, magnetic resonance coupling systems have shown the highest energy efficiency. With a 95.0% efficiency at a comparatively short transfer distance of 0.03 m and a transmitted power of 300 W, Spark Connected's 2020 implementation [80] is ideally suited for high-power industrial applications where accurate alignment is possible. Similar to this, Zhang et al.'s 2022 review [77] demonstrates that magnetic coupling resonant-dynamic WPT (MCR-DWPT) has a great potential for medium-range high-power charging in mobile robotics. It can reliably supply 500–1000W at 0.1 m with up to 90% efficiency.

However, due to their resilience and simplicity of integration in commercial solutions, inductive coupling techniques continue to be widely used. The commercial system by WiBotic and Clearpath Robotics [78] operates at 80.0% efficiency with a power level of 200 W and tight alignment tolerances (0.02 m), but the Yildiriz et al. research from 2023 [76] reports 85.0% efficiency at 0.05 m and 500 W. For UGVs operating in controlled indoor or warehouse settings, where alignment accuracy is high and shorter distances are allowed, these solutions are perfect.

Despite being less studied, capacitive coupling has the benefits of cost effectiveness and small form factors. A bidirectional capacitive system that delivered 100 W at 70.0% efficiency over 0.02 m

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was demonstrated by Sarin et al. [79]. Its bidirectional capabilities and potential for lightweight applications make it a tempting contender for modular or swarm robots, even though its efficiency is inferior to that of inductive and resonant approaches.

Long-range charging is made possible by microwave power transfer (MPT), although usually at the expense of decreased energy efficiency. A system that achieved 60.0% efficiency across an impressive 5.0 m distance with 200 W output was demonstrated by Cao et al. [81]. The technology's long-range features make it appealing for field-deployed UGVs or situations where contactless, line-of-sight power delivery is required, despite the safety, beam alignment, and environmental interference issues it presents.

The 2024 study by Bin Hassan et al. [74] provides a unique use of resonant inductive coupling intended for robots that inspect tough settings. With a 109.7W output and a 47.14% efficiency over 1.0 m, this design balances medium power levels with long range, making it suitable for use cases where mechanical restrictions or dynamic misalignment are significant problems.

In conclusion, context should guide the selection of WPT technology for UGVs. For close-range industrial applications, high-efficiency magnetic resonance and inductive systems are recommended, whereas capacitive and microwave systems cater to certain operational limitations such form factor or extended range. For next-generation UGV platforms, hybrid solutions that incorporate the advantages of several WPT techniques may become more and more feasible as research advances.

3.2. *WPT for Unmanned Aerial Vehicles (UAVs)*

Table 3 presents a comparative summary of recent WPT implementations for unmanned aerial vehicles (UAVs), illustrating the diversity of WPT technologies, their trade-offs, and their application contexts. The evaluation spans various coupling mechanisms including inductive, capacitive, magnetic resonance, RF-based, and laser power transfer, each offering distinct performance characteristics across efficiency, transfer distance, and power delivery.

Table 3. Comparison of Recent WPT Implementations for Unmanned Aerial Vehicles (UAVs).

Year / Ref.	WPT Technology	η (%)	d (m)	P_{out} (W)
2024 [82]	Inductive and Capacitive Coupling	81.2	0.03	130
2024 [83]	Inductive Coupling	50.0	0.03	100
2024 [84]	Magnetic Resonance	70.0	0.05	200
2023 [85]	RF-Based WPT	60.0	10.0	50
2022 [86]	RF-Based WPT	65.0	15.0	60
2022 [87]	Laser Power Transfer	50.0	100.0	500
2018 [88]	Laser Power Transfer	55.0	120.0	600

Because of their reasonable efficiency at close proximities and ease of integration, short-range inductive and capacitive coupling devices continue to dominate lightweight UAV applications. Chai et al. [82] developed a combination inductive–capacitive WPT system that achieved 81.2% efficiency over 3 cm with a transmitted power of 130 W, making it the most significant recent implementation. This hybrid method preserves a compact coil design appropriate for on-board UAV deployment while enhancing power transfer stability.

On the other hand, Wu et al. [83] described a traditional inductive coupling system that operated within the same 3 cm range with 50% efficiency and 100 W output. The difference in performance between these two implementations emphasises how useful it is to combine different coupling techniques in order to get around issues like low coupling coefficients and coil misalignment.

The magnetic resonance coupling implementation by Tian [84] showed an excellent balance between efficiency and range, delivering 200 W at 70% efficiency over a 5 cm air gap. In semi-

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structured situations, this mid-range approach gives UAVs more flexibility during landing or hovering phases without imposing strict alignment constraints.

The wireless charging envelope is greatly expanded by RF-based WPT systems, such those created by Li et al. [86] and Gou et al. [85]. These devices used relatively low transmission power (50–60W) to achieve 60–65% efficiency at 10–15 m distances. The increased operational range and aerial mobility make them perfect for in-flight energy replenishment, especially for long-duration UAV missions, even though their efficiency is not as high as that of near-field techniques. A trend towards AI-augmented power management techniques is also indicated by the work by Li et al., which uses deep reinforcement learning to optimize UAV flight patterns for maximum energy gain.

Out of all the technologies surveyed, laser-based WPT systems had the longest effective transmission range. Systems capable of transmitting 500–600W across distances greater than 100 m were shown by Lahmeri et al. [87] and Ouyang et al. [88]. Their energy efficiency is still only 50–55%, though, and their practical deployment necessitates a precise line-of-sight, steady air, and safety measures because of the exposure to laser radiation. Laser WPT is a viable option for long-term high-altitude UAV operations and extensive deployment plans in spite of these difficulties.

In conclusion, mission profile, power requirements, flying time, and environmental restrictions should all be taken into account when selecting WPT technology for UAVs. For stationary or precise hovering applications, short-range inductive/capacitive and resonant systems work best; RF and laser-based solutions increase endurance and range at the expense of complexity and efficiency. More flexible and effective UAV energy solutions might soon be possible thanks to emerging hybrid systems and AI-assisted power management, which are predicted to close the gap between these strategies.

3.3. WPT for Autonomous Underwater Vehicles (AUVs)

Table 4 presents a comprehensive comparison of recent WPT technologies tailored for autonomous underwater vehicles (AUVs). The implementations vary in terms of coupling method, energy efficiency, transfer distance, and power delivery, highlighting the trade-offs and design considerations unique to underwater environments.

Table 4. Comparison of Recent WPT Implementations for Autonomous Underwater Vehicles (AUVs).

Year / Ref.	WPT Technology	η (%)	d (m)	P_{out} (W)
2024 [89]	Inductive Coupling	91.55	0.05	1080
2023 [90]	Inductive Coupling	88.0	0.04	1000
2023 [91]	Inductive Coupling	85.0	0.06	1200
2022 [92]	Inductive Coupling	80.0	0.03	51
2023 [93]	Inductive Coupling	75.0	0.02	500
2024 [94]	Capacitive Coupling	83.0	0.1	400
2018 [95]	Microwave Power Transfer	60.0	0.5	300

Due to its resilience in salty conditions, misalignment tolerance, and mature supporting hardware, inductive coupling continues to be the most widely used technique in underwater wireless power transfer. Using flexible magnetic couplers, Zhang et al.'s most recent development [89] showed a high-efficiency (91.55%) WPT system that could deliver more than 1 kW at a distance of 5 cm. This concept addresses docking concerns while ensuring dependable power transfer by facilitating mechanical flexibility to various AUV hull geometries.

Similarly, Wen et al. [90] achieved 88% efficiency over 4cm by using tiny planar magnetic couplers to increase gearbox stability. The scalability of inductive solutions across different vehicle types is demonstrated by Lyu et al.'s platform [91], which supports heterogeneous AUVs and achieves 85% efficiency at 6 cm.

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Chen et al. [92] investigated bidirectional inductive converters on the lower end of the power scale, emphasizing system integration above maximal power throughput. Their method is perfect for lightweight AUVs or sensor platforms with low power requirements because it achieved 80% efficiency at a modest 51 W output over 3 cm.

According to Yang et al. [93], metal hull constructions have the potential to drastically alter magnetic fields and lower WPT efficiency. They found that at 2 cm, 75% efficiency was achieved. This emphasizes that when incorporating WPT systems into metallic AUVs, compensatory magnetic design or shielding techniques are required.

Mahdi et al. [94] introduced the capacitive coupling technique, which is a noteworthy substitute. Their design and review case reached an efficiency of 83% at a power level of 400 W at 10 cm. Capacitive devices are more sensitive to seawater conductivity and need exact control over dielectric spacing, although being typically smaller and maybe less expensive. Nonetheless, this study's encouraging results point to a growing interest in capacitive WPT for soft-bodied or flexible underwater devices.

However, despite offering longer transfer lengths (0.5 m), microwave power transmission, like the system created by Song et al. [95] has lower efficiency (60%) and may present safety and regulatory issues. In torpedo-style AUVs or other situations where non-contact, medium-range energy distribution is preferred above peak efficiency, microwave WPT, despite its lower efficiency, can be useful.

All things considered, the examined literature shows that inductive coupling is still the best option for underwater WPT because of its ability to balance efficiency, dependability, and versatility. Nevertheless, microwave-based and capacitive approaches continue to gain popularity and provide special advantages for particular use cases. It is anticipated that future developments will concentrate on hybrid coupling techniques, enhanced coil geometries, and adaptive control algorithms to get around alignment and environmental limitations and eventually enable longer-duration and more autonomous underwater missions.

4. Role of Sensing in WPT Systems

In order to convert WPT systems from passive energy transmitters into intelligent, adaptable platforms, sensing technologies are essential. Real-time data about the surroundings and the relative positions of coils can be obtained by integrating sensors into the wireless power framework. This allows the system to respond dynamically in order to preserve the best possible energy transfer. Alignment correction and adaptive tuning are made easier by the ability of magnetic field sensors, Hall effect sensors, and IMUs to detect variations in coil orientation and distance. Environmental sensors can track variables that may impact energy transfer, such as temperature, vibration, or surrounding obstructions [96].

Transmitter and receiver coil alignment is frequently evaluated using magnetic field sensors. By analyzing the changes in field strength and orientation that these sensors pick up, misalignments or variations in coil separation can be deduced. By monitoring the movement and orientation changes of mobile receivers, Inertial Measurement Units (IMUs) help WPT systems account for mechanical motion. In order to improve safety and control while in operation, optical or camera-based sensing systems can provide visual input for alignment and obstacle identification. Mobile platforms can be visually tracked using LiDAR and camera-based systems, which enables accurate spatial coordination between Tx and Rx units. Furthermore, sensorless approaches such as monitoring input impedance or reflected power which can provide low-cost alternatives for detecting coil displacement or the presence of foreign objects [97].

Dedicated hardware is not necessary for sensing in certain sophisticated configurations. The presence of foreign objects or receiver misalignment can be inferred using sensorless detection techniques including tracking changes in input impedance or examining the coil's electromagnetic response. This is particularly helpful in embedded or restricted systems where it might not be feasible to add physical sensors.

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WPT systems can use this sensor data to track the quality of energy transfer, identify irregularities, and even forecast possible breakdowns or dangerous situations. These features are crucial for enabling intelligent, self-sufficient power distribution in practical settings, especially those where dependability and security are critical. WPT systems can continue to operate effectively in dynamic environments by integrating real-time sensing, which results in longer runtimes, safer power delivery, and less manual intervention.

5. AI-Enhanced Control and Optimization

WPT systems are transformed by artificial intelligence (AI), which gives them the ability to decipher complicated sensor data, make judgements on their own, and continuously improve performance. Predictive maintenance, adaptive tuning, and real-time control are made possible by the use of AI into WPTs. Those are all essential for implementing WPT in circumstances that are unpredictable and dynamic. AI provides strong tools for increasing the autonomy and effectiveness of WPT systems, especially machine learning and deep learning. AI models are able to undertake predictive maintenance, dynamically modify gearbox characteristics, and learn the best coil placements. Over time, reinforcement learning algorithms can adjust to coil misalignment and educate the system to maximize power delivery while minimizing energy waste [98].

Using past sensor data, machine learning algorithms can be trained to identify the best alignment patterns between transmitter and reception coils. Convolutional neural networks (CNNs), for instance, can reduce misalignment and improve coupling efficiency by analyzing field maps or visual inputs to establish optimal orientation. For anticipatory adjustments, recurrent models such as Long Short-Term Memory (LSTM) can forecast mobile receiver movement patterns. AI-enabled real-time control systems can also adjust load impedance and resonance frequencies in response to positional and environmental feedback [99]. By rewarding configurations that produce high power transfer and penalizing those that do not, reinforcement learning can also be used to continuously improve the behaviour of the system.

As demonstrated by architectures like Mask R-CNN, deep learning models have also been applied to resonant beam charging applications to identify and follow target devices in crowded surroundings. These methods give WPT systems the ability to precisely localize and focus energy delivery, which is particularly helpful in situations involving several devices or in settings where positional changes occur frequently. Applications like autonomous robotics, medical implants, and drone charging stations, where mobility, dependability, and accuracy are crucial and benefit greatly from these characteristics.

AI is also capable of supporting impedance matching and dynamic frequency adjustment in response to external inputs. It can predict changes, lower energy losses, and modify energy production in response to sensor inputs. WPT systems may become more robust and effective because to these predictive and adaptive features, especially in robotic and IoT applications where low downtime and continuous operation are essential.

6. Application Scenarios

There are numerous uses for integrating AI and sensing into WPT systems in a variety of fields. Such solutions allow mobile inspection robots to operate continuously in dangerous or challenging-to-reach environments. These robots have a longer operational range and time since they can wirelessly recharge while in the field rather than having to go back to a stationary charging base. For deployment in distant or dangerous locations, including nuclear decommissioning or search and rescue operations, smart WPT systems can facilitate autonomous recharging without human supervision [100].

Smart WPT systems enable the scalable deployment of sensor nodes across wide regions in the context of IoT sensor networks. For example, sensors used in precision agriculture that track crop health, weather, and soil moisture need dependable power sources in order to function independently. Energy may be delivered by intelligent WPT systems without causing environmental disturbance or needing maintenance. These technologies are also advantageous for wearable electronics. Wireless

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charging is a convenient way to fuel gadgets like fitness trackers, health monitors, and augmented reality glasses. AI and sensors provide adaptive alignment, which guarantees safe and efficient power transfer even when the wearer moves [101].

AI-guided docking stations with WPT technology offer contactless, autonomous charging for aerial drones. This is particularly useful for delivery or surveillance drones that must fly over large areas on short notice. The docking procedure becomes more effective with intelligent control and sensing, lowering the possibility of misalignment and downtime. AI-assisted docking stations with WPT systems that recognize and track drones in flight can be used by drone-based delivery platforms to enable smooth mid-mission recharging. These examples show how the scalability, autonomy, and operational longevity of contemporary gadgets are greatly increased by combining WPT with AI and sensing. The following are another examples of implementation scenarios for different fields:

- Mobile Inspection Robots: Wirelessly powered machines that operate continuously in industrial or nuclear sites without the need for human interaction.
- IoT Sensor Networks: Long-term power supply for dispersed sensors in agricultural or smart city applications.
- Wearable electronics: Dynamically positioned, safe, and adaptable energy transfer to body-worn devices.

Table 5 shows showcases a broad spectrum of strategies for integrating sensing technologies into WPT systems. This demonstrate a strong shift toward highly integrated and application-specific implementations. Kim et al. [101] explores batteryless, implantable electronics for physiological monitoring. This work exemplifies the merging of biomedical sensing with ultra-low power inductive WPT, delivering real-time physiological data through embedded sensing and edge processing. Its contribution lies in enabling continuous operation for medical implants, highlighting the importance of ultra-compact design and bio-compatibility.

The relevance of environmental and circuit-level sensing in stabilizing WPT systems in urban electric power IoT applications is also highlighted by He et al. [102]. The authors demonstrate how adaptive control algorithms may sustain effective energy delivery in spite of urban electromagnetic noise and fluctuating power demands by optimizing circuit parameters based on real-time sensor data. One viable approach to scalable IoT power solutions is the use of sensor feedback as a tuning input.

A more network-centric innovation was presented in 2023 by Li et al. [103] with their IRS-based technique. Intelligent Reflective Surfaces (IRS) are included into WPT architecture to optimize and reroute electromagnetic waves for energy and sensor purposes. In complicated radio frequency situations where direct line-of-sight isn't always possible, this method is especially helpful. Beamforming and phase shift optimization together represents a major breakthrough in intelligent, adaptable infrastructure.

Yang et al. [104] investigate RF beamforming as well while designing a radar and WPT system that works together. Their combined usage of antennas for tracking and energy transfer is made possible by their radar-based sensing. This strategy strikes a balance between power delivery and positional awareness, but it might work best in high-frequency applications like automated guided vehicles or industrial robotics that have centralized control infrastructure.

By addressing wireless power in distributed sensor networks, Huda et al. [105] expand the perspective in 2022. This study offers a thorough overview of the various applications of sensing data, including power scheduling, system diagnostics, and wider network coordination, in addition to alignment and power tuning. It presents sensing as a crucial architectural layer for WPT-reliant IoT systems, in addition to being a technical enabler.

The integration of the IoT into mobile robotic platforms is rapidly transforming how robots perceive, act, and interact within distributed environments. Table 6 provides a cross-sectional overview of recent research efforts focused on various dimensions of IoT for mobile robots, including architectural frameworks, connectivity strategies, and intelligent coordination.

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Table 5. Comparison of recent works on smart sensing in wireless power transfer (WPT) systems.

Work	Sensing Strategy	WPT Method	AI/Signal Processing Use and Key Contributions
He et al. (2024) [102]	Environmental and circuit-level parameter sensing	Magnetic coupling	Circuit optimization using real-time sensing; enhanced stability and energy efficiency in urban networks
Kim et al. (2024) [101]	Bio-integrated physiological sensing	Wireless bio-compatible inductive coupling	Microcontroller-based logic for real-time signal processing; enabled seamless low-power medical monitoring
Li et al. (2023) [103]	IRS-based sensing and RF shaping	IRS-aided RF beamforming	Joint optimization of IRS phase and beam control; improved joint sensing and energy transfer
Yang et al. (2022) [104]	Radar-based shared antenna sensing	RF beamforming (ISWPT)	Co-optimized beamforming for sensing and WPT; integrated radar-power system for precision and delivery
Huda et al. (2022) [105]	Sensor-node feedback	Hybrid inductive + RF WPT	ML-based power control and adaptive routing; emphasis on autonomy and node energy balancing

IRS = Intelligent Reflective Surface; ISWPT = Integrated Sensing and Wireless Power Transfer.

Table 6. Recent IoT-enabled mobile robotics studies.

Study	Type and Platform	Application	Key Features
Kabir et al. (2023) [106]	Review of IoRT architecture on mobile robot systems	General robotics	Layered protocol model, cybersecurity, and scalability insights
Zou et al. (2023) [107]	System-level design for networked robots	Surveillance UGVs	ZigBee + sub-GHz, edge/cloud hybrid, low-power communication
Aijaz (2021) [108]	Connectivity study on AMR fleets	Logistics robotics	Bluetooth mesh networking for infrastructure-less operation
Eze (2022) [109]	Survey on IoT-cloud integration	Agri/healthcare robots	Cloud offloading, privacy concerns, real-time responsiveness
Simoens et al. (2018) [110]	Foundational IoRT review	Distributed robotics	Reusable sensor data, modular deployment, autonomy in open systems

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One of the most thorough and current evaluations of IoT in mobile robots is the review by Kabir et al. [106]. It presents a tiered model that covers data analytics, network communication, application services, and device-level sensing. This paper lays a strong conceptual framework for future advancements by highlighting the significance of cybersecurity, scalability, and data integrity in the Internet of Robotic Things (IoRT).

The Zou et al. study [107], on the other hand, places more emphasis on real-world application. Using ZigBee and sub-GHz wireless communication protocols, their hybrid autonomous robotic system shows how lightweight, low-power networks can provide real-time, cooperative decision-making among several ground robots. This system's smooth integration of cloud and edge computing platforms exemplifies the distributed intelligence trend, in which data processing is spread dynamically according to bandwidth and latency limitations.

Aijaz [108] addresses infrastructure-less situations, one of the most realistic issues in IoT-enabled mobile robotics. This work paves the way for deployment in industrial environments where Wi-Fi or cellular connectivity is scarce or impractical by putting forth Bluetooth mesh networking as a scalable and affordable substitute for warehouse and logistics robots.

Another important topic covered in Eze's survey [109], which examines the current state of cloud-integrated IoT for a range of application domains, including precision agriculture, healthcare, and service robots, is cloud robotics. This study highlights the simultaneous difficulties of handling massive amounts of sensor data while preserving user privacy and quick reactions, particularly in situations when safety is a top priority.

Lastly, one of the first and most important reviews of the IoRT paradigm is presented by Simoens et al. [110]. Despite being a little older, it is still important since it articulates the benefits of networked robotic systems, such as the capacity to reuse common sensor data, deployment modularity, and the trend towards autonomous, adaptive behaviour in open spaces.

Overall, new research shows that developments in wireless protocols, edge/cloud computing, and embedded sensors are driving a rising convergence between IoT and mobile robotics. Real-time data fusion, security-by-design strategies, managing dynamic network topologies, and AI-enhanced autonomy in robotic platforms with limited resources are some of the major obstacles that lie ahead. As more and more robots are used in rural, industrial, and urban settings, the Internet of Things will play a bigger role in enabling and enhancing their capabilities.

In conclusion, these pieces highlight important developments in this specific sector. First of all, as gadgets work in less regulated situations, real-time sensing is becoming more and more necessary. Second, in order to produce reliable, effective, and scalable WPT, it is becoming more and more important to combine sensing with AI or signal processing, whether through beamforming, impedance feedback, or circuit optimization. Lastly, the architecture is being shaped by application specificity: sensing methodologies are contextually unique in everything from drone systems and reflecting wireless networks to biomedical implants and urban IoT. This specialization will probably be furthered in future research as generalizable frameworks for incorporating sensing into the heart of wireless power ecosystems are sought after.

7. Challenges and Future Directions

Even while AI-integrated WPT systems show promise, there are still a number of obstacles to overcome. The intricacy of combining hardware and software components is one of the main ones. Robust architectures and effective communication protocols are necessary for real-time coordination of sensors, computers, actuators, and power systems.

The processing overhead that AI algorithms create is another issue. Stronger models can provide better control and predictions, but they also demand more processing power, which may not be possible in devices with limited resources or that are lightweight. Lightweight or edge-AI models that can carry out necessary functions without taxing the hardware are therefore becoming more and more necessary.

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Safety and electromagnetic interference (EMI) are also important concerns. It is crucial to make sure that adjacent gadgets or human users are not negatively impacted by wireless energy transfer. To guarantee safe operation, energy delivery systems must be established in conjunction with shielding, intelligent scheduling, and safety standards.

Future studies may investigate edge-AI systems or neuromorphic computing to further lower latency and energy usage. Centralized or distributed AI controllers may also be useful for multi-agent systems that involve fleets of robots or sensors synchronizing their charging schedules. Furthermore, even more compact and effective WPT components could result from material and miniaturization improvements. Plug-and-play deployment across multiple platforms will be made possible by the design of modular, AI-ready coil systems. These technologies' convergence suggests that wireless power will be a fundamental component of truly autonomous, intelligent systems in the future, rather than only a convenience.

8. Conclusions

Combining wireless power transfer with artificial intelligence and sensing could make it a fundamental component of autonomous systems. AI-enabled WPT can improve autonomy, robustness, and flexibility in everything from smart IoT devices to inspection robots. Although the creation of small, retractable coil designs is a significant advancement, the full potential of WPT in next-generation applications can only be realized with the integration of intelligent control and feedback systems.

The basic ideas of WPT have been examined in this study, along with some of its drawbacks when used in dynamic or uncontrolled contexts. We have demonstrated that while sensors can supply the critical positional and environmental awareness, artificial intelligence (AI) can provide the computational intelligence to act on this data instantly. As a result, smart WPT systems have evolved into intelligent subsystems that can identify anomalies, optimize themselves, and manage their energy on their own.

The examples covered, such as wearable technology, dispersed IoT systems, and autonomous robots, demonstrate the adaptability and necessity of this strategy in contemporary technological ecosystems. Wireless energy distribution has enormous potential for scalability, adaptability, and efficiency, despite current integration, computing, and safety problems.

In future work, cooperation within the domains of robotics, materials science, embedded AI, and power electronics will be crucial in future research. A world where intelligent energy systems smoothly fuel our growingly connected and autonomous society will become a reality with continued advancements in these fields.

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