Computers, Materials & Continua

Tech Science Press

https://doi.org/10.32604/cmc.2026.082458

REVIEW

Inductive Wireless Power Transfer for Autonomous Underwater Vehicles: A Review of Coupler Design, Misalignment Challenges, and Eddy Current Loss Mitigation

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Received: 16 March 2026; Accepted: 22 May 2026; Published: 15 June 2026

ABSTRACT: Autonomous underwater vehicles (AUVs) play a crucial role in oceanographic research, monitoring the environment, and exploring resources in the ocean. Nevertheless, the operational efficiency of these devices is frequently constrained by the limited battery capacity and the requirement for charging while connected to a power source. Wireless power transfer (WPT) offers a non-contact alternative to conventional wet-mate electrical connectors, with inductive coupling receiving particular attention because of its relatively high efficiency, safety, and suitability for underwater charging over short transfer gaps. However, it is limited by the transfer distance, coil misalignment, coupler design constraints, and eddy-current losses caused by conductive seawater. This review assesses the current state of inductive coupling technology with respect to AUVs. It discusses recent advancements in energy sources for AUVs, current technologies for underwater WPT, magnetic coupler design, challenges related to misalignment and their impact on WPT systems, as well as various strategies to mitigate these challenges. The review also covers the analysis and mitigation of eddy current loss and highlights the technical and engineering challenges encountered in power delivery. In general, inductive WPT has significant potential for making AUV charging performance more successful. Experimental studies have indicated efficiencies exceeding 90% in certain controlled situations; however, the literature also demonstrates that performance frequently deteriorates under misalignment and inadequate underwater conditions, which remain major challenges to practical implementation.

KEYWORDS: AUVs; underwater wireless power transfer; inductive coupling; wireless charging; eddy current losses; misalignment sensitivity and coupler design

1 Introduction

Traditional wet plug-in connectors are widely employed in various industries, including offshore renewable energy, oil and gas, and undersea observatories, for underwater charging purposes [1]. These connectors, consisting of plugs and receptacles, facilitate power transfer under aquatic conditions [2]. However, these connectors present several drawbacks, such as the need for expensive and complex sealing mechanisms and the necessity for physical connections, which may pose challenges under fully submerged environments [3]. Additionally, direct electrical contact connectors face limitations that may render them unsuitable for sustained and real-time monitoring in standard cabled seafloor observatories [4].

For underwater energy supply, WPT is an appealing alternative to traditional wet plug-in connectors. It can extend AUV operational endurance and reduce detectability [5]. WPT technology can now transmit electrical power from one location to another without requiring direct physical electrical contact [6]. But it is essential to ensure that data can be sent back and forth between the main and secondary components of WPT systems without difficulty. This is what makes closed-loop control and system status monitoring possible. This will make underwater wireless charging more stable and efficient. Inductive power transfer (IPT) technology has also been used in electric vehicles (EVs) [7–11] trains, and AUVs [11], where it is a safer, more practical, and more efficient way to charge than conductive methods. When it comes to AUVs, inductive charging eliminates the need to take the vehicle out of the water to charge or replace the battery. This means that vehicle downtime is significantly reduced. This technology allows AUVs to dock and charge themselves with unmanned surface vessels (USVs), so people don't have to be present [12].

In the past few years, WPT devices designed solely for AUVs have become very popular, as they can make AUVs more durable and useful [13]. The implementation of WPT systems utilizing magnetic resonance coupling and adjustable ring-shaped magnetic couplers has demonstrated encouraging outcomes in enhancing charging power while preserving transmission efficiency [13,14]. Additionally, the idea to employ multiple-input and multiple-output (MIMO) WPT systems emerged as a viable strategy to markedly enhance the durability of AUVs [15].

To reduce energy loss in WPT underwater systems, researchers have focused on improving coupling mechanisms, using adaptive control algorithms, and developing docking devices. These improvements could make WPT systems for AUVs more efficient. Few studies reveal the design and comparative evaluation of various WPT systems, including capacitive and inductive systems, to determine the optimal strategy for AUV applications [5,16]. Furthermore, research efforts made possible the development of new coil structures that can improve the performance of WPT systems for AUVs by accounting for the unique characteristics of the underwater environment [17,18]. Control algorithms and compensation techniques have been improved to increase the efficiency of UWPT systems in AUVs. Moreover, practical concerns that need to be addressed include minimizing energy consumption, efficient pathways, and network topologies to successfully implement UWPT systems in AUVs [19,20].

The advantages of WPT over conventional power delivery systems have been extensively examined in the literature. WPT, especially through resonant magnetic coupling, has emerged as a promising technology for wireless charging of electronic devices and systems. This technology gives us a sustainable energy source [21]. Many people are interested in wireless power systems because they can provide a reliable, long-term energy source for Internet of Things (IoT) applications. WPT could be a good way to improve computing power in this area [22]. There has also been a huge increase in demand for wireless power transfer systems that can power multiple loads. This is because consumer portable electronics have made significant progress [23]. Fig. 1a,b shows a typical UWPT system showcases the practical implementation of the technology [16,24] and Fig. 1c,d is wireless charging and docking system structure for AUVs.

1.1 Autonomous Underwater Vehicles

Autonomous Underwater Vehicles are unmanned marine robots designed to function independently in underwater settings. AUVs are employed in a wide range of applications, such as marine geoscience, offshore oil exploration, rescue operations, submerged pipeline repair, archaeological work, ecological monitoring, oceanography, and mine warfare [25,26]. Furthermore, they play important roles in collecting data in underwater sensor networks (USNs), exploring natural resources, performing security and defense work, and other key areas [26–28]. The main goal of developing AUVs is to make marine robotics more agile and easier to control, while also providing a foundation for further research in this sector [29]. They are used for pipeline inspection, serving as relays in submerged communication networks, and detecting undersea fishing nets [30,31]. However, the use of AUVs is accompanied by numerous obstacles. Challenges in navigating

AUVs include unstable undersea currents, restricted visibility, and the lack of GPS signals [31]. In addition, Underwater Vehicles face restrictions such as restricted battery capacity, challenges in communicating underwater, and complications in navigation [32]. AUVs are propelled by underwater thrusters, but these thrusters often malfunction in real-world engineering situations, which creates operational difficulties [33]. Moreover, the analysis of sonar data obtained from AUV operations and the mapping of underwater objects using photos captured by AUVs provide additional challenges [30,34]. AUVs are responsible for optimizing the path of optical underwater sensor networks in the presence of changing ocean currents, which introduces additional level of complication to their operations [35]. Fig. 2. shows an overview of an underwater wireless charging system [36].

This article is organized as follows. Section 2 discusses the different energy sources used for AUVs. Section 3 provides a brief overview of current technologies used for underwater wireless power transfer. Section 4 provides overview of inductive WPT underwater systems, including recent advancements and challenges. It includes inductive, resonant, loosely coupled transformer design for WPT underwater systems and recent advancements in coupler designs for AUVs. In Section 5, a review of misalignment challenges in WPT Underwater Systems its effects on WPT systems and mitigation strategies were discussed in detail. Underwater power delivery challenges such as the effects of seawater, temperature, attenuation of electromagnetic waves, eddy current losses, and pressure on the IWPT system are studied in Section 6. Technical and engineering challenges in designing IWPT systems for AUVs are presented in Section 7, followed by the conclusion and future work in Section 8.

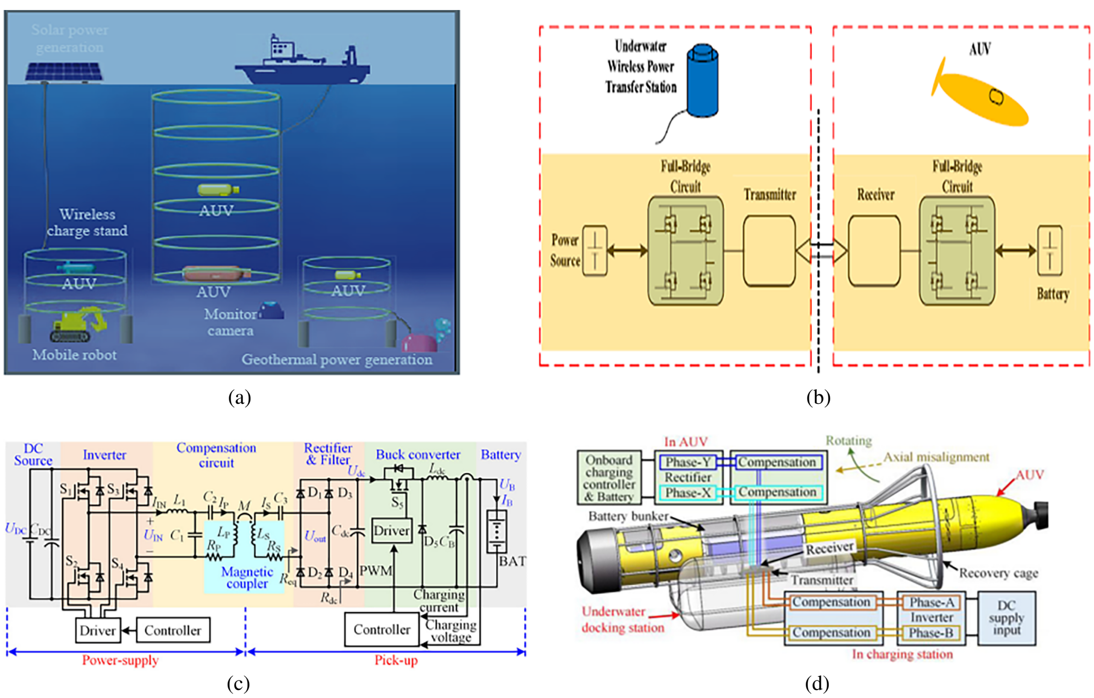


Figure 1: Conceptual diagram of WPT for AUV charging. (**a**) WPT system for AUV charging applications; (**b**) block diagram of an UWPT circuit for AUV battery charging; (**c**) circuit architecture of the UWPT charging system; (**d**) AUV docking and wireless charging configuration using inductive power transfer.

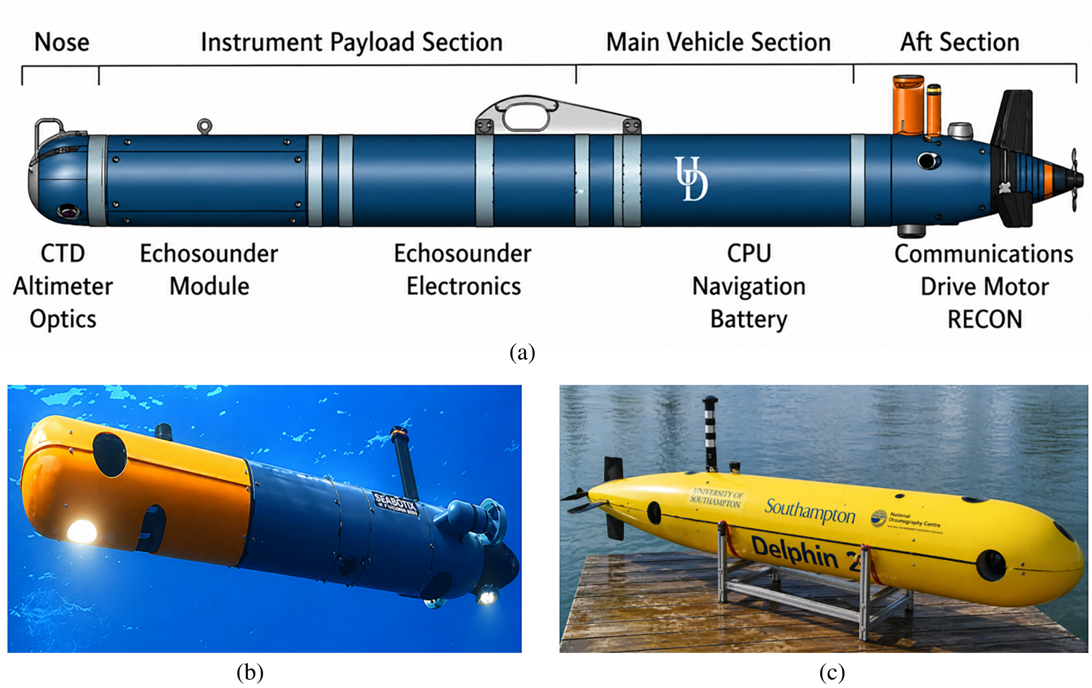


Figure 2: Typical REMUS 600 and Delphin2 AUVs. (**a**) The REMUS 600 vehicle with a specialized Simrad EK60 echo sounder payload section; (**b**) AUV in sea operation [37]; (**c**) Delphin2 [29].

2 Energy Context for AUV Operation and Motivation for Underwater Wireless Charging

2.1 Battery Technology in AUV

Battery technology stands as a pivotal aspect of AUVs, it has direct influence on their performance and operational capacities. AUVs use lithium-ion batteries, which have limited energy density, making it hard to keep working for a long time and over a large area. This includes a comparison between complete battery systems and hybrid solutions. To help AUVs recharge their batteries and fix power issues, underwater docking stations have been established [38]. Underwater docking stations are a new technology that looks promising and assist AUVs charge up and store extra data. However, they are limited due to the amount of battery power maintenance cost assumption [39]. Additionally, the thermal safety and reliability of lithium-ion batteries have major effects on the development of AUVs, especially for long missions with high speeds.

2.2 Ocean Thermal Energy for AUV Power

Ocean Thermal Energy Conversion (OTEC) is a promising way to generate renewable energy by using the temperature difference between deep, cold saltwater and shallow, warm seawater to produce electricity [40]. Ocean currents have a significant impact on the quantity of energy AUVs use. Studies demonstrate that AUVs can use ocean currents to save energy [41]. A significant number of individuals also acknowledge that solar, thermal, and wave energy are the best sources of electricity for AUV operations in the future [42]. Efforts have been made to promote the use of ocean thermal energy for underwater vehicles, recognizing it as a reliable and efficient energy storage option [43]. Moreover, the utilization of trajectory optimization methods that account for ocean currentshas proven to be effective in decreasing the energy consumption of Underwater Vehicles [28].

2.3 Fuel Cell Systems for AUVs

Fuel cell systems are being recognized as a viable power source for AUVs due to their ability for achieving superior efficiency and energy density. Highlighting the significance of effectively managing heat in the design of AUVs driven by fuel cells, it emphasizes the need to carefully consider the distribution of heat within the energy system. Furthermore, their investigation into the size and enhancement of energy systems for long-distance Underwater Vehicles shown the capability of hybrid fuel cell/battery systems to increase the range of bigger AUVs. Additionally, a study investigated the modelling of a grid-independent PV/SOFC micro-CHP system, showcasing the possibility of combining fuel cell technology with renewable energy sources to achieve highly efficient power generation. Performed empirical analysis on a Proton Exchange Membrane (PEM) fuel cell designed for maritime power generation, providing vital knowledge on the practical implementation of fuel cells in marine settings. They provided insights into the practical concerns involved in deploying fuel cell systems in underwater vehicles [44].

2.4 Solar Power Integration in AUVs

Solar power has become a viable option for supplying continuous power to AUVs and other underwater devices [45]. Although solar cells positioned above water or on land have been widely used, there is a growing interest in the usage of underwater solar cells (UWSCs) as a more suitable option for providing energy to long-endurance AUVs. Researchers have found the best solar technologies for underwater use, noting the limits of silicon-based cells and suggesting better options [46]. They have also developed and tested models of solar-powered underwater vehicles, such as the solar-powered autonomous underwater vehicle (SAUV), to assess their performance in underwater environments [47]. In addition, studies have examined how submerged solar cells perform under different aquatic conditions. Results show that the power density of these cells is crucial for their effectiveness in both shallow and deep water [48].

2.5 Energy Harvesting Techniques for AUVs

The energy harvesters play an important role in ensuring that the long-term operations of AUVs are possible. Scientists believe that the use of photovoltaics to capture solar energy is a new way of providing power to underwater sensors, equipment, and autonomous vehicles. Scientists also discovered that investigating dye-sensitized solar cells and their incorporation into underwater photovoltaics was a feasible method for energy harvesting [49]. Nevertheless, the lack of stability of materials presents a challenge for harvesting underwater energy [50]. Piezoelectric energy harvesting has become a viable technique for UWSNs, alongside mechanical and solar energy harvesting [51]. Underwater piezoelectric energy harvesters are a promising approach for AUVs to harvest energy from the surrounding fluid [52]. Moreover, the effective extraction of energy from pipe flow driven by bubbles indicates a promising method for underwater energy harvesting [53].

3 Current Technologies for Underwater Wireless Power Transfer

3.1 Inductive Power Transfer (IPT)

Underwater Inductive Wireless Power Transfer (UIWPT) emerges as a promising technology for supplying power to AUVs and other submerged equipment. However, existing WPT systems for AUVs encounter challenges such as extended transmission distances, unstable AUV attitudes, and energy loss during power transfer [13,14,54]. Presently, IPT is the most developed and widely used method of underwater WPT for charging AUVs, especially those that need high levels of power transfer and are based on conventional designs of magnetic couplers [55]. However, UIWPT faces obstacles such as frequency splitting, eddy current loss, magnetic waveform attenuation in seawater, and disruption caused by ocean currents. In addition, the performance of UIWPT systems has been compared to that of CWPT systems, highlighting the advantages of inductive systems [16]. The classification of different Underwater WPT systems used in the Literature, their working principle and range shown in Fig. 3 and the structure of IPT system is shown in Fig. 4.

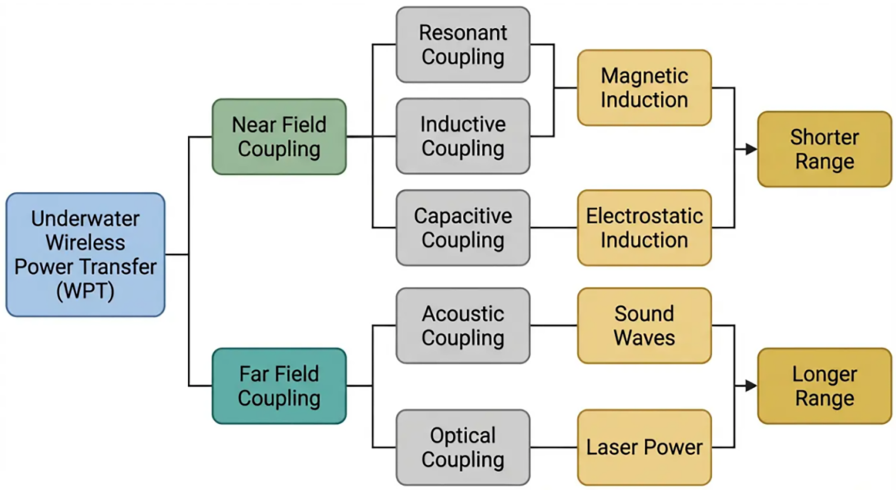


Figure 3: Underwater WPT systems classifications, principle of working and range.

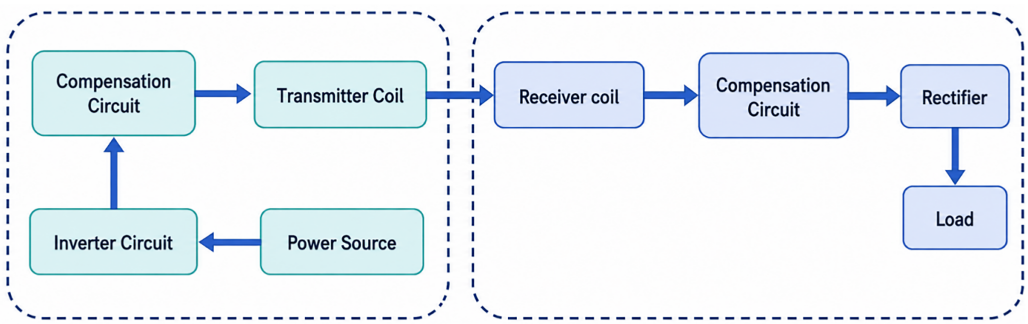


Figure 4: Components and working principle of underwater IWPT system.

3.2 Magnetically Coupled Resonant Wireless Power Transfer (MCR-WPT)

The advancement of WPT technology has seen significant progress in recent years, especially in the area of MCR-WPT. This technology has made significant progress by proving that resonant coupling can occur simultaneously on both the sending and receiving ends [56]. Various studies have focused on different aspects of this technology, including impedance-matching circuits energy-efficient performance surface routing for WPT [57], and the design of an underwater magnetic coupler [58]. The principles of resonant WPT have also been used to create currents in strongly coupled magnetic resonance systems [59]. Fig. 5 shows the components and how MCR-WPT functions. Moreover, the usage of MCR-WPT technology in several areas, such as mid-range WPT for magnetic levitation vehicles, power supply systems for AUVs, ultralight battery-less UAVs, and implantable biomedical devices [60,61]. Research has examined the impact of airspace in waterproof sealed environments for undersea WPT [62], the optimization of PCB layout for high-frequency inverters [63], and a comparative analysis of coil structures on MCR-WPT performance.

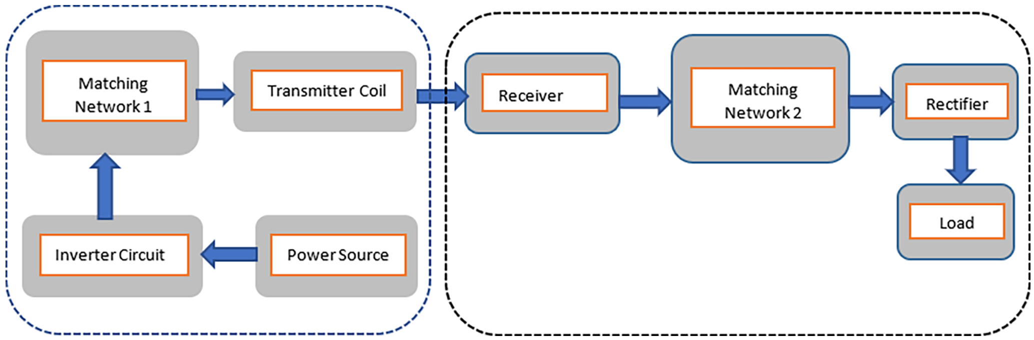


Figure 5: Components and working principle of underwater MCR-WPT system.

3.3 Capacitive Wireless Power Transfer (C-WPT)

Capacitive Wireless Power Transfer (CWPT) is a rapidly developing technology that has significant potential for use in underwater applications, specifically for providing power to AUVs. Although IWPT has traditionally been the preferred method in underwater conditions, but new studies have revealed multiple benefits of CWPT [64,65]. The concept of CWPT involves using interconnected capacitances to transmit power from a transmitter plate to a receiver plate, utilize time-varying electric fields for WPT [66,67]. Fig. 6 shows the working principle and different parts of CWPT systems. The MCR-WPT model has been further refined using the capacitive segmentation method that ensures reliable currents in large single-turn coils at frequencies above 10 MHz.

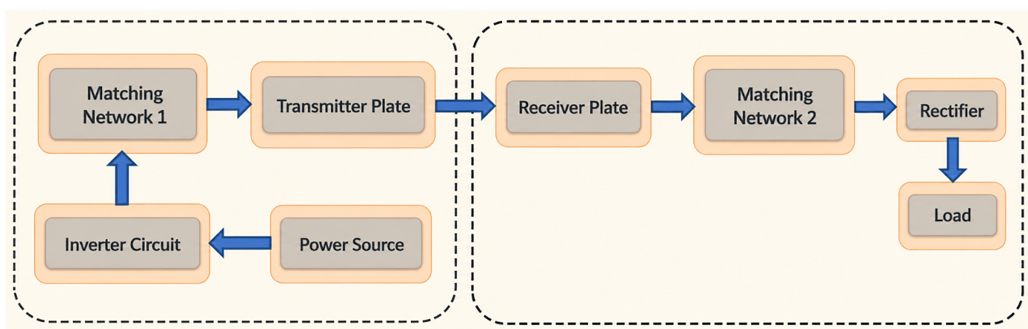


Figure 6: Components and working principle of underwater C-WPT system.

Several studies have concentrated on developing and evaluating CWPT devices specifically designed for underwater use. An undersea CWPT system with four plates has been suggested for AUVs, demonstrating the capability of efficiently transferring power in underwater conditions [68]. Furthermore, researchers have investigated the use of parasitic capacitance in helical coils filled with saline water to transmit wireless power underwater. This highlights the capacity of Capacitive systems to adapt to the specific characteristics of the underwater environment. Moreover, studies have examined the advancement of bidirectional undersea CWPT systems, which suggests the possibility of flexible power transfer capabilities in underwater conditions [5]. While the study of CWPT for underwater applications is still in its early phases, the potential to achieve optimal PTE and overcome the specific constraints posed by underwater environments is recognized [17,69].

One significant advantage of CWPT compared to IPT is that it eliminates ferrite core-based mechanisms, which are employed in steering and shielding the magnetic flux. Such an approach could reduce system cost, weight, and component count. Nevertheless, this method has certain trade-offs related to power limitations, operating requirements, coupling, and technology development for charging underwater AUVs.

3.4 Acoustic Power Transfer

Acoustic coupling power transfer underwater refers to the transmission of power via acoustic waves in aquatic environment. This method is highly relevant for a range of applications, such as WPT for AUVs and underwater sensor networks (USNs). Multiple studies have focused on optimizing WPT techniques for underwater applications, with the goal of reducing energy loss and improving efficiency [13,68,70]. The importance of acoustic-structure coupling study has been emphasized as essential for understanding the vibration and underwater acoustic radiation of structures in the underwater environment [71]. Moreover, the study of how acoustic waves interact in underwater environments has led to research on innovative techniques for accurately measuring distances underwater and creating acoustic frequency combs. These advancements have the potential to be applied in different sectors related to acoustics. Acoustic power transfer works through transducers, layout of typical system presented in Fig. 7.

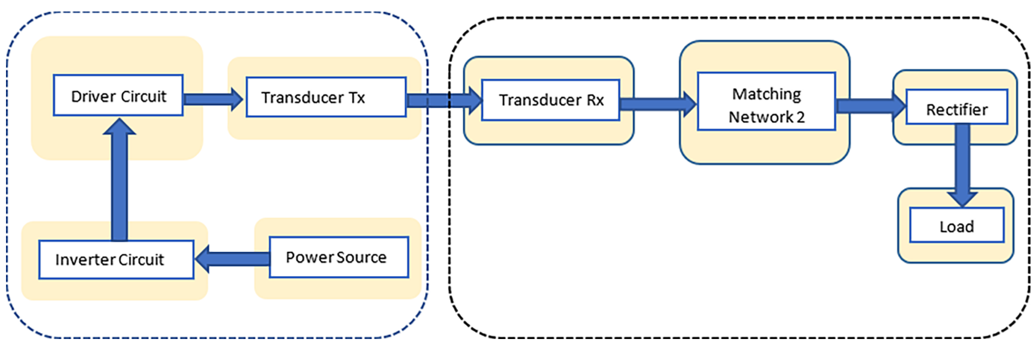


Figure 7: Components and working principle of underwater acoustic power transfer.

3.5 Radio Frequency (RF) Power Transfer

The underwater Radio Frequency (RF) Power Transfer principle is crucial for allowing communication and providing energy in submerged conditions. Combining underwater optical wireless communication (UOWC) with RF technology is considered crucial for facilitating communication between the air and water [72]. Researchers have demonstrated the potential of underwater WPT using radio waves. This shows that RF technology can move energy in underwater communication [15]. The advantages of RF WPT systems strengthen the potential of RF technology in underwater communication and energy transfer. RF systems have also demonstrated the ability to wirelessly deliver power to IoT devices over long distances and to power devices in underwater environments. Also, RF energy transfer technology is known for its ability to achieve long-range power transfer to devices [73]. Fig. 8. Shows the working mechanism of RF power transfer.

3.6 Piezoelectric Power Harvesting

Piezoelectric energy harvesting has been an established technology in the last ten years due to its ability to transform ambient vibrations into electrical energy. This technology provides significant benefits such as a high-power density and effective electromechanical coupling [74]. Piezoelectric energy harvesting is a process that involves gathering vibration energy from the surrounding environment and transforming it into usable power. The working principle of Piezoelectric energy harvesting is presented in Fig. 9. This technology is widely used in various applications, including undersea energy harvesting, where it captures kinetic energy from water's movement [75]. Research has focused on improving the efficacy of piezoelectric power harvesters. Researchers have explored novel designs, such as hybrid piezoelectric and electromagnetic harvesters, in order to enhance the amount of power generated and expand the range of frequencies for energy harvesting [76]. In addition, researchers have investigated the creation of multi-stable piezoelectric energy harvesters to overcome obstacles and obtain a significant energy production with little excitation intensity [77].

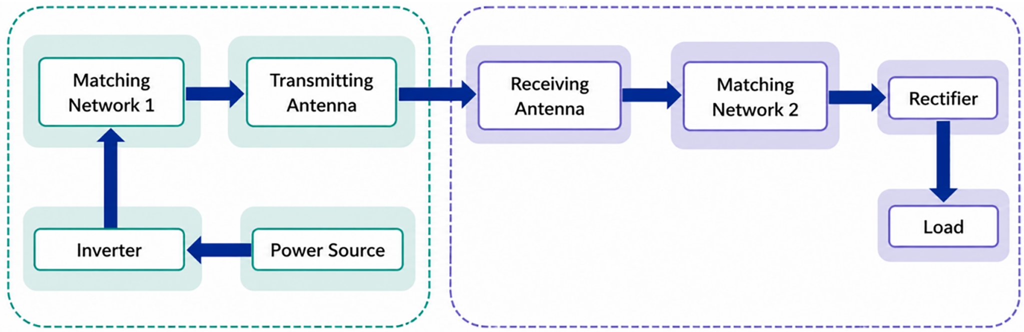


Figure 8: Working mechanism of underwater (RF) power transfer.

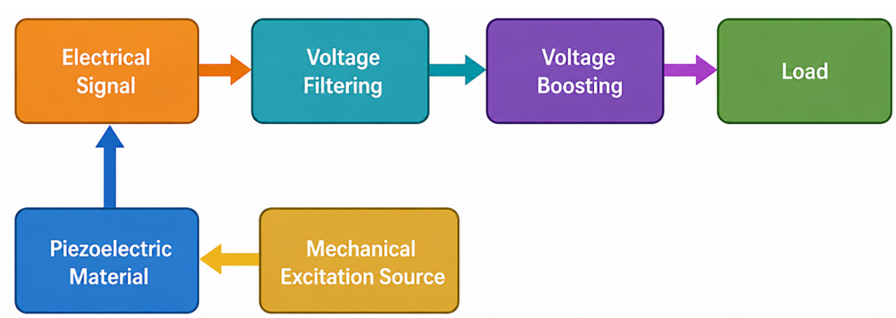


Figure 9: Components and working principle of piezoelectric power harvesting.

IPT is the most advanced and reliable method for charging underwater AUVs, yet this doesn't mean it's the best choice for all design constraints. IPT is usually the best choice when you need a lot of power transfer, better field confinement, and proven methods for designing couplers. But IPT usually uses ferrite materials and magnetic shielding structures, which can make things stronger, more expensive, and harder to put together. In contrast, CWPT could be better because it is simpler to build and uses less complicated materials. However, it is still not as well developed for many underwater AUV charging situations and may have different limitations in coupling behavior, plate design, and environmental sensitivity. Consequently, IPT and CWPT are expected to be considered competing, but application-dependent, methodologies rather than unequivocally superior or inferior choices.

4 Overview of Inductive WPT Underwater Systems, Recent Advancements and Challenges

4.1 Overview of Inductive WPT Underwater Systems

IWPT systems have become a major area of interest due to their flexibility and safety, and can be used for many things, such as charging electric cars, powering UAVs, and deploying biomedical devices [78,79]. IWPT technology is ideal for both low- and high-power applications, such as charging mobile phones and tablets, and charging electric cars [55]. The IWPT's low misalignment effects and high efficiency are highly significant. It can keep power supply equipment and devices electrically separate, making it safe and reliable for energy supply in underwater communication [80]. It also charges devices wirelessly using electromagnetic fields or waves, extending their battery life [58]. IWPT offers technical advantages unmatched by other power sources, making underwater equipment much safer, more reliable, easier to use, and less visible [81].

Underwater IPT systems have become a very attractive technology due to their ability to provide energy supply to various underwater devices such as underwater vehicles, ocean buoys, and sensors. However, it faces challenges such as loss of eddy currents, frequency splitting, and attenuation of magnetic waves in seawater [16]. Inductive and magnetic resonant coupling WPT systems are now more common in mobile consumer electronics because they don't emit radiation [82]. WPT technology has enabled wireless power transfer to the underwater communication system, making it much more effective [83]. The development of specialized components like circumferential coupled dipole-coil magnetic couplers has facilitated wireless charging applications for autonomous underwater vehicles [58]. Additionally, bidirectional underwater WPT systems, including both capacitive and inductive approaches, have been explored to cater to different underwater power transfer needs [5].

Ref. [84] presents typical conventional WPT system shown in Fig. 10a. similarly, Ref. [85] presents Loosely coupled transformer (LCT) design for underwater wireless power transfer shown in Fig. 10b. The circuits contain transmitter, resonant tank circuits, compensation topology, converter and receiver for wireless power transfer and LCT System. To explain the theory behind inductive WPT systems, the inter relation between the two coils can be represented with the help of mutual inductance M and the coupling factor k, as shown in Eq. (1) below.

$$k = \frac{M}{\sqrt{L_1 L_2}}, \quad 0 \leq k \leq 1 \tag{1}$$

where L_1, L_2 are the self-inductances. Eq. (1) depicts the effectiveness of magnetic coupling. The induced voltage on the receiver side can be represented as shown by Eq. (2).

$$V_2 = j\omega M I_1 \tag{2}$$

where ω shows the angular frequency and I_1 is the transmitter current. The resonant WPT operation and the quality factor of each coil branch is commonly written as shown by Eqs. (3) and (4).

$$\omega 0 = \frac{1}{\sqrt{LC}}, \quad f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

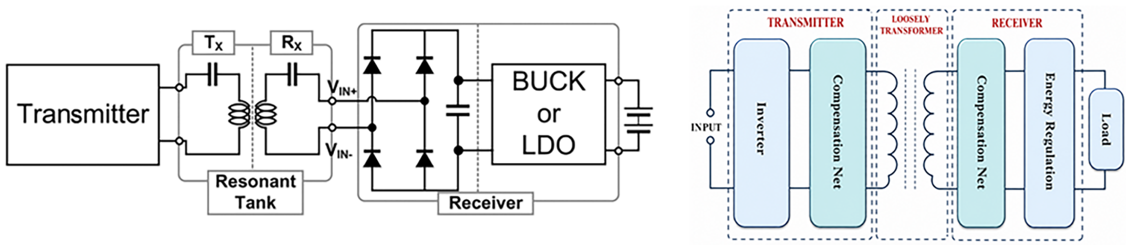
$$Q_1 = \frac{\omega_0 L_1}{R_1}, \quad Q_2 = \frac{\omega_0 L_2}{R_2} \tag{4}$$

where L and C are the effective inductance and compensation capacitance and R_1 and R_2 are the equivalent AC resistances of the transmitter and receiver coils.

Additionally, the secondary-side impedance reflected to the transmitter side may be expressed as shown by Eq. (5).

$$Z_2 = \frac{(\omega M)^2}{Z_2} \tag{5}$$

where Z_2 is the equivalent impedance.



(a) (b)

Figure 10: Typical traditional resonant WPT system and LCT design. (**a**) RWPT system; (**b**) LCT design.

4.2 Loosely Coupled Transformer (LCT's) Design for WPT Underwater

Loosely coupled transformers are integral components in various applications, such as wireless power transfer systems. The design of efficient WPT systems for electric vehicles relies significantly on the structure and size of these transformers. LCT's facilitate power delivery over large air gaps through magnetic coupling, making them well-suited for applications like IPT systems [86]. However, optimizing the design of such systems, such as contactless battery chargers, necessitates a comprehensive analysis of components like the primary-side series resonant converter to ensure efficiency [87]. In the realm of power electronics, the utilization of LCT's can present challenges like increased leakage inductance, leading to additional power dissipation in transformer windings [88]. Despite these challenges, the design considerations for IPT systems aim to minimize gap variation and misalignment effects to enhance power transfer efficiency.

In underwater wireless power transfer, the design of a LCT's is a critical aspect that influences efficiency and performance. Several studies have delved into optimizing various aspects of this technology. Ref. [89] worked on optimizing the frequency of a loosely connected underwater wireless power transmission system, considers the loss caused by eddy currents. It is essential because eddy currents can have a significant effect on the efficiency of the system. In order to develop LCT transformer for WPT underwater, it is necessary to carefully address numerous important factors. The main focus is on the layout and dimensions of the transformer, as these elements have a major impact on the effectiveness of the WPT system. In addition, the design must emphasize high misalignment sensitivity to provide optimal performance even in the presence of coil displacement or misalignment [90]. Addressing misalignment is a crucial problem in WPT systems, and the use of inventive coil designs and adaptable hardware can assist in reducing this challenge. When developing an LCT for UWPT, it is crucial to consider the influence of leakage inductance on power dissipation, particularly when utilizing commercially available cores [88]. Furthermore, the design should strive to minimize discrepancies in gap size and the negative impact of misalignment, in order to maximize the efficiency of power transfer. Implementing optimal structural designs for ferromagnetic cores can further improve the efficiency of WPT systems [91].

Despite these challenges, theoretical investigation, simulation, and undersea experiments carried out on IPT prototype systems offer proof of the feasibility of LCTs for effective power transmission underwater. Empirical findings show that LCTs possess the ability to transfer 10 kW of power with a transmission efficiency of 91% across a 25 mm distance in the air. This illustrates the ability of LCTs to fulfil the energy needs of underwater applications [85].

4.3 Magnetically Coupled Resonant Wireless Power Transfer (MCR-WPT) Underwater

Resonant Wireless Power Transfer is a revolutionary technology that employs resonance conditions to enhance the efficacy of power transfer and enables charging without necessitating exact alignment between the transmitter and receiver [57]. Resonant inductive linkages have attracted considerable attention for providing power to various devices, such as portable electronics, medical implants, lighting systems, and electric vehicles [92]. Studies in this area have explored several elements like the creation of resonant systems using Tesla's resonators, the use of metamaterials to improve the efficiency of power transfer, and the application of relay resonators to improve energy efficiency over varying transmission distances [93,94]. Prior research has focused on improving WPT systems by considering characteristics such as the ability to handle misalignment, minimize disturbances, and to tolerate displacement. These factors are crucial for enhancing the overall performance of the system [95,96].

The latest developments in MCR-WPT have drawn considerable attention because of its potential uses, particularly in underwater environments. This technology provides advantages such as the ability to transfer power across medium distances, high levels of efficiency, and functioning without the emission of radiation [97]. Researchers are concentrating on the improvement of WPT systems by examining factors such as coil layouts, transmission characteristics, frequency coordination, and load resistor optimization. The goal is to boost the efficiency and performance of these systems. In addition, the advancement of WPT systems has prompted the investigation of novel technologies such as self-resonant systems that do not require extra compensation capacitors. These systems have gained attention because of their high efficiency [82]. Research in underwater scenarios has also examined the impact of hulls on AUVs with various WPT systems [92].

Scholars have investigated different approaches, including the use of a constant magnetic field to ensure consistent power output and transfer efficiency. Researchers have also investigated the utilization of ferrite cores to enhance the magnetic coupling between resonant coils in MCR-WPT systems.

Table 1 shows that recent work on couplers has primarily focused on three engineering directions: improving hull-to-coupler alignment, reducing receiver size, reducing coupler sensitivity to axial and rotational misalignment, and reducing magnetic leakage or loss due to seawater. Additionally, this shows that the development of couplers for AUV charging is not only about making them more efficient. Instead, it is being shaped progressively more by factors such as docking tolerance, compact integration, and the underwater environment.

Table 1: Comparison of different IWPT coupler designs for AUV applications.

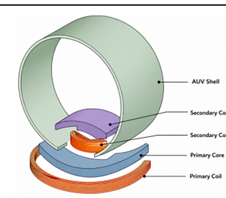
Reference	Year	Coupler Structure	Design Methodology	Results	Coupler Structure
[98]	2023	Pendulum-Type	The methodology involves characterizing the ID-shaped magnetic coupler using the reluctance model, providing a detailed design flow of the magnetic coupler, and conducting finite element method simulation analysis.	-When properly aligned, the experimental prototype achieved a DC-DC efficiency of 95.985% with a transmission power exceeding 3 kW. -Furthermore, the variation in mutual inductance is below 10% within the rotational and axial misalignment range of [−30, 30 mm].	

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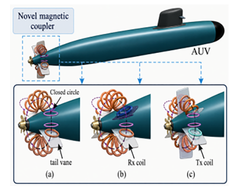
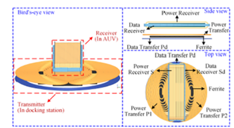
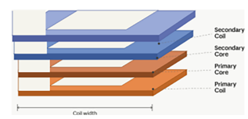
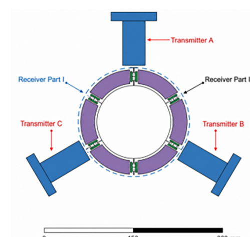
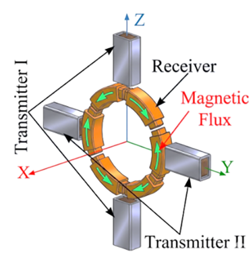
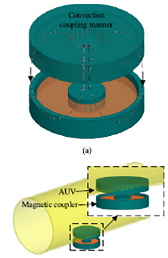
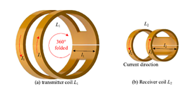
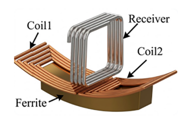
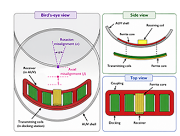
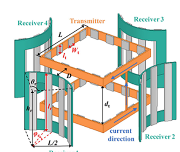
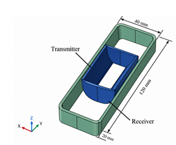
Table 1 (continued)

Reference	Year	Coupler Structure	Design Methodology	Results	Coupler Structure
[99]	2024	Energized solenoid	The methodology consists of optimization model to find number of Tx coils. Experimental validation in seawater, simulation for each Tx coil. Rx coils offset in various directions, investigation of the impact of tail vane shape and material on magnetic field distribution. Analysis of magnetic flux distribution under seawater.	-The innovative magnetic coupler efficiently reduces EMF leakage in seawater, showcasing its potential for practical use in wireless charging systems for AUVs. -The output power and PTE both rise as the number of Rx coils increases, ranging from 125.33 W and 80.22% to 362.68 W and 81.42%, respectively.	
[100]	2023	Decoupled Magnetic Structure	The methodology involves the design and implementation of a system using bipolar and unipolar coils for power and data transmission, with a focus on reducing crosstalk and achieving decoupling, verified through experiments.	-The system can achieve an output power of 936 W with a dc-dc efficiency of 94.12% and can realize full-duplex communication. -The proposed SWPDT system can effectively transfer power and data simultaneously and reduces interference from the power channel to the data channel. -The receiver is lightweight (741 g) utilizing orthogonal coils to receive perpendicular flux.	
[101]	2022	Arc-Shaped Coupler	The methodology involves designing and optimizing the magnetic coupler using FEM, simulating variables of core thickness and design angle, studying loss distribution, and experimentally validating performance.	-The suggested arc-shaped UWPT magnetic coupler is well-suited for the curved shell of AUVs and achieves a high level of PTE. -Fe-based nanocrystalline soft magnetic material reduces the volume and weight of the receiver -The experimental prototype transmits 3000 W power at a 91.9% dc–dc efficiency when the system is well-aligned.	
[102]	2018	Segmented coil design	The study employed a methodology that involved using: finite element analysis with ANSYS Maxwell to validate the suggested coil structure. Double-sided LCC compensation topology applied, and circuit analysis performed using a mesh current method. Prototype of the rotation-resilient wireless charging system constructed & tested.	-The suggested coil configuration, with receiver coiled in the opposite direction, guarantees uninterrupted power transfer for wireless charging even when there is rotational misalignment. -When perfectly aligned, the system can deliver 745 W with a dc-dc efficiency of 86.19%. It also maintains its efficiency even under worst-case rotational misalignment.	
[103]	2023	Decoupled transmitters and arc solenoid receiver	The design methodology included: decoupled transmitters and a segmented arc solenoid receiver. Also compensated for mutual inductances between the Tx and Rx and utilized phase control to ensure stable output power. The proposed anti-misalignment technique was validated by experimental prototype.	-The suggested WPT system for AUVs, featuring a novel magnetic coupler, is capable of generating an output power of 700 W while maintaining output fluctuations in power below 5% using the composite anti-misalignment approach.	

(Continued)

Table 1 (continued)

Reference	Year	Coupler Structure	Design Methodology	Results	Coupler Structure
[58]	2020	Dipole-coil-based magnetic coupler	The methodology includes the analysis of: the magnetic coupler structure, consideration of Fe-based nanocrystalline soft magnetic material and the construction of a wireless charging system prototype for validation.	-The proposed dipole-coil-based magnetic coupler successfully transfers 630 W under water with a high DC-DC efficiency of 89.7%. -The optimized dimensions and the use of Fe-based nanocrystalline soft magnetic material result in a greatly reduced receiver weight and similar performance to the traditional ferrite material. -The circumferential coupled flux linkage has a constrained magnetic field distribution.	
[104]	2023	360° folded spatial unipolar magnetic coupler	The technique comprises the utilization of: FEA to design the coupler, the establishment of a 5 kW WPT system with LCC-S compensation, the evaluation of the prototype in various environments, the examination of resonances, the development of circuit topology for LCC-S compensation, and the application of harmonic approximation for a 5 kW IPT system.	-The magnetic coupler effectively minimizes the magnetic field leakage into the internal region of an AUV, hence reducing the EMI effects on the electronic gadgets installed onboard. -The results show that a power transfer of 5 kW can be achieved with a dc-dc efficiency of 96.8% in saltwater. -The 360° rotational misalignment effectiveness of Designed coupler is capable of retaining 82.9% of the power.	
[65]	2021	Arc bipolar transmitter and a compact dipole-coil-based receiver	The methodology encompasses: the proposal of an innovative magnetic structure for wireless charging of AUVs, the construction and testing of a prototype of system, and the investigation of the impact of geometric factors on the performance of the magnetic coupler through simulation.	-Research highlights magnetic structure is viable for charging AUVs, with stable coupling against three-dimensional misalignment. -The idea has the advantageous feature of AUVs being shown good interoperability, even if they have varied sizes and power capacities. -Additionally, the system can provide 1.05 kW of power to an AUV with a dc-dc efficiency of 95.1%.	
[105]	2023	Overlapped direct-quadrature transmitter and a dipole receiver	The methodology involved proposing a docking design, a novel magnetic structure, and a practical wireless charging circuit, followed by developing, modeling, and analyzing the wireless charging circuit, and experimental prototype to verify the design.	-The suggested wireless charging system designed for recharging AUVs is capable of maintaining a consistent output even when there is misalignment in both rotational and axial aspects. -It is capable of delivering 1.2 kW of power to the load, with a system efficiency of 90%. -Additionally, a compact magnetic receiver only 552 g.	
[106]	2023	A cube-shaped Tx coil and an arc-shaped Rx coil	The methodology involves utilizing a multi-objective genetic algorithm to optimize the variables of the coil, employing a hybrid injection technique for communication based on LCC-S compensation topology, and constructing an experimental prototype.	-The research suggests employing a cube-shaped Tx coil and an arc-shaped Rx coil for charging swarm AUVs. -The system attains a PTE of 92.25% when operating with four loads and a total output power of 200 W, showcasing superior offset insensitive characteristics.	
[107]	2022	N/A	A novel coupling coil topology is presented for wireless charging of AUVs in a WPT system. Initially, a compact and lightweight magnetic coupling device is suggested for the receiving end, which can conform to the unique arc shape of the AUV. This device enhances the connection between the Tx and the Rx.	-The results indicate that the embedded experimental device is able to maintain an output voltage of 50 V and successfully achieve normal charging of a continuous load. -The system has a maximum charging power of 170 W and an efficiency of 92%. When a slight angular deviation occurs at the receiving end, the PTE of the system consistently exceeds 90%, with a fluctuation rate of no more than 2.5%.	

5 Misalignment Challenges in WPT Underwater Systems

5.1 Introduction to Misalignments and Importance of Alignment in UWPT Systems

Alignment in WPT systems is a critical factor that significantly impacts the efficiency and effectiveness of the system. Proper alignment of the transmitting and receiving coils is essential to ensure high-efficiency transmission, especially in applications like electric vehicles. Accurate alignment is essential for a range of applications, such as wireless charging systems for electric cars, where obtaining optimal efficiency is the main objective. Furthermore, precise alignment is even more essential in situations when the coils are not exactly positioned or are obstructed by barriers such as thick metal walls. Technologies such as Metal Surface Guided-Wireless Power Transfer Systems (MSG-WPT) can facilitate power transfer in harsh environments, emphasizing the need of alignment [108]. Alignment plays a vital role in WPT systems for automobiles, since it has a substantial impact on the overall performance and efficiency of the system [109].

Moreover, research has demonstrated that alignment has a direct effect on the overall PTE and the operation of the system. Research on antenna alignment employing intermodulation for powered medical devices highlights the importance of alignment in attaining efficient power transfer. Furthermore, studies on thermal effects in WPT modules for electric vehicles highlight the significance of alignment in enhancing the acceptance and implementation of electric vehicles. Significant challenges can arise from underwater misalignment in WPT systems. This is primarily due to the complex underwater environment and the effects of docking mechanisms on AUVs [110]. Misalignment can occur in two forms: axial misalignment and rotational misalignment. These types of misalignments can have a negative impact on the efficacy and reliability of power transfer. Researchers attempts to enhance the ability of WPT systems to handle misalignment by integrating inductive and capacitive coupling, and by using compensation topologies to improve performance when misalignment occurs [111]. In addition, several studies have explored the optimization of coil design in order to enhance PTE and increase tolerance to misalignment [112]. The reduction in PTE in inductive power systems induced by misalignment is mostly due to decrease in mutual inductance resulting from coil misalignment [113].

The influence of misalignment can be represented by Eqs. (6) and (7).

$$M = M\left(x, y, z, \theta, \varnothing\right) \tag{6}$$

$$k\left(x, y, z, \theta, \varnothing\right) = \frac{M\left(x, y, z, \theta, \varnothing\right)}{L_1 L_2} \tag{7}$$

where x, y, and z denote the translational offsets and $\theta, \varnothing$ represent angular misalignments. A local sensitivity measure can by represented by Eq. (8) and the transferred power in an inductive link is shown by Eq. (9).

$$S_x = \frac{1}{M_0}\frac{\partial M}{\partial x}|_0, \quad S_\theta = \frac{1}{M_0}\frac{\partial M}{\partial \theta}|_0 \tag{8}$$

$$P_{out} \propto \left(\omega M\right)^2 \tag{9}$$

where S_x and S_θ denotes better tolerance to axial and M shows moderate reductions.

5.2 Causes of Misalignment

UWPT misalignments may occur from multiple sources, with each source having a distinct impact on the efficiency and efficacy of the system. An important issue with WPT technology is the misalignment of the pads, which happens when the receiver and transmitter coils are not correctly positioned. This leads to a decrease in the power level of charging and causes the charging process to take longer [113]. This problem is especially relevant in vehicles that have a dynamic charge, where power is lost because the receiver and transmitter coils are not properly aligned while the vehicle is moving. In the harsh underwater environment, misalignments such as axial and rotational misalignments are bound to occur during charging process. These misalignments have a direct effect on the distance between the transmitter and receiver coils [110]. The transfer efficiency of UWPT systems for marine vehicles is influenced by various parameters, including the coupling state and load situation [114]. In addition, misalignments in both lateral and orientational directions can greatly decrease the effectiveness of the system, resulting in a zero coupling coefficient and limiting the transfer of power [115].

5.3 Impact of Misalignment on WPT Systems and Review of Misalignment Issues

Misalignments in UWPT systems can have a substantial effect on their efficiency and performance. Research indicates that when the transmitter and receiver coils are not properly aligned laterally and angularly, it can cause variations in mutual inductance, leading to a reduction in transmission efficiency [116]. It has been found that misaligned resonant coils in wireless power systems lead to a substantial decrease in transfer efficiency [117]. In addition, misalignments can reduce power efficiency and reduce the maximum power in inductive coupled WPT systems [118]. Scholars have also examined the effects of misalignments on the efficiency of power transfer. The effectiveness of WPT systems significantly decreases when there is axial misalignment between the transmitter and receiver coils [119]. In addition, it was discovered that the PTE of resonator-coupled WPT systems decreases as the angular misalignments rise [120]. Pad misalignment is a significant concern in wireless electric vehicle charging systems. It can lead to a decrease in charging power level and delay the charging process. Both the lateral misalignment and air-gap change that occur during charging can have an impact on the magnetic coupling between the power supply rail and the charger. This can result in oscillations in the coupling coefficient of the wireless EV charging system.

Research has demonstrated that misalignments in UWPT systems can result in the occurrence of eddy current losses, which have a negative impact on the overall performance of the system [121,122]. The presence of ECLs near the coupler of AUVs can have a significant impact on the overall efficiency of the system [123]. Moreover, misalignments in underwater wireless optical communication systems can diminish system performance by affecting the received intensity [124]. It is essential to enhance the performance of UWPT systems by addressing misalignments using new coil topologies, metamaterials, and optimization approaches.

5.4 Alignment Enhancement Techniques and Different Solutions Adopted

Ocean currents have a significant impact on the effectiveness of WPT systems for AUVs in submerged environments. Ref. [103] presented a WPT system that allows for free rotation. This system uses a unique magnetic coupler that employs segmented solenoid coils. The purpose of this system is to improve the system's ability to tolerate misalignment in both rotational and axial directions. This novel coupler utilizes a composite anti-misalignment technique to achieve an output power of 700 W, while ensuring that the output power fluctuation remains below 5%. The magnetic coupler consists of two separate transmitters and one receiver that have adjacent reception coils wrapped in opposite directions. This design allows for mutual inductance compensation between the receiver and transmitters. Additionally, coordinated phase control between transmitters ensures stable output power amidst rotational and axial misalignments.

The author in [98] introduced an innovative magnetic coupler with an ID-shaped design that includes a pendulum-type receiver. This design demonstrates a condensed structure, a composition that is light in weight, a generous ability to handle misalignment, and a high density of power for the receiver. The suggested system demonstrates a remarkable ability to maintain a steady output even when there is a misalignment in both rotational and axial directions, with a range of [−30, 30 mm]. Furthermore, the system consistently maintains an efficiency of over 95%, with fluctuations below 1%.

Ref. [106] Proposed a misalignment tolerant WPT system that utilizes the innovative Hybrid Tx coils shown in Fig. 11a to charge AUVs. Firstly, coil tilt angle theory (CTAT) is explained and confirmed to determine the most favorable tilt angle of the conical coil. Using CTAT, the hybrid transmitter is designed to create a circular homogeneous magnetic field zone with a diameter of 30 cm in the charging plane. The results demonstrate that the suggested transmitter outperforms conventional transmitters in terms of output power and stability of PTE within the operational zone. The output power fluctuations are restricted to a maximum of 5.7%, and the PTEs are consistently maintained at around 86% in the region of extreme misalignment, over a transfer distance of 2 cm.

Ref. [125] presented a coil structure compatible with AUVs, addressing rotational misalignment to stabilize the output power of a WPT system. The proposed coaxial coil structure, depicted in Fig. 11b, ensures constant mutual inductance during AUV rotation. Experimental evaluation on an LCC-S-compensated WPT prototype demonstrates that the proposed coil structure remains unaffected by rotation but is sensitive to radial and axial eccentricity, achieving 92.7% efficiency at a 2-kW output power.

A new coupling structure shown in Fig. 11c for AUVs is presented in [126], which includes a solenoid transmitting coil and dual coupled planar coils as the receiving coil. The results indicate that this coupling structure effectively reduces variations in mutual inductance when there are changes in axial misalignments, in comparison to the solenoid-unipolar planar coil coupling structure. As the axial misalignment grows from 0 to 40 mm, the power transmission efficiency decreases from 85.04% to 78.3% in saltwater, with a variance in output power of less than 4.15%.

Researchers in [110] developed a new type of magnetic coupler, shown in Fig. 11d, which has a simple design, lightweight, has strong resistance to misalignment, and maintains stable self-inductance for AUVs. The results demonstrate the effective transmission of 735.6 W of power to the AUV with a DC-DC efficiency of 90.87% when the alignment is optimal. The output power experiences a maximum variation of 28.9% and the DC-DC efficiency experiences a maximum variation of 0.89% within a specified range of axial and rotational misalignments.

Ref. [127] proposed a novel solution aimed at enlarging resonance range, enhancing efficiency, and stabilizing output. Adopting the LCC-S-S compensation circuit and a portable omnidirectional magnetic resonant extender depicted in Fig. 11e, the system achieves an average output of 15 W with fluctuations under 14.7% for angular misalignment from −90° to +90°. Even at extreme angular positions, the system maintains over 60% transmission efficiency, reaching 17.7 W output power with efficiency exceeding 70%. This represents a substantial efficiency improvement compared to conventional 1- to -1 WPT systems.

Ref. [128] introduced a new IPT system featuring dual transmitters and receivers with integrated decoupling coils, as shown in Fig. 11f. This system achieves a maximum DC-DC efficiency of 93.14% at a vertical air gap of 200 mm while delivering 700 W to the load in a fully aligned position. Notably, the proposed system outperforms conventional systems, exhibiting better misalignment performance and higher efficiency, particularly evident at 400 W power level.

Ref. [80] proposed a mistuned inductive power transfer (IPT) system, as illustrated in Fig. 11g, along with corresponding design methods aimed at improving misalignment tolerance. Employing series-series compensation and a variable inductor (VI) on the secondary side, the system achieves a maximum efficiency exceeding 96% for full power output within specified misalignment ranges. Experimental validation demonstrates horizontal and vertical direction misalignment ranges of ±47% and +140%, respectively, validating the system's improved charging freedom and stability in harsh underwater environments.

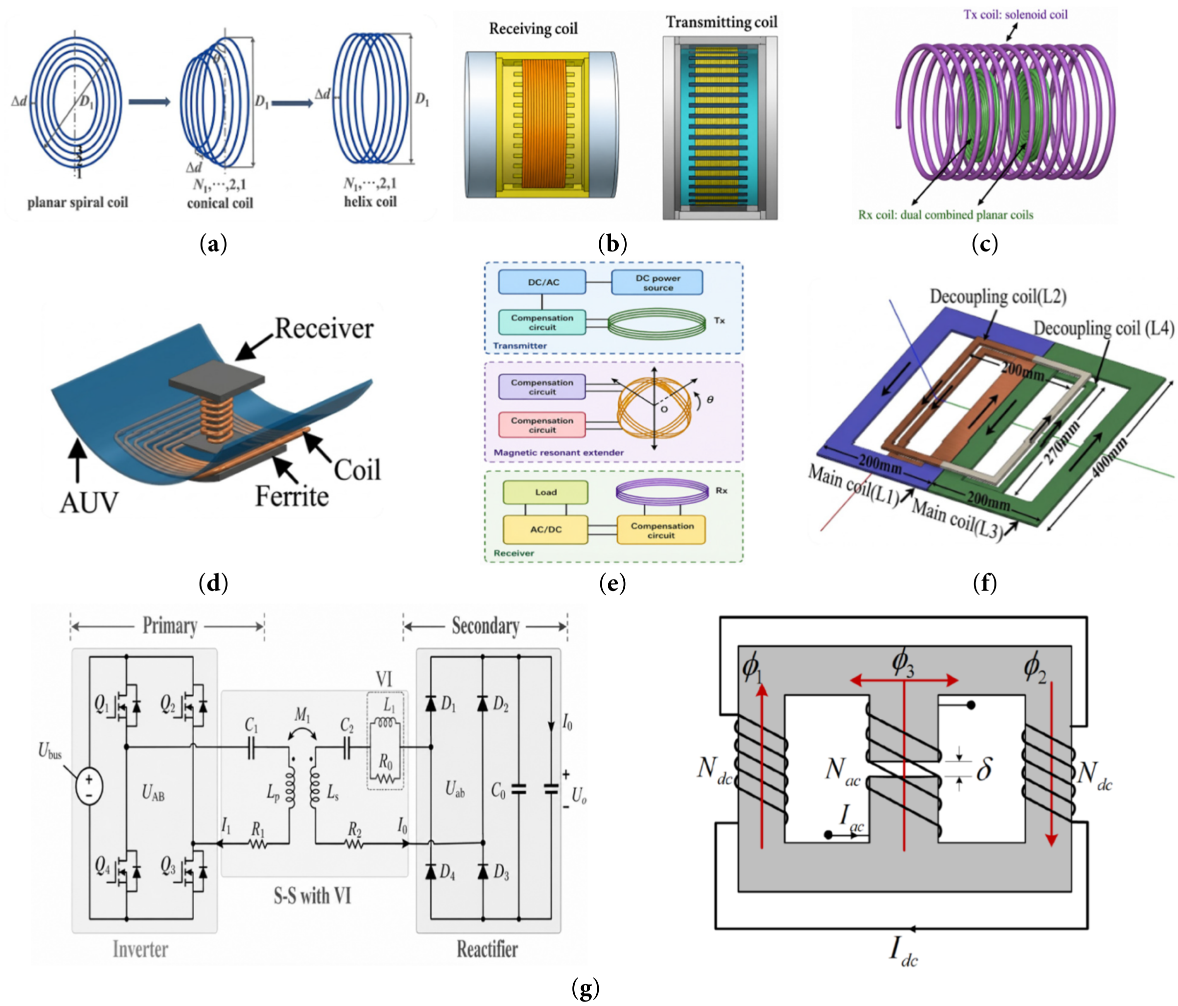


Figure 11: Different magnetic couplers and circuits proposed for misalignment enhancements. (**a**) Different coil structures used in WPT systems; (**b**) transmitting and receiving coils for IWC; (**c**) solenoid and planar coil configuration for WPT; (**d**) receiver coil and ferrite structure integrated into the AUV wireless charging system; (**e**) magnetic resonant WPT system for AUV charging; (**f**) decoupling coil structure for improving WPT efficiency; (**g**) primary and secondary compensation circuits of the WCS.

These innovative solutions demonstrate significant progress in addressing misalignment challenges in underwater wireless power transfer systems for AUVs, enhancing system efficiency, stability, and adaptability in complex underwater environments. Misalignment is one of the major problems in WPT systems especially in underwater due to harsh environment and salinity of water. It is difficult to maintain alignment for WPT systems and it directly effects system efficiency of systems.

Table 2 also reveals that efficiencies higher than 90% are generally observed when a standardized setting is used, but in non-standardized environments, efficiency levels may be around 76%–83%. The frequencies in Table 2 indicate that saltwater AUV charging systems are most likely to be found in the 50–85 kHz range. However, results at higher frequencies should be taken with a grain of salt because Section 6.6 shows that stronger seawater-related eddy-current penalties occur at higher frequencies.

Table 2: Misalignment performance comparison of different couplers designed for AUV charging.

Reference	Power Level/Voltage	Transfer Gap	DC-DC Efficiency	Misalignment	Efficiency under Misalignment	Operating Frequency	Fluctuation
[99]	65 V	50 mm	81.42%	2 and 6 Rx coils	80.22% to 81.42%	50 kHZ	n/a
[98]	3 kW	50 mm	95.985%	±30	>95%	85 kHz	<1%
[58]	630 W	8 mm	89.7%.	Axial and rotational 0 to 30 mm	85.37% and 87.08%	50 kHZ	n/a
[101]	3 kW	N/A	91.9%	Axial 20 mm rotational 10°	90.59% and 90.19%	85 kHz	n/a
[104]	5 kW	10 mm	96.8%	Rotation 0°~360°	82.9%	200 kHz	
[107]	170 W	10 mm	92%–90%	0° to 10°	<90%	50 kHZ	2.5%
[106]	200 W	5 cm	92.25%	20 mm lateral and axial and 10° rotational	N/A	249 kHz and 1.5 MHz	9.7%
[129]	664 and 485 W		92.26%	0° and 22.5°	92.10%	252.6 kHz	
[80]	1-kW	50 to 120 mm	>87%	47% and 140%	96.1% to 92.3% for H and 96.1% to 87.8% for V	85 kHz	3.8%
[105]	1.2 kW	N/A	90%	Rotational and axial ± 30	88.4% and 89.4%	85 kHz	1.7% and 6.5%
[102]	745 W	N/A	86.19%	Rotational 0° to 30°	76.24%	472 kHz	
[103]	700 W	N/A	Almost 95%	Rotational and axial	Relatively stable	200 kHz	<5%

5.5 Cross-Study Engineering Synthesis and Comparability of Reported Results

The studies summarized in Tables 1 and 2 demonstrate that various coupler families adapt to distinct engineering priorities rather than a singular universal performance objective. Couplers that are made to keep the magnetic field more evenly distributed across space usually work better with combined misalignments than simpler, more traditional setups. To identify AUV docking situations where both axial and rotational deviations can happen at the same time, pendulum-type and compact hull-compatible designs seem to be the best choices. For situations where receiver compactness and geometric compatibility with the vehicle hull are important, conformal and arc-based structures are better.

Another phenomenon that occurs again and again is the trade-off among the transfer gap, power level, and efficiency. The highest efficiencies reported in the studies we examined typically occur when the alignment is controlled, the transfer gaps are short, and the operating conditions are carefully set. However, these numbers can't be directly compared across all studies because the systems reported have very different operating frequencies, compensation topologies, coupling geometries, output powers, and experimental environments.

The third significant thing to consider is the test environment. Some research studies may evaluate the performance in seawater, while others may report either aligned or unaligned performances that primarily take place in air or laboratory settings and whose nature is not clearly specified. Seawater validation studies provide stronger support for using AUVs, but air experiments are valuable as well.

In general, the literature claims that no single coupler family is the best for all situations. Designs for real AUV charging systems, on the other hand, must find a balance between tolerance for misalignment, compactness of the receiver, control of the leakage field, underwater loss mechanisms, operating frequency, and required power level.

6 Underwater Power Delivery Challenges

6.1 Attenuation of Electromagnetic Waves

Seawater, characterized by high conductivity and permittivity, causes substantial attenuation of electromagnetic waves, rendering traditional wireless power delivery and communication methods ineffective in underwater applications. The consequences of this high attenuation are profound. Data communication distances and speeds are severely limited, typically reaching only around 10 m in distance and Mbps in speed [130]. Electromagnetic wave propagation in seawater presents issues such as eddy current loss, frequency splitting, magnetic waveform attenuation, and interference from ocean currents. In addition, challenges such as high attenuation, multipath fading, frequency dispersion, and signal distortion make it more difficult to efficiently transmit wireless power in marine environments. To address these issues, scientists have resorted to other techniques for effective transmission of wireless power in aquatic environments. These techniques involve investigating acoustic waves and magnetic induction as possible ways of bypassing the constraints caused by the propagation of electromagnetic waves in seawater [131,132].

6.2 Dynamic and Harsh Environment

The efficacy of underwater WPT systems is strongly affected by the unpredictable characteristics of the ocean, which include phenomena like eddy current loss, frequency splitting, magnetic waveform attenuation in saltwater, and disruption caused by ocean currents [122]. Moreover, underwater setting presents obstacles such as unpredictable and erratic transmission of signals, interference factors, restricted energy availability, and rapid changes in space and time, which complicate the establishment of dependable underwater wireless networks. Moreover, the efficiency of transmitting power wirelessly in saltwater is shown to be reduced compared to air, primarily due to the loss of energy caused by eddy currents. This highlights the influence of the aquatic environment on the effectiveness of WPT [122]. Moreover, the influence of the aquatic environment on WPT efficiency has been examined in relation to AUVs. The installation of WPT systems on AUVs has revealed a significant loss of eddy current near the coupler. This highlights the importance of designing effective WPT couplers for underwater vehicles [123].

6.3 Corrosion and Biofouling

Biofouling, which refers to the unwanted colonization of organisms on aquatic surfaces, leads to material degradation, surface corrosion, and economic loss. It is a practical challenge in underwater charging and docking systems because long-term exposure to seawater can degrade surfaces, alter interface conditions, and reduce the reliability of submerged hardware. Corrosion in aquatic environments poses an additional threat to long-term infrastructure performance. For this reason, antifouling surface strategies and self-healing anticorrosion coatings remain relevant to the long-term reliability of UWPT charging platforms.

6.4 Seawater Conductivity and Permittivity

The efficiency of IWPT systems is reduced when used underwater due to the occurrence of eddy current loss (ECL) caused by the high conductivity of the water medium [78]. This phenomenon is exacerbated by the fact that the resistance variation in seawater is proportional to the square of the working frequency, leading to increased ECL in underwater WPT systems [122]. Additionally, seawater conductivity directly influences the electromagnetic attenuation characteristics and phase distribution features of the ocean, further affecting the performance of underwater WPT systems. The electrical characteristics of saltwater, such as permittivity and conductivity, have a substantial impact on the parasitic effects of submerged winding coils, thus influencing the overall functioning of the WPT system [133].

To address the challenges posed by the conductive nature of saltwater, the study analyzes the energy dissipation and thermal production in UWPT systems, and assess the impact of seawater on the overall efficiency of the system [134]. Additionally, it is crucial to consider the use of shielding coils and the examination of ECL in UWPT systems with misalignments. in order to reduce the impact of seawater conductivity on the system's performance [121,135].

In the context of electromagnetic waves, seawater acts as a dissipative medium with finite conductivity and permittivity. The characteristics of seawater may be mathematically expressed using its complex permittivity, as indicated by Eq. (10) and the propagation constant in a conductive medium is expressed by Eq. (11).

$$\tilde{\varepsilon} = \varepsilon - \frac{j\sigma}{\omega} \tag{10}$$

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} \tag{11}$$

where ε, σ, and ω are the permittivity, conductivity, and angular frequency. And α, β denotes the attenuation factor, the phase factor, and μ indicates the permeability of seawater.

The skin depth for conductive environments can be calculated using Eq. (12) which shows that increasing the frequency or conductivity decreases the depth of penetration of the field.

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{12}$$

6.5 Pressure and Temperature Considerations

Factors like ocean currents, pressure, and temperature fluctuations can indeed impact the stability of power transfer in underwater IWPT systems [136]. The high pressure experienced underwater presents major challenges for IWPT systems, as it results in added weight from the installation of equipment and thrusters, hence impacting the operational depth of AUVs [137]. In order to tackle this difficulty, researchers have investigated novel methods, such as employing multi-layer fluid-solid-coupling shell structures, to improve pressure resistance without augmenting the overall thickness of materials. Furthermore, the hull design of AUVs can have an influence on the effectiveness of UWPT systems, involving both capacitive and inductive systems [16]. In order to create a highly efficient and flexible system for transmitting electricity wirelessly underwater, it is essential to consider several factors such the orientation of the coils, misalignment of the coils, and the effects of seawater [15].

6.6 Eddy Current Losses (ECL) and Factors Influencing Eddy Currents

When dealing with UWPT systems, it is crucial to carefully evaluate the ECL caused by the conductivity of seawater in order to ensure optimal operation. Designs that fail to consider ECL can result in unforeseen declines in system efficiency [36]. The presence of eddy currents in the conductive saltwater medium might lead to power dissipation and detuning effects in the UWPT system [138]. It is crucial to optimize the frequency of the WPT system in order to reduce the effects of ECL. Increased frequencies can worsen eddy current losses because of the enhanced conductivity of saltwater [89]. In addition, the change of resistance in seawater is directly related to the square of the operating frequency. This amplifies the effect of frequency on eddy current losses in underwater IWPT systems [122]. When the frequency or coil current rises, it is necessary to consider the significant ECL in the design of UWPT systems for AUVs [116]. An empirical study has shown that ECLs have a negative effect on system efficiency, highlighting the importance of reducing these losses in order to maintain optimal system performance [78].

The induced current density may be described as depicted in Eq. (13). Loss due to eddy current is caused by the time-varying magnetic field producing an electric field and current in the conductive medium, seawater.

$$J = \sigma E \tag{13}$$

And the time-average eddy current loss can be expressed as:

$$P_{eddy} = \int_V \frac{|J|^2}{\sigma} dV = \int_V \sigma |E|^2 dV \tag{14}$$

where J, E are the current density and induced electric field. V is the volume of conductive region.

With sinusoidal forcing, electric field is dependent on frequency, which is related to Faraday's law, such that $E \propto \omega Bl$, where B represents magnetic field density and l represents a characteristic path length. Thus, eddy current loss varies proportionally shown by Eq. (15).

$$P_{eddy} \alpha \sigma \omega^2 B^2 V \tag{15}$$

Eq. (15) demonstrates that increasing operating frequency increases seawater-related losses.

An equivalent eddy-current-loss resistance can be defined as.

$$R_{eddy} = \frac{P_{eddy}}{I_1^2} \tag{16}$$

where I_1 is the transmitter current. Thus, it is more accurate to claim that the equivalent loss due to eddy currents is proportional to the square of the frequency than to say that the resistance of seawater is proportional to f_2.

6.6.1 Mitigation Strategies

The literature thoroughly discusses the various methods taken to reduce Eddy Current Loss in underwater Inductive Power Transfer systems. For instance, Ref. [139] introduced a new coil structure with the objective of reducing ECL's in WPT systems for underwater vehicles. This emphasizes the need of innovative design techniques in tackling this issue. Additionally, Ref. [135] examined the efficacy of shielding coils in minimizing ECLs, highlighting the importance of optimizing the operating frequency while considering these losses. The effect of ECL on the efficiency of IWPT systems has been extensively investigated in the context of underwater applications. Although many methods have been investigated, a unified mitigation framework has not yet been established.

The researchers in [140] introduced a new approach that utilized Maxwell's equations to compute eddy current losses and system efficiency in coreless wireless power transfer systems operating in seawater. Their findings unveiled an optimal resonant frequency that maximizes transmission efficiency. Similarly, the introduction of a coil configuration in [139] featuring transmitter coils aligned symmetrically was aimed at enhancing power transfer efficiency and minimizing eddy current losses. The proposed construction enhances PTE by approximately 10% and decreases ECL. The study presents in [141] propose a multi-objective design approach for UWPT system for AUVs, considering the impact of seawater ECL. The research examines the efficacy of the design technique for the UWPT system. It also focuses on achieving a consistent voltage output, optimizing system efficiency, and reducing inverter electrical stress. Additionally, Ref. [89] established an analytical model to quantify ECL's, concluding that the optimum operating frequency in seawater should exceed the resonant frequency for maximum efficiency. Similarly, Ref. [36] proposed an efficient modeling approach using Z-parameters to predict eddy current losses, enabling precise design and analysis of UWPT systems.

6.6.2 Frequency Selection in Saltwater AUV Charging

The studies examined demonstrate operating frequencies between 50 kHz and 1.5 MHz, but these values are not adequate for charging saltwater AUVs. Locating the right frequency for underwater IPT systems is a critical decision. A higher frequency can make the induced voltage stronger and the passive components smaller, but it may also increase eddy-current losses in seawater. The literature reviewed indicates that a single universal ideal frequency does not exist, as the optimal frequency is dependent upon coupler configuration, transfer gap, power level, and the electromagnetic properties of the adjacent medium. However, from a practical perspective for AUV charging, the data in Table 2 shows that the best range for saltwater docking-oriented systems is usually in the low-to-moderate kilohertz range, especially around 50–85 kHz, where several studies show consistent operation and competitive efficiency. On the other hand, frequencies between 200 and 250 kHz can still work well in specialized layouts, but they should only be used for such structures and not as an overall design standard.

7 Technical and Engineering Challenges

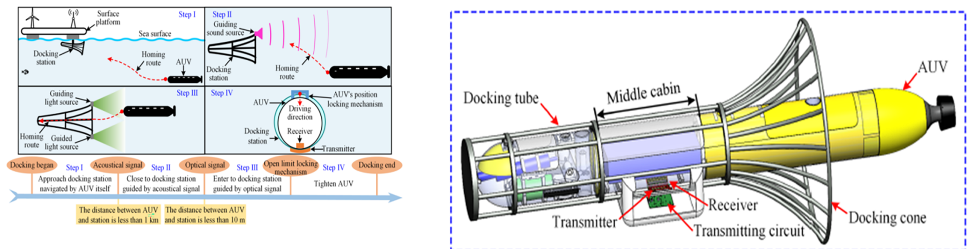
7.1 Electromagnetic Coupler Structure

The undersea environment poses various challenges, including higher pressure, corrosion, and restricted space. It is necessary for coupler design to endure these situations while yet maintaining optimal performance [123]. Nevertheless, conventional coupler designs might not be adequately suited for functioning underwater. Hence, it is imperative to create customized coupler designs specifically designed for the underwater environment in order to optimize efficiency and dependability [136]. The design of couplers should be tailored to be compatible with the particular constructions of underwater vehicles, such as AUVs. Optimal PTE can be accomplished by ensuring compatibility with vehicle structures [21,125]. Furthermore, it is essential to attain optimal magnetic flux coupling in order to maximize the efficiency of power transfer in Inductive power transfer systems. The primary objective in coupler designs should be to maximize the magnetic flux coupling between the transmitter and receiving coils in order to improve the PTE [110]. Rotational misalignment can cause instability in power transmission in IWPT systems. It is important for coupler designs to have characteristics that prevent rotational misalignment, therefore guaranteeing consistent output power even in changing underwater conditions [125].

7.2 Underwater Docking

Underwater docking is vital for the functioning of AUVs as it facilitates important tasks such as recharging, data transfer, and recovery. The procedure covers various crucial aspects, including energy provision, communication exchange, and guidance, all of which are essential for prolonging the durability of AUVs [142]. Docking devices commonly employ horn-shaped openings that facilitate the successful docking of underwater electrical equipment [136]. Underwater optical beacons play a crucial role in AUV docking by facilitating autonomous navigation to the docking station. Visual recognition and localization of these beacons are required for this purpose. In addition, underwater docking systems play a crucial role in facilitating long-lasting operations in the maritime environment, as long as the vehicle is capable of navigating to and meeting up with the station [143]. For successful underwater communications between AUVs or Remote Operated Vehicles (ROVs) and a docking station or underwater sensor nodes during survey missions, it is crucial to have efficient transmission and reception of high-speed short-range signals.

The advancement of underwater docking techniques aims to provide robust energy supply, information processing, and communication support for AUVs. This improvement ultimately enhances work efficiency, prolongs AUV endurance, and reduces costs associated with underwater operations [38]. Various methods have been proposed for AUV docking, including electromagnetic guidance based on the magnetic dipole model, event-based circular detection using spiking neural networks, and adaptive neural network control for visual docking, all contributing to the evolution of underwater docking technology [144,145]. The submerged AUV wireless charging system developed by [105] is seen in Fig. 12. Four additional means have been incorporated into the AUV's navigation system: auditory guidance, optical guiding, mechanical guidance using a docking cone, and position locking once the AUV has berthed. Position locking is a method used to prevent the movement of an AUV caused by ocean currents while it is being charged.



(a) (b)

Figure 12: Operation principle and docking scheme proposed by [106] and proposed SWPDT system by [100]. (**a**) Operation principle and Docking scheme; (**b**) SWPDT system.

7.3 System Alignment and Stability

In underwater monitoring systems, stability ensures consistent and accurate data collection, which is essential for economic development and environmental management. Similarly, in underwater communication systems, stability and alignment are crucial for maintaining signal integrity and ensuring seamless data transmission. Moreover, in the realm of wireless power transfer and IWPT systems, stability is paramount for maintaining efficient power transfer. Fluctuations in the distance between coils, resonance frequencies, and the frequency at which the inverter switches can all affect the stability of PTE and output power in Inductive WPT systems [79]. Ensuring stable and aligned resonance technology is vital for optimizing power transfer efficiency and maximizing transfer power in WPT systems, especially in challenging underwater environments.

8 Conclusion and Future Research Directions

This paper presents a comprehensive review of the recent advancements and current challenges in UWPT for AUVs. The research highlights the major impact of UWPT technologies, including IPT and magnetically coupled resonant WPT, on enhancing the efficiency and autonomy of AUVs. This review reveals significant progress in optimizing magnetic coupler designs, augmenting alignment tolerance, and mitigating eddy current losses. Additionally, the integration of adaptive control techniques has shown promise in bolstering the strength of UWPT systems against the unpredictable and demanding conditions of underwater environments. With these technological advancements, there are still some unresolved issues. The efficiency of UWPT systems is hindered by the sensitivity to misalignment and the intricate interaction of eddy currents. With the increasing need for longer and more extensive underwater missions, it is essential to develop UWPT systems that are more durable and energy efficient. A major issue in Underwater WPT systems is low efficiency due to eddy current losses present in seawater. There is some early work to compute eddy current losses and a few innovative approaches to solve ECL problems in underwater. But still, new innovative UWPT systems are required to solve this problem. Future work will focus on improving tolerance to axial and rotational misalignment and minimizing eddy-current losses in conductive seawater. Additionally, more experiments in real underwater conditions, such as exposure to seawater, dynamic motion, changes in pressure, and long-term reliability effects, are needed to enable fair comparisons across studies.

Acknowledgement: Thanks to Prince Sattam bin Abdulaziz University for supporting this work. The author declares that AI-assisted tools such as Grammarly were used in the writing, editing, or preparation of this manuscript.

Funding Statement: The author extends appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/03/34113).

Availability of Data and Materials: The data presented in this study will be available on request from the corresponding author.

Ethics Approval: Not applicable.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

AUV	Autonomous Underwater Vehicle
WPT	Wireless Power Transfer
USV	Unmanned Surface Vehicle
UWPT	Underwater Wireless Power Transfer
EVs	Electric Vehicles
IWPT	Inductive Wireless Power Transfer
OTEC	Ocean Thermal Energy Conversion
CWPT	Capacitive Wireless Power Transfer
MCR-WPT	Magnetically Coupled Resonant Wireless Power Transfer
UOWC	Underwater Optical Wireless Communication
LCT	Loosely Coupled Transformer
SWPDT	Simultaneous Wireless Power and Data Transfer
EMF	Electromagnetic Field
CTAT	Coil Tilt Angle Theory
ROV	Remotely Operated Vehicle
MSG-WPT	Metal Surface Guided Wireless Power Transfer
GPS	Global Positioning System
IOT	Internet of Things
USN	Underwater Sensor Network
MIMO	Multiple-Input Multiple-Output
UWCS	Underwater Solar Cells
SAUVs	Solar-powered Autonomous Underwater Vehicle
PEM	Proton Exchange Membrane
UAV	Unmanned Aerial Vehicle
PTE	Power Transfer Efficiency
RF	Radio Frequency
Tx	Transmitter
Rx	Receiver
ECL	Eddy Current Loss

VI	Variable Inductor
FEA	Finite Element Analysis
FEM	Finite Element Method
EMI	Electromagnetic Interference

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