Master's Thesis

Coil Array Inductive Power Transfer System for Autonomous Underwater Vehicle

Yu Cheng
Program of Information Science and Engineering
Graduate School of Information Science
Nara Institute of Science and Technology

Supervisor: Professor Minoru Okada
Network Systems Lab. (Division of Information Science)

January 10, 2021

A Master's Thesis
submitted to Graduate School of Information Science,
Nara Institute of Science and Technology
in partial fulfillment of the requirements for the degree of
Doctor of ENGINEERING

Yu Cheng

Thesis Committee:

Professor Minoru Okada
(Supervisor, Division of Information Science)
Professor Yuichi Hayashi
(Co-supervisor, Division of Information Science)
Associate Professor Takeshi Higashino
(Co-supervisor, Division of Information Science)
Assistant Professor Quang-Thang Duong
(Co-supervisor, Division of Information Science)
Assistant Professor Na Chen
(Co-supervisor, Division of Information Science)

Coil Array Inductive Power Transfer System for Autonomous Underwater Vehicle*

Yu Cheng

Abstract

For a long time, providing a stable, safe, and efficient power supply for underwater electromechanical equipment has always been a concern in deep-sea exploration. Compared with the complicated docking mechanism, potential safety hazards, and expensive price of traditional wet-mate connectors, wireless power transmission (WPT) technology can transmit energy without any electrical contact between the power supply and the electrical equipment, which provides an effective solution to the aforementioned drawbacks of wired charging. There are many uncontrollable factors in the seawater working environment. Therefore, this topic takes the equivalent circuit and magnetic field distribution as the theoretical basis to study the energy transmission characteristics of underwater WPT and proposes corresponding improvements and solutions to the current problems and deficiencies. Especially for the unstable output voltage of the receiver and excessive magnetic flux density at the internal of AUV.

Keywords:

Autonomous underwater vehicle, inductive power transfer, underwater wireless power transfer, undersea

*Master's Thesis, Graduate School of Science and Technology, Nara Institute of Science and Technology, January 10, 2021.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background and research purpose

In the foreseeable future, the electrification of ocean systems, renewable ocean power sources and ocean energy networks will be necessary, which will help accelerate the growth and deployment of ocean renewable energy and ways to explore and understand the ocean [1]. To achieve electrification in the ocean, it is necessary to deploy corresponding sensor networks underwater and process the data received by underwater sensors in a timely manner. At the same time, underwater sensors are also an important tool for studying the marine environment. They can easily and flexibly explore underwater terrain and ecological environment, which provides convenience for the deployment of underwater sensor networks. A good underwater AUV needs to have good equipment waterproofness, long-distance underwater controllability and durability. For the water resistance of the equipment, we can use high-performance waterproof and pressure-resistant materials. The remote controllability needs to solve the problems of long-distance underwater communication. The durability of electrical equipment requires low energy consumption AUV and high-energy batteries or continuous equipment. Energy supply. Sufficient energy supply can keep underwater sensors and AUV equipment in an efficient and stable working state for a long time. Reducing human interference when electrical equipment is working underwater can also improve work efficiency and reduce deployment costs. Therefore, the energy supply for underwater electrical equipment has become a novel research direction. Such methods can solve the energy supply problem of underwater equipment economically and ensure the system to perform long-term and stable work [3]. In traditional marine engineering, power is supplied to underwater equipment through wet plug-in interfaces [4]. For the traditional wet plug interface technology, its high cost, complex docking method, poor safety performance, and easy to be corroded by seawater, make its disadvantages in marine engineering increasingly obvious. Wireless Power Transfer (WPT) simplifies the connection between underwater equipment and power supply, reduces the continuous operating cost of underwater equipment, saves a lot of resources, and gradually gains the favor of scholars.

The ocean itself and its surroundings contain a lot of energy, such as tidal energy, wave energy, ocean current energy, sea temperature difference energy, and sea salt difference energy. Ocean energy is rich, widely distributed, clean and pollution-free, but low energy density and strong regionality. These advantages make it attractive as a grid-connected energy, and may also make it an isolated and remote ocean energy source, thereby providing a valuable source of ocean space. Continuous development provides power solutions that are attractive. The rapid development of distributed ocean energy applications (such as underwater sensor networks, ocean sensors and monitoring technologies, ocean automatic network buoys, and deep sea and tsunami buoys) is beneficial. In particular, it can power an autonomous underwater vehicle (AUV) whose service life is limited by its battery power.

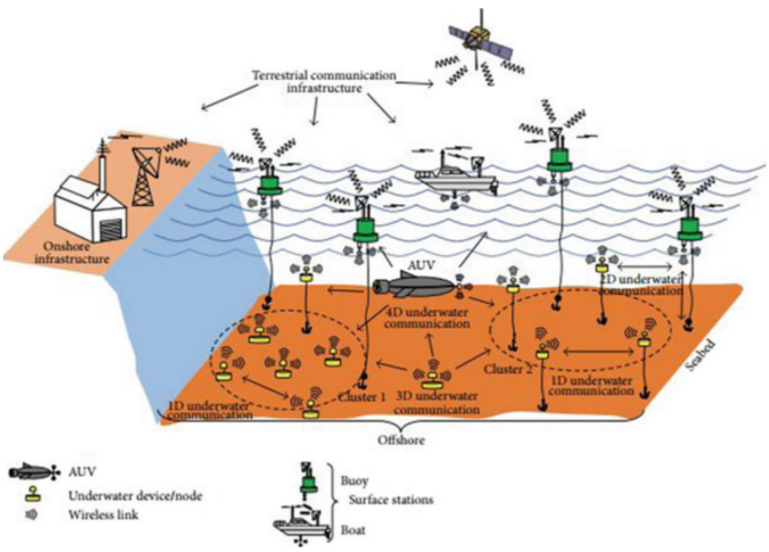


Figure 1.1: Underwater sensor networks architecture [2].

1.2 Wireless power transfer technologies

Broadly speaking, power transfer without direct "electrical contact" between the primary and secondary is wireless power transfer. Wireless energy technology can be divided into two main categories, Near-field (nonradiative region) power transfer and Far-field (radiative region) power transfer. Near-field means the area within about 1 wavelength (λ) of the antenna. The range of near-field devices is conventionally divided into two categories:

- Short range – up to about one antenna diameter: $D_{range} \leq D_{ant}$. This is the range over which ordinary nonresonant capacitive or inductive coupling can transfer practical amounts of power.

- Mid-range – up to 10 times the antenna diameter: $D_{range} \leq 10D_{ant}$. This is the range over which resonant capacitive or inductive coupling can transfer practical amounts of power.

Far-field or radiative region – Beyond about 1 wavelength (λ) of the antenna, the electric and magnetic fields are perpendicular to each other and propagate as an electromagnetic wave; examples are radio waves, microwaves, or light waves. $D_{ant} << \lambda$.

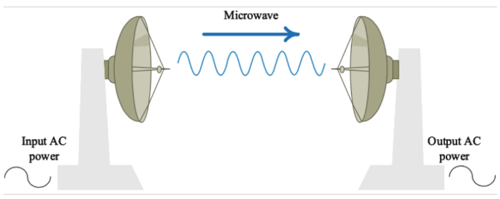
Therefore, long-distance wireless power transmission includes microwave, light, and sound wireless power transfer. Short-distance wireless power transfer includes short-distance magnetic field transmission using inductive coupling or electric field using capacitive coupling transmission. The respective characteristics are shown in the table 1.1.

1.3 Underwater wireless power transfer

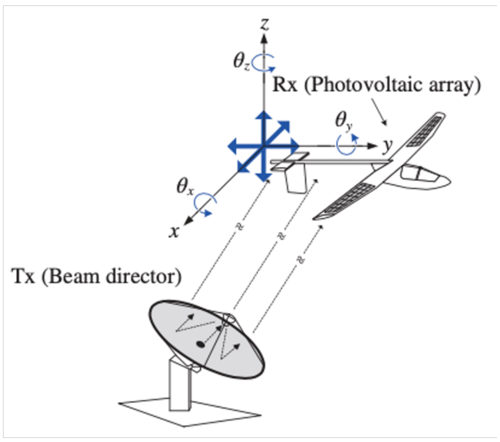
WPT technology has unique advantages in special environments, and along with the continuous development of landing application research and the emergence of a large number of results, it has attracted the attention of underwater technology researchers. As early as 2000, he et al. developed a sub-level rail-type charging device. As shown in the figure, the transmission efficiency is about about. At the same time, the study launched a preliminary discussion on the loss in seawater. The difference between water and air

Table 1.1: The different wireless power transmission technologies.

Technology	**Range**	**Frequency**	**Antenna devices**	**Applications**
Microwaves	hm - km	GHz	Parabolic dishes, phased arrays, rectennas	Satellite, drone aircraft
Optical	dam - km	≥THz	Lasers, photocells, lenses	Drone aircraft, space elevator
Capacitive	cm - m	kHz – MHz	Metal plate electrodes	Smartcards, biomedical implant
Inductive	mm - m	Hz – GHz	Tuned wire coils, lumped element resonators	Electric toothbrush, smartphone, electric vehicle

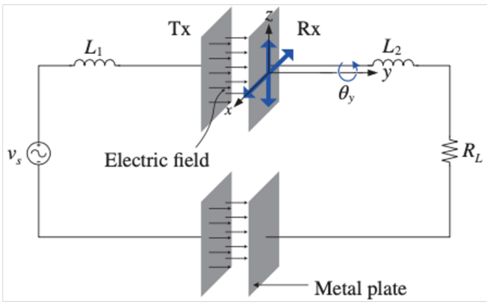


(a) Microwave power transfer [1].

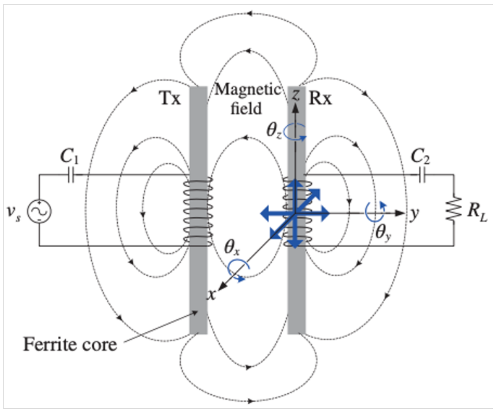


(b) Laser power transfer [3].

Figure 1.2: Far-field wireless power transfer.



(a) Capacitive power transfer [3].



(b) Inductive power transfer [3].

Figure 1.3: Near-field wireless power transfer.

1.4 The main research content of this thesis

Research on the characteristics of underwater wireless energy transmission. The design of the underwater wireless energy transmission coil, this research obtained by changing the size, spacing and distribution of the coil It provides reference materials for the subsequent research on the wpt system of multiple coil groups.

1.5 Roadmap

The first chapter analyzes the background of this research and its research purpose and significance, analyzes the characteristics and advantages and disadvantages of mainstream WPT technology, and provides a basis for using IPT technology as an underwater wireless energy transmission system in the following text. A detailed summary and analysis of the current research status of related technologies at home and abroad, including underwater wired energy transmission technology, WPT technology in underwater and air media, and an explanation of the research focus of this article.

The second chapter focuses on the analysis of the basic theory of wireless energy transmission. The equivalent circuit model and network port model are used to derive the main transmission performance indicators of the system, and the influence of design parameters on the system performance is analyzed to provide theoretical support for subsequent design. Take sea water as an example to simulate the working environment of the system under water. And through simulation software to simulate and analyze related models.

Chapter 3 first analyzes the basic principle of the parallel MRC-WPT circuit, and then based on the WPT model of the ordinary air-core coil, respectively, to address the horizontal offset and angular offset of the transmitter coil and the receiver coil, a new type of battery that can meet the charging requirements is proposed. The wireless energy transmission method of two-dimensional air-core coil and three-dimensional air-core coil enables the transmission efficiency of the underwater MRC-WPT system to be steadily improved. According to the structural characteristics of each method, the corresponding underwater wireless robot model is designed to meet the application conditions.

The fourth chapter first studies the magnetic field characteristics of the air gap coil, focusing on the analysis of the magnetic core's restraining effect on the coil magnetic field, and simulates the magnetic field distribution of the coil containing the air gap core, and proposes a new type of four-phase core coil. The method of wireless energy transmission. By studying the transmitting phase of the four transmitting coils, the induced magnetic fields in the four receiving coils will not cancel each other, and stable energy transmission can be carried out. Then the four-phase magnetic core coil transmission scheme is simulated. Aiming at the characteristics of its magnetic field distribution, the AUV model proposed in the previous article is taken as an example, and a universal application model of the structure is designed under water.

2 Basic principles of IPT

This chapter will first introduce the principle of IPT technology from the physical level, and then introduce the principle of IPT technology from the circuit level, analyze the relationship between different equivalent models, and derive system energy transmission indicators that can represent system performance. And analyze the influence of relevant design parameters on system transmission performance. Analyze the influence of the medium on the system performance in the WPT process, and propose an equivalent model in the underwater working environment. Perform simulation analysis on the derivation to ensure that complete theoretical support is provided for more detailed theoretical research and research on new IPT technology. Fig. 1(a) depicts the circuit model of IPT systems [4]-[5]where the transmitting coil L1 and the receiving coil L2 are directly connected to the power source and the load impedance ZL, respectively. Denote M12 as the mutual inductance, R1 and R2 as the equivalent AC resistance of coils.

2.1 Compensation network technology

SS, SP, LCL ...

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

2.2 Underwater WPT system model

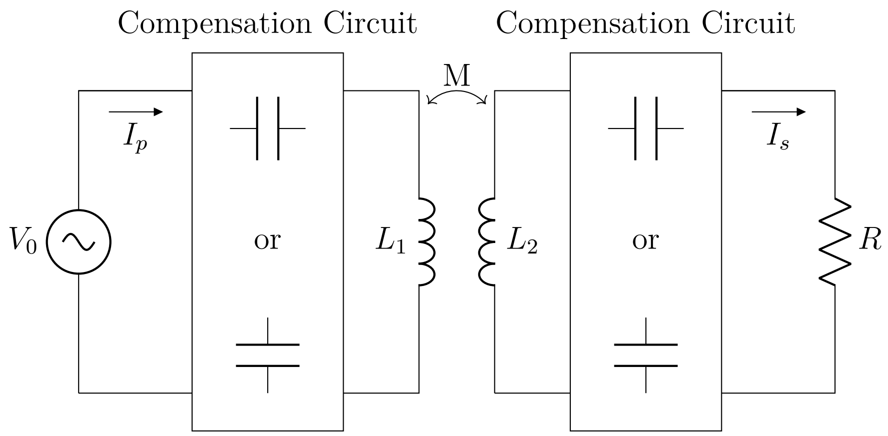


Figure 2.1: test

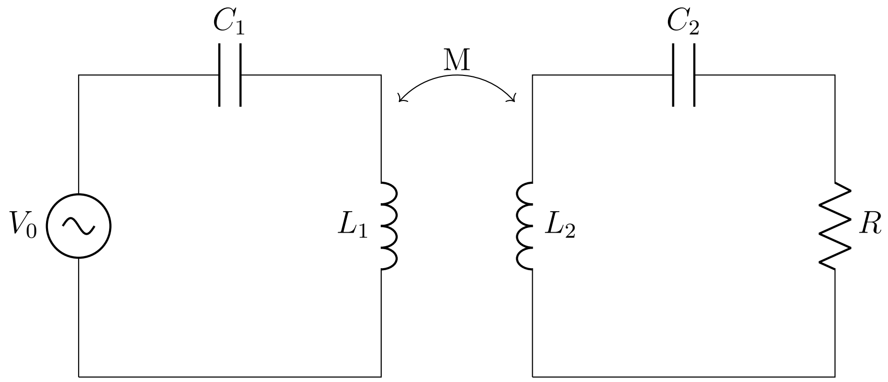


Figure 2.2: SS.

3 Coil array WPT

Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui

3.1 Simulation evaluation

3.1.1 Simulation evaluation

3.2 Coil array WPT in the air

3.3 Coil array WPT under seawater

4 Conclusion

L

4.1 Future works

Acknowledgements

First of all, I would like to thank my supervisor, Professor Minoru Okada. Professor Okada is kind, knowledgeable, and rigorous in scientific attitude. Thank him for giving me an opportunity to study in Japan and let me do wireless power transfer research that I am interested in. He has continued to help me during my three years of study and life. At the same time, I would like to thank Professor Yuichi Hayashi for my research advice and guidance, so that I have a deeper understanding of the weak research environment. With his help, Which greatly improved my research.

Then I would like to thank Associate Professor Takeshi Higashino and Assistant Professor Duong Quang Thang. With their help, they have made me better understand the knowledge of wireless power transfer and wireless communication, and they have helped me overcome the difficulties in professional understanding and helped me complete this topic. Thank them very much. Here, I would also like to thank Assistant Professor Chen Na for her continuous help and encouragement in my studies, so that I have a better understanding of the field of communication.

I would also like to thank the members, staff, and seniors of the Network Systems Laboratory for their companionship in the study and life. We studied together and played together, and established a strong friendship together. Thank you to the international students who have helped me while studying abroad. Thank you for your kindness to me.

Finally, I would like to thank my family for their support of studying abroad, let me choose the knowledge I like, and always provide me with abundant financial support.

Thank you all for your attention!

References

[1] Orekan, T., Zhang, P.: Underwater Wireless Power Transfer—Smart Ocean Energy Converters. Springer Briefs in Energy. Springer, Cham (2019)

[2] Nayyar, Anand & Balas, Valentina. (2019). Analysis of Simulation Tools for Underwater Sensor Networks (UWSNs): Proceedings of ICICC 2018, Volume 1. 10.1007978-981-13-2324-9_17.

[3] Chun T. Rim, Chris Mi: Wireless Power Transfer for Electric Vehicles and Mobile Devices, First Edition. Joho Wiley & Sons, (2017)