6. UAP Thesis Proposal:
Design of an Inductively-Coupled AUV Recharging System

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1 Project Overview

Many autonomous underwater vehicles (AUVs), like those developed by the MIT SeaGrant AUV lab, use a lithium-ion polymer battery as their source of power. Currently, recharging these batteries is a time-consuming and labor-intensive effort which involves removing the vehicle from the water, opening the vehicle, removing the battery, charging in an external charging setup, and then returning the battery and reassembling the vehicle. By designing a charging system utilizing inductive coupling, the battery can be recharged while the vehicle remains closed and in the water. This will greatly simplify the charging process, allowing the vehicle to quickly charge and return to operation.
2 Project Background and Previous Works

The MIT SeaGrant AUV Laboratory has spent the last fifteen years developing autonomous vehicles for underwater exploration and research. These vehicles are equipped with computer systems to control their navigation, control, and data acquisition, as well as sensors to explore the underwater environment. Due to their autonomous nature, the vehicles require an on-board power supply to drive the on-board equipment that controls everything from navigation to running underwater experiments. Running so much equipment for any length of time requires a high energy density battery. Lithium-ion polymer batteries are conventional for AUVs because they possess a higher energy density than many other types of batteries, so they are able to run for long periods on a single charge. The current method of charging these batteries involves removing the AUV from the water, opening the casing, removing the battery from the AUV, and charging it in an external unit. This process is time consuming, and potentially damaging to the AUV as the watertight case must be opened repeatedly. A simple and efficient method of charging the batteries will allow improve AUV performance, and allow the vehicle to spend more time performing missions.

There have been several advances toward using inductive coupling to simplify charging of the AUV. In Design of an AUV Recharging System[1], Gish proposes a larger docking system involving inductively-coupled transfer for battery charging. However, this work focuses on physical and electrical simulation using a linear coaxial-wound transformer, and did not take into account any actual charging schemes.

The most recent work toward a simpler recharging system is found in Design of an AUV Recharging System[3]. This work details a method of charging the batteries through a separable plug-like transformer, including designing and simulating electronics to regulate the charging of the battery. The paper also tests a basic version of the charging electronics, finding agreement with the simulations. Unfortunately, Miller was not able to integrate the
system with an AUV to test actual charging.

In *Inductively-Coupled Power Transfer for Electromechanical Systems* [2], a similar approach of using separable core transformers is examined for several power transfer applications. This work details the design and implementation of inductive power transfer systems, including the feedback control to drive the systems. Development of non-contact power transfer for electric vehicles described in this thesis can also be applied toward applications involving battery charging for AUVs.

A detailed analysis of separable core transformers is found in *The Effects of Separable Cores on High Power Transformer Design* [4]. This work provides models and simulation of various effects that arise in the separable core transformers we wish to use for the AUV recharging system. A commercial application of using a separable transformer to recharge an electric car is also examined, providing insight toward applications with AUVs.

## 3 Proposed Research

The prior works have paved the way for, but not established, a fully implemented on-board charging system for use with an AUV. Such a system would integrate the charging circuitry with the on-board power management of the vehicle, as well as provide the necessary connection interfaces to standard power sources. This would allow the AUVs to be charged quickly, without needing to remove the AUV from the water or open the water-tight casing.

The inductively-coupled system will need to be composed of several parts to utilize the separable core transformer. The available shore-side power supply will be the 120 V, 60 Hz supply found either on the dock or ship which the AUV is charging from. Because a transformer operating at 60 Hz would be excessively large, the shore-side supply will need to be converted to a higher frequency, which will drive the transformer and pass power between the supply and the AUV. On the AUV side, the AC voltage will be converted to DC, and
then reduced to the proper voltage to charge the battery. A complete diagram of the system can be seen in Figure 1.

The system will be designed to accommodate two different models of AUV, the Odyssey 3 and Odyssey 4. The major differences between these two models is their batteries. Both use lithium-ion polymer batteries, but the Odyssey 3 runs on a nominal 34 V, while the Odyssey 4 will use a higher voltage battery at 90 V. Since the battery chemistry is the same, we can use similar charging profiles to charge each of them. The large difference in voltages may require different transformer designs, as the ratio of turns in the transformer determines the voltage delivered to the secondary of the transformer on board the AUV. This allows a single setup to be used on the shore-side primary, which can connect to either of the two AUVs interchangeably.

Our specifications for the system state that it should be able to deliver a peak current of 10 A to the battery for charging. This requires a nominal power of 1 kW to be delivered by the battery, which must be supplied by the shore-side connection. At this rate, the batteries will require upward of 5 hours to charge, such that faster charging approaches may be investigated.
3.1 Transformer Design

The design of the separable core transformer determines the capabilities of the recharging system. The transformer must be low loss at the operating frequencies, and be small and light enough to package with the AUV. The transformer must also step the voltage from the shore-side electronics to the AUV electronics up or down appropriately. In previous efforts, an E core transformer was used, with 20 winding turns on the primary side (shore-side) and 8 turns on the secondary (AUV-side) [3]. This transformer was designed to operate at 20 kHz, and specifically designed to charge the batteries on the Odyssey 3.

To provide a system usable on both the Odyssey 3 and Odyssey 4, a single primary setup will be used, with a different number of secondary turns used for each vehicle. The transformer design will be reexamined, particularly with respect to the operating frequency. By increasing the operating frequency, we can reduce the losses in the transformer, and reduce the size of the transformer. The choice of transformer may also be reevaluated according to the transformer’s characteristics. A cylindrical core transformer may prove to make a simpler connection than the current E core transformer, while keeping similar energy transfer characteristics.

3.2 Shore-side Electronics

Power on the shore-side needs to be converted from the available 120 V at 60 Hz to a higher frequency signal with which we can drive the transformer primary. This can be achieved by rectifying the input to a DC voltage, and then converting back into an AC signal at our desired frequency. Ideally, this stage should be low loss, as we would like to maximize the power delivered to the transformer.

To convert from AC to DC, a diode bridge rectifier will be used, producing a DC voltage of 170 V. The conversion from DC to AC will use a H-bridge switch, consisting of four
switches operating in pairs to periodically flip the voltage across a load, in this case the transformer primary. An H-bridge is chosen to maximize the voltage across the transformer, reducing the current through the transformer, which should reduce the power dissipated. This produces an output to the transformer primary of 340 V, which will be stepped down by the transformer to a more reasonable value for each AUV.

### 3.3 AUV Electronics

The secondary coil of the separable core transformer is located aboard the AUV, and delivers the power needed to charge the battery. However, the secondary provides an AC voltage at the frequency that the transformer was driven, and the battery requires a variable DC voltage. To convert, the signal must again be converted to DC, then actively stepped down to the required voltage.

Converting from AC to DC is done similarly to on the shore-side with a diode bridge rectifier. The conversion between this new DC supply and the variable supply needed by the battery utilizes a Buck converter. Since we wish to charge the battery at a constant current, the Buck converter is driven with feedback from the current delivered to the battery, controlled by a microcontroller. This microcontroller will monitor the current fed to the battery, as well as the cell voltages within the battery, and determine the optimal current from these measurements. With this approach, the battery can be quickly charged to its nominal voltage, and then slowly charged to full capacity.

### 4 Conclusion

For the current SeaGrant AUVs, recharging the batteries is a complicated and tedious process. By creating a simple non-contact inductively-coupled recharging system, the process can be expedited, and the vehicles can return to their missions in less time. This method of
recharging opens up possibilities for autonomous docking and recharging, as well as opportunities to recharge the vehicle more quickly.

References


