Non-Contact Wet Mateable Connectors for Power and Data Transmission

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***Abstract*—Subsea systems rely on wet mate connectors in many form factors for power transmission and communications. Reliability is a universal concern, because a failed connector can cause lost production, lost scientific data, or lost military capability. Conventional wet mate connectors use dynamic seals, moving parts, and displaced compensation fluids to protect critical components from corrosion and contamination when unmated, while providing contact for power and data connections when they are mated. This complexity increases cost and decreases reliability.**

Battelle performed failure modes, effects, and criticality analysis (FMECA) for typical wet mate connectors to guide the development of alternatives. Multiple configurations of non-contact connectors were developed, using inductive power coupling and radio frequency and optical communication to eliminate many of the failure modes associated with conventional wet mate connectors. The non-contact connectors do not require dynamic seals, tolerate more contamination and bio-fouling at the interface and are less sensitive to misalignment during mating. This paper describes case studies of Battelle wet mate non-contact connectors, as well as developmental connectors, collectively referred to as "OceanHub" connectors.

Keywords—wet mate connector, failure analysis, non-contact connector, inductive coupling, data transfer

I. Introduction

Commercial, scientific, and military subsea systems rely heavily on wet mate connectors for power transmission and communications. Depending on the application, these connectors can have a variety of form factors, but a universal concern is reliability. A failed connector can have serious consequences due to lost production, lost scientific data, or lost military capability. Wet mate connectors, especially those that incorporate power and communications, are complex and expensive. The complexity is driven by the need to protect critical components from corrosion and contamination when the connectors are not mated while providing correct contact of power and data connections when in the mated condition.

Over the course of several programs, Battelle has studied this issue and developed a viable alternative that can increase the reliability of wet mate connectors and reduce the risk of connector failure. To begin, an analysis was performed to understand the failure modes, their effects, and criticality (FMECA) for typical wet mate connectors [1]. A FMECA documents the ways in which a part or an assembly can fail. For each failure mode, the effect of the failure is analyzed and documented. The criticality and probability of each failure mode is then assessed. Over the following programs, Battelle has worked to develop a portfolio of commercially viable non-contact wet mateable connectors, collectively referred to as "OceanHub" connectors. This paper will focus on this work by breaking it into three specific case studies.

II. Case Study #1: ROV-Compatible Connector Prototype

In 2009 Battelle presented a paper detailing work performed to develop a non-contact wet mateable connector for full ocean depth and remotely operated vehicle (ROV) manipulation. Fig. 1 shows a computer-aided design (CAD) rendering of the cross section of the connector. The function of the connector was to facilitate power transfer to, and data transfer to and from, underwater sensors. [2] The work culminated in proof-of-concept hardware being built and tested in a salt water environment.

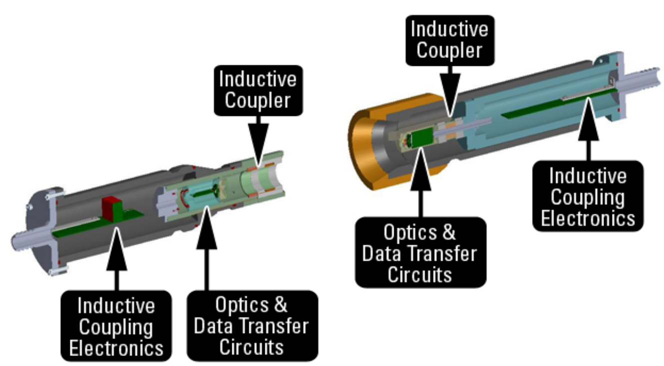

Fig. 1. Non-contact wet mateable stab connector

Power was transferred via inductively coupled primary and secondary transformer cores. The transformer design goal was 10W at 85% efficiency. As stated previously, a proof-of-concept transformer was fabricated and tested in a simulated saltwater environment. Real world power transfer of 10W at 75% efficiency was achieved. The drop in efficiency was attributed to the wire used in the transformer windings, since a

The Office of Naval Research and Commander, Submarine Force, U.S. Navy supported development of the UUV Docking and Recharging Station (UDRS) described in this paper.

solid wire was used in both the primary and secondary coils. Litz wire is the preferred wire for the frequency at which the transformer was operating, and suggests that 85% efficiency could be achieved using Litz wire windings.

Data transfer was accomplished via an optical coupling method, through windows located on the centerline of each connector half. The optical path includes high index lenses and beam splitters to pass both directions of communication through a single window. Transmission occurs through an 850 nm light-emitting diode (LED) to a coupled photodiode. The system circuitry developed has a serial transceiver chipset to convert an RS232/422/485 signal to levels appropriate for the LED and diode. The chipset used was limited to a data transfer rate of 600 kbps and the LED used implied a bandwidth of 17.5 MHz. However, the data rate was held to a lower value by built-in limiters to extend the life of the LED. Accordingly, higher data rates should be achievable by using laser diodes rather than LEDs in the optical coupler.

The proof-of-concept transformers were combined with prototype power converters to determine end-to-end efficiency. Power and data transfer were tested in parallel to simulate a real world situation. Data transfer operated at 115.2 kbps and several different loads were simulated. The overall end-to-end power transfer efficiency was about 66%. An improvement of 10-15 percentage points is possible with the switch to Litz wire and further refinement of the circuit.

The wet mateable connector is housed in two halves designed to be manipulated by an ROV. The connector halves are about 3.5" in diameter, and each has 4" long flats to facilitate gripping by a manipulator. The two halves do not require a specific orientation for mating. They can be engaged with 40-60 lbf, withstand a tensile load of 3000 lbf once mated, and have a depth rating of 23,000 ft. The circuitry needed for power and data transfer is pressure tolerant and housed in the connector bodies, with a pressure balanced oil filled (PBOF) connector.

III. CASE STUDY #2: UUV RECHARGING AND DATA TRANSFER

In September 2011, Battelle and Bluefin Robotics performed at-sea trials of an Unmanned Underwater Vehicle (UUV) Docking and Recharging Station (UDRS). [3] Prototype development was initially sponsored by the Office of Naval Research (ONR), while Commander, Submarine Force (COMSUBFOR) funded the final assembly and testing. The goal of UDRS was to demonstrate the capability to remotely launch and recover multiple UUVs and to provide the capability to recharge vehicles, offload mission data, and download new missions to the UUV, with all activities performed underwater. The vehicle used was a custom modified Bluefin-12.

Non-contact power and data transmission were again incorporated to increase the reliability of the connection. In the previous case study, a single pair of inductive coupled primary and secondary cores was used to transmit 10W of power. In the UDRS configuration, a much higher power transfer rate was desired, such that the system could recharge a 6 kW-hr battery in 4-6 hours. Target system efficiency was 75%. A system of eight primary and secondary cores was implemented, with the design goal of 250W per transformer pair. Fig. 2 shows the electromagnetic finite element analysis (FEA) of this loosely coupled transformer. The system goal was to transfer 1.5 kW accounting for losses.

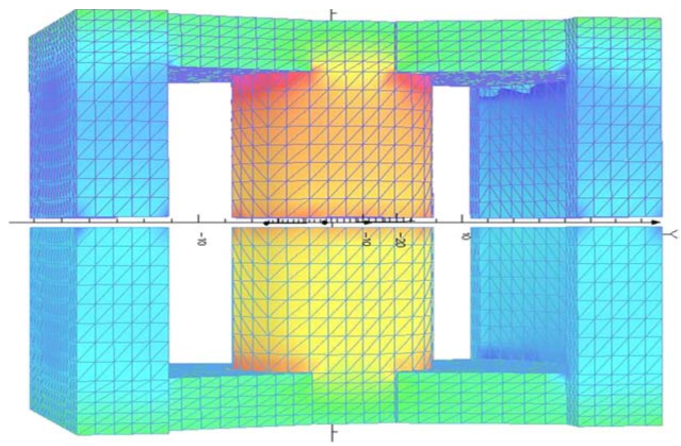

Fig. 2. Electromagnetic finite element analysis of loosely coupled transformer

High speed data transfer was desired primarily to offload mission data, but the data transfer system would also have to handle uploading new sortie instructions to the UUV and providing feedback on housekeeping functions such as battery charging. Based on a tradeoff study that evaluated available technologies against program constraints, Battelle chose the Wi-Fi 802.11b standard as the data transfer method, with the option for future upgrades. Preliminary in-water testing in a laboratory salt-water tank proved that potted custom built patch antennas could pass a signal through up to 7 inches of water. The system design locates the two antennas across a gap of 0.5 inches.

The transformers were arranged in a configuration unique to the UUV application. Fig. 3 shows the arrangement on the docking station side, where pairs of transformers were mounted on spring loaded brackets, two per side of the vehicle, for a total of four separate brackets. These brackets were incorporated into two vehicle clamps, one on each side of the vehicle, which aligned and secured the vehicle. The Wi-Fi antenna was incorporated into one of the two vehicle clamps.

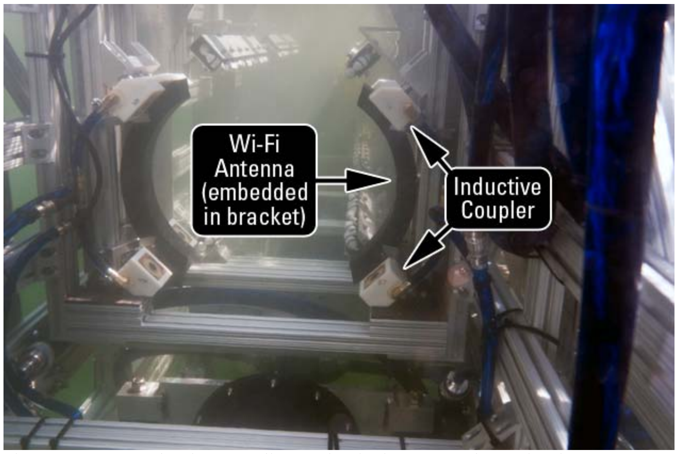

Fig. 3. UDRS Inductive coupling and Wi-Fi antenna shown in-situ

Initial calculations predicted an efficiency of better than 90% for the transformer cores. Preliminary testing in a laboratory saltwater environment, using a 1000 W proof-of-concept transformer, demonstrated 95% efficiency for the transformer. Next, the full system electronics were built and the system tested end-to-end, using an electronic load to emulate the battery. Measurements were recorded for two possible battery voltages, 27V and 32V. Fig. 4 shows the efficiency curves, and indicates that 75% system efficiency is possible. During this phase, battery charging was limited to 500W. As illustrated in Fig. 5, total system efficiency for a wireless (non-contact) UUV charging system is calculated using a combination of the following subsystem efficiencies: wireless power transfer subsystem efficiency and on-vehicle battery charger subsystem efficiency. Any comparisons between power transfer options for a wireless UUV charging system should account for total system efficiency as described herein.

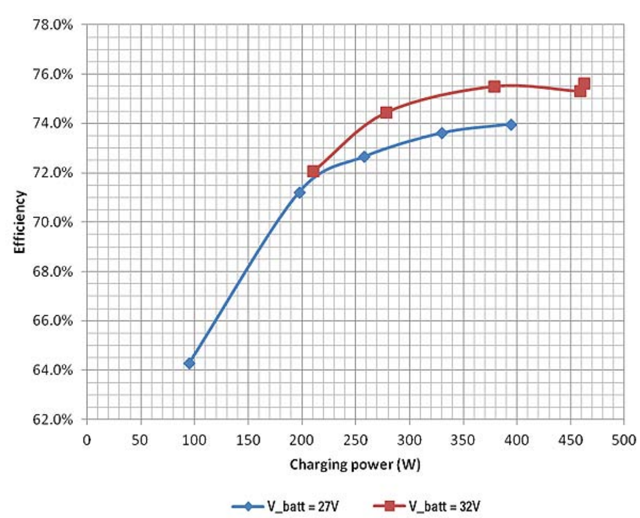

Fig. 4. Power transfer and charger system efficiency

The power and data transfer systems were both demonstrated as part of an at sea trial that incorporated a complete UUV mission—that is, the vehicle launched autonomously from the UDRS, performed a mission, autonomously docked back into the UDRS, transferred its mission data wirelessly, and recharged its batteries wirelessly. During this at-sea demonstration, the system transferred power at a rate of 450W. Again, the transfer rate was limited by the existing hardware configuration, and would scale up predictably. Data transfer was 600 KB/s from UUV to UDRS, and 400 KB/s from UDRS to UUV. The data rate was limited by the existing 802.11b hardware; it is anticipated to scale by a factor of 5-10 or greater with the newer standards available.

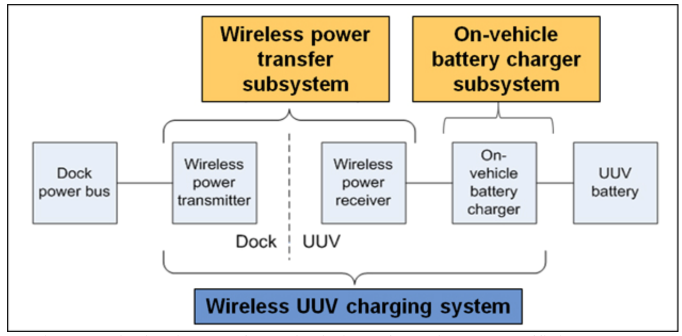

Fig. 5. Block Diagram for Calculation of Total System Efficiency

IV. Case Study #3: Next-Generation OceanHub Connector

Battelle is currently conducting internally funded research and development (R&D) to demonstrate next-generation non-contact wet mateable power and data transfer. Battelle's OceanHub R&D effort focuses on increased power transfer, increased system efficiency and reduced payload size. Power is transferred via a single pair of inductive coupled transformer cores of new design, resulting in an approximately 50% volume savings compared to the UDRS implementation. Computer simulation predicts system efficiency reaching 90%, as shown in Fig. 6, which plots system efficiency as a function of power. Due to higher achieved system efficiency, the system power output will increase to 1700 W. Output voltage and current ranges for this new configuration of the OceanHub connector are 20-34 VDC, 0-50 ADC.

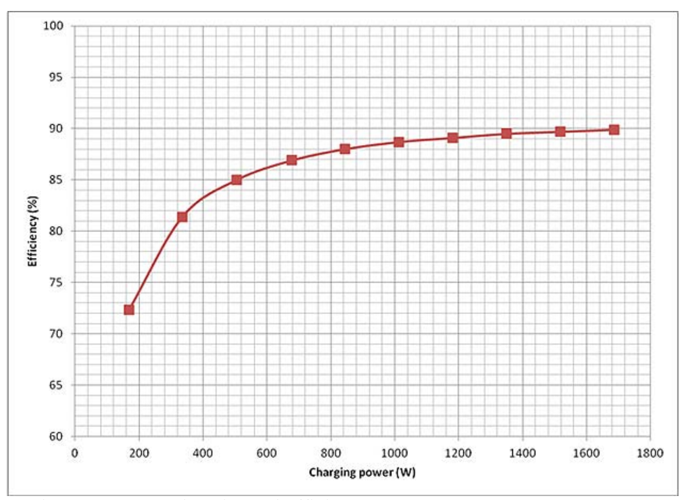

Fig. 6. OceanHub estimated efficiency curve

A study has been completed to assess the current state of the art for data transmission, with several candidates being considered for integration with the improved inductive coupling power transfer. Optical data transmission holds the greatest promise for high data rates but also involves the most technical risk. With new standards available, Wi-Fi holds the promise of reaching a 1.5Gbps raw data rate in water.

With baseline analyses complete, fabrication of a prototype unit is underway. Power conversion electronics for both the primary and secondary sides have been designed and are being fabricated or procured. The transformer cores are ready, and the transformer housing and test stand are in final design stages. The project will culminate in an end-to-end system demonstration in a laboratory seawater environment.

V. Conclusion

Battelle believes there is value in developing commercially viable non-contact wet mateable connectors. Through several projects, each building on previous successes, we have been able to show continually improving power transfer system efficiency, increased levels of power transfer, and increased rates of data transfer in real world settings with the portfolio of OceanHub connectors. Non-contact wet mate connectors could improve the reliability of virtually any underwater system relying on wet mate connections. From security to monitoring of natural habitats, having a network connected with a non-contact connector could reduce total cost of ownership, improve network reliability, reduce downtime and free up resources for more important functions.

References

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