Engineering Analysis

Underwater Drone Sensor Package

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2022-NOV-10

ENGR 446 Report

Contents

I. Glossary

PEC	Pulse Eddy Current
CDS	Corrosion Detection System
UW	Underwater
HE	Hall Effect
PWM	Pulse Width Modulation
ADC	Analog Digital Converter
EC	Eddy Current
SMU	Sensor Module Unit
CU	Command Unit
RU	Relay Unit
MCU	Microcontroller unit
PCU	Power Control Unit

II. Proposed Solution

This solution consists of sensor module units (SMU) installed on AUVs, air-water communication relay nodes (RN), and a centralized command unit (CU).

A. *System Description*

The sensor modules collect data and communicate with both the drones and central command. The relay's possesses transceivers for both radio and water communications that allow for underwater sensor modules to communicate with the land-based command unit. Below is an example deployment scenario.

A harbor purchases several drone systems and equips them with sensor modules. Relay devices are installed on piers to give communication coverage throughout the harbor. The relays communicate via Wi-Fi to the central command unit and use an underwater sonic/laser communication method to communicate with the sensor modules. The sensor modules use mesh network technology to increase the signal and range of underwater communications.

Directed by the CU, the sensor modules control their respective drones to systematically scan new and moored vessels for corrosion. All data is saved and processed at the CU. AI algorithms are employed on the new and archived data to enhance the detection capabilities of the system. A few employees monitor and review to finding of the system. Harbor members and boat owners pay a monthly subscription to regular scan and updates from the system on the health of there hulls which pays for the system.

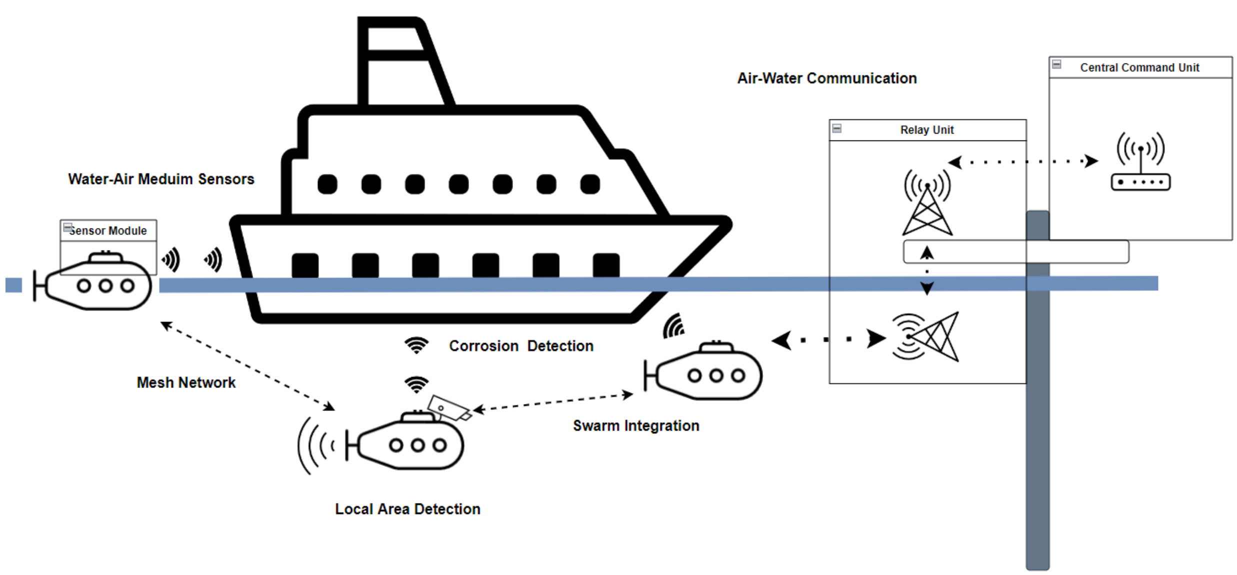

Figure 1: A sample deploy system using the sensor modules, relays, and CCU.

The focus of this analysis is on the SMU and corrosion detection from an autonomous drone. Other aspect of the system will be considered in a later report.

1) *Sensor Module*

The focus of this report is the sensor module. Figure 2 shows the component breakdown.

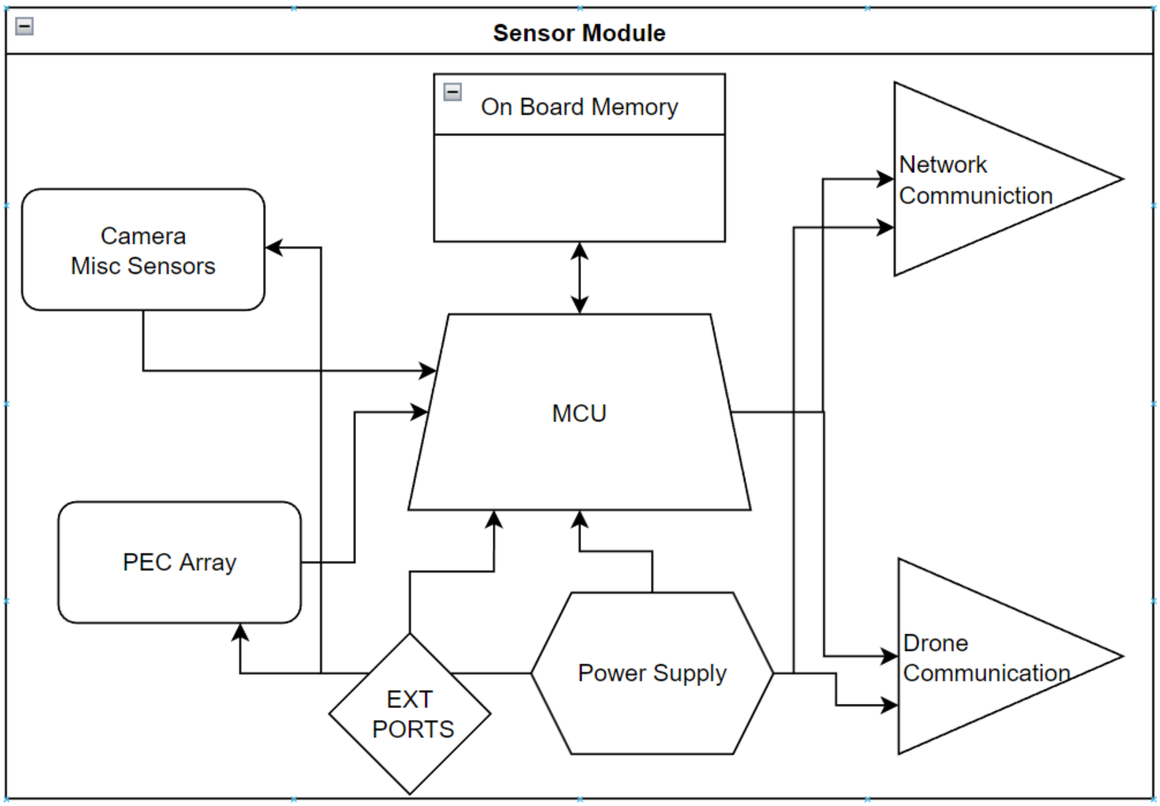

*Figure 2: Sensor module system diagram. *PEC: Pulse Eddy Current*

The MCU handles all processes within the SMU. It has communication links with the system network and the drone itself. The MCU has external ports (EXT PORTS) which allow a wired connection with an external computer or peripheral device. The onboard memory is for local data storage and backup storage in case of network communication failure. The camera and misc. sensor unit are to assist in navigation, obstacle avoidance, and manual override of a human operator.

2) *PEC Array*

The pulse eddy current (PEC) array is the primary unit of the sensor module and the focus of this report. The PEC array system model is shown in Figure 3.

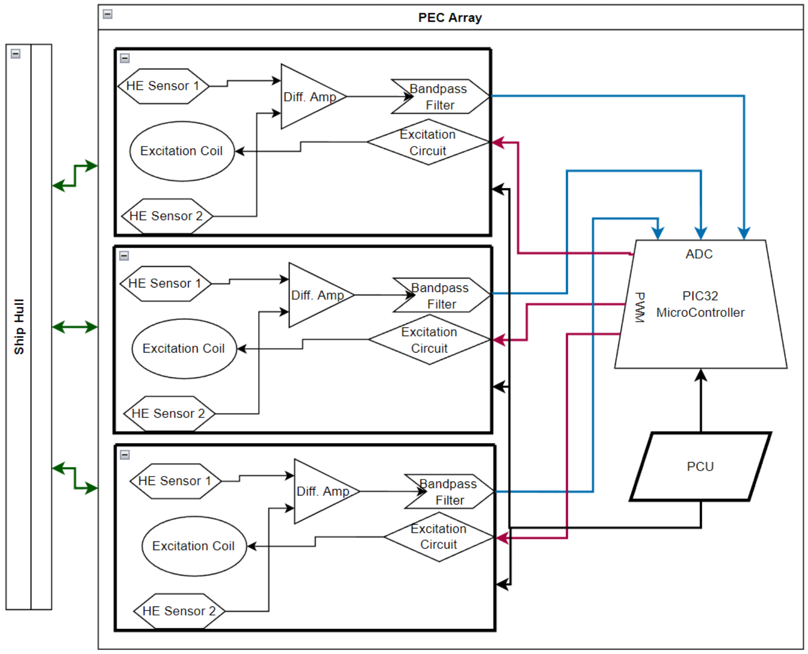

Figure 3: PEC array system. The array is made of one or more PEC detection units (Figure 4).

The PEC array consists of multiple instances of the PEC detection Unit (Figure 4). Each unit can detect corrosion in its area of effect. The area of effect of an individual unit is small (~40mm); consequently, an array of these devices will be used to create a large scan field.

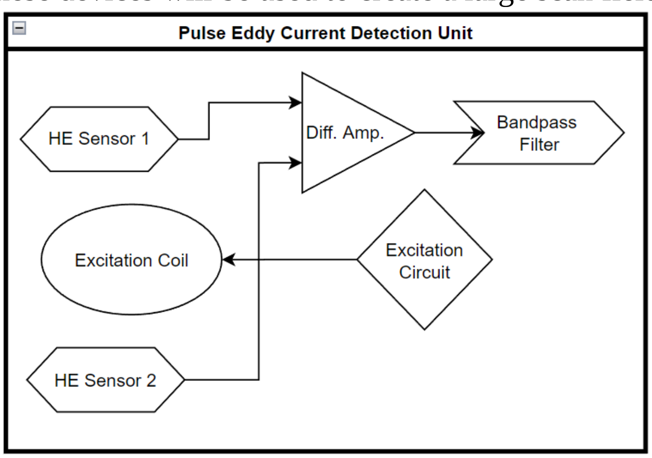

Figure 4: PEC detection unit

A description and analysis of each component in the PEC detection unit is covered in Section III.

III. Engineering Analysis

The PEC array is primary unit of the sensor module. Other component may be purchased OTS and require little analysis. A custom design is required for the PEC array to function on an AUV. Consequently, the engineering analysis will focus on this component.

A. *Pulse Eddy Current Hardware Design*

The PEC sensing device will include

1. An excitation coil
2. 2 Hall Effect sensors
3. A PWM excitation circuit
4. An amplifier circuit
5. A bandpass filter

The 2 HE sensor allow for a differential measurement. A differential measurement can reduce the need for a reference signal and make the sensor more versatile [1].

a) *Pulsed Eddy Current Detection Theory [1]*

EC detection uses an AC-driven inductor to induce eddy currents in a conducting sample. The induced eddy currents vary around flaws or defects in the conducting material. A magnetic sensor can detect these currents and variations. The penetration depth of these signals is related to the frequency of the driving signal as shown in the equation below [1].

$$\delta = \sqrt{\frac{2}{\varpi\mu\sigma}}$$

δ is the penetration depth at 1/e reduced density, ω is frequency, μ is magnetic permeability, and σ is electrical conductivity. Traditional EC uses a sinusoidal input at a given frequency. With only one excitation frequency, the sensor is limited to one penetration depth distribution. Alternatively, many frequencies (and therefore depths) can be expressed if a modulated square wave drives the inductor. The Fourier transform and power spectra of a pulsed square wave demonstrates this property (Figure 5 and Figure 6). This is known as pulsed eddy current detection (PEC).

$$f(t) = \begin{cases} A, & -\frac{T}{2} \le t \le \frac{T}{2}, \\ 0, & |t| > \frac{T}{2}, \end{cases} \qquad F(\omega) = \frac{2\sin\omega T/2}{\omega}.$$

Figure 5: Pulse waveform in time and frequency domain [1]

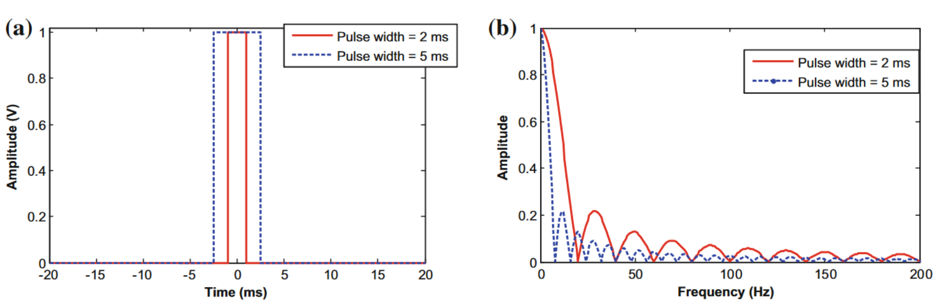

Figure 6: Power spectra of different pulses [1]

With PEC, the input wave may be modulated to achieve different depths and apply varying power to the inductor coil. Varying the pulse width also eliminates the need for a reference signal [2] (Figure 7).

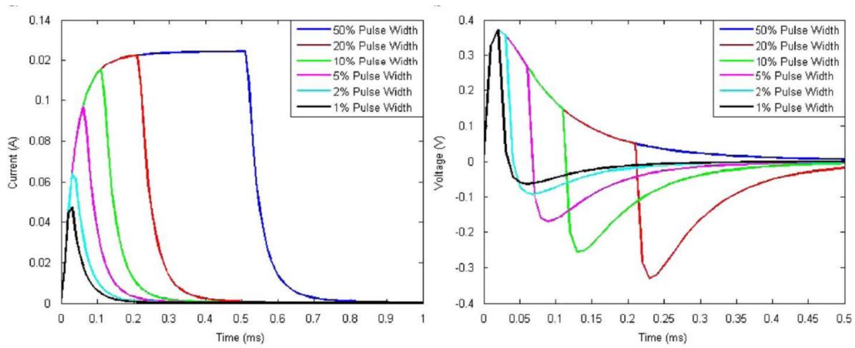

Fig. 5. Time-domain transient responses obtained through numerical modelling: (a) excitation current input with varied pulse width and (b) transient response on an unflawed section of the specimen with varied pulse width.

Figure 7: Simulated transient response of PEC [2]

2) *Hall Effect*

Magnetic sensors are commonly used at the detector for a PEC system. These devices detect the coupled magnetic field induced by the driving coil. This field is directly proportional to the eddy currents in the material.

Hall Effect (HE) sensor have the sensitivity requirements and are commonly used in this application [1], [3]. The governing equation for a HE sensor is

$$V_{HE} = K\ B$$

Where K is a constant coefficient specific to the device and B is the magnetic field density.

3) *Excitation Circuit*

Figure 8 shows the current response in the excitation coil to PWM input from a microcontroller.

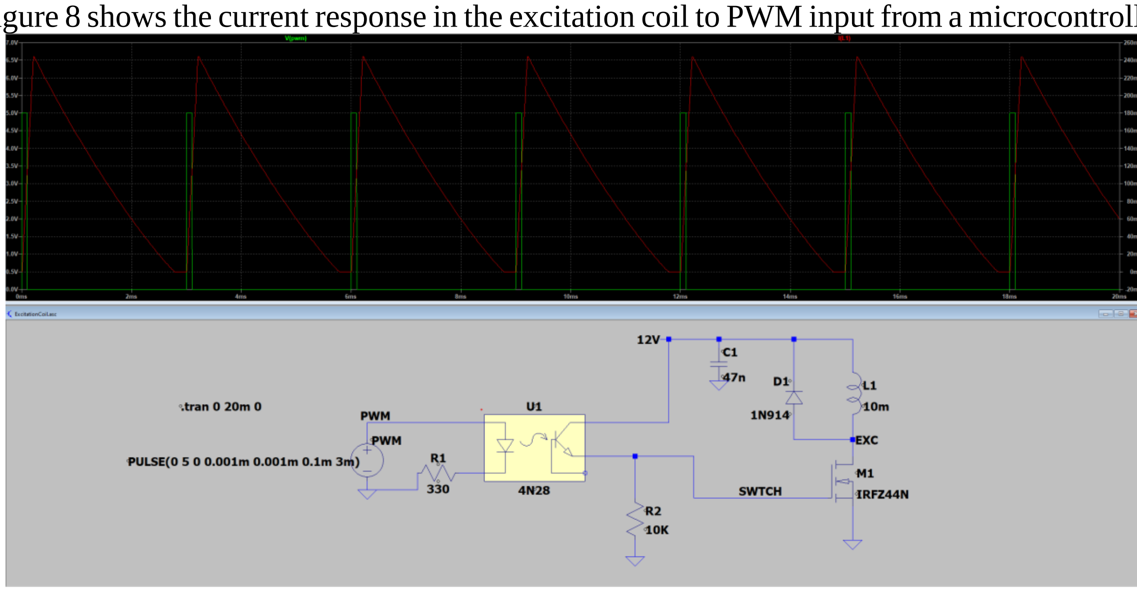

Figure 8: Simulated excitation inductor circuit for PEC sensor unit. Green plot shows pulses from PWM controller. Red show inductor current (peak 245mA).

An optocoupler (4n28) is used to isolate the microcontroller from the high-power inductor circuit.

A IRFZ44N NMOS transistor was selected to control the current to the excitation coil L1. The IRFZ44N is fast switching and has a drive voltage of 10V [4].

The 10mH inductor was selected as an overestimation place holder.

The 1N914 diode is place to drain the stored energy of the inductor to reverse power surge back through the NMOS. The 1N914 is fast switching and can dissipate 500mW of power. With a peak power surge from the inductor of

$$P_{peak} = I_{max} * V_{drop} = (250mA * 1V) = 250mW \,,$$

we have a 2x safety factor for the component.

The capacitor C1 is for filtering of noise from 12V supply line. It may be tuned as necessary.

a) Resonance analysis

C1 and L1 in the above circuit form a parallel resonance circuit. Although, the supply voltage is DC, the PWM control creates an AC response. For the current values, the resonance frequency was calculated as

$$f_{resonance} = \frac{1}{2\pi(LC)^{\frac{1}{2}}} = 7.341kHz$$

Since the pulse frequency of PEC system falls between 80kHz and 1MHz, the circuit should not enter resonance during operation.

4) *Amplifier Circuit*

Figure 9 shows the designed differential amplifier circuit and it’s simulated response to input from HE sensors.

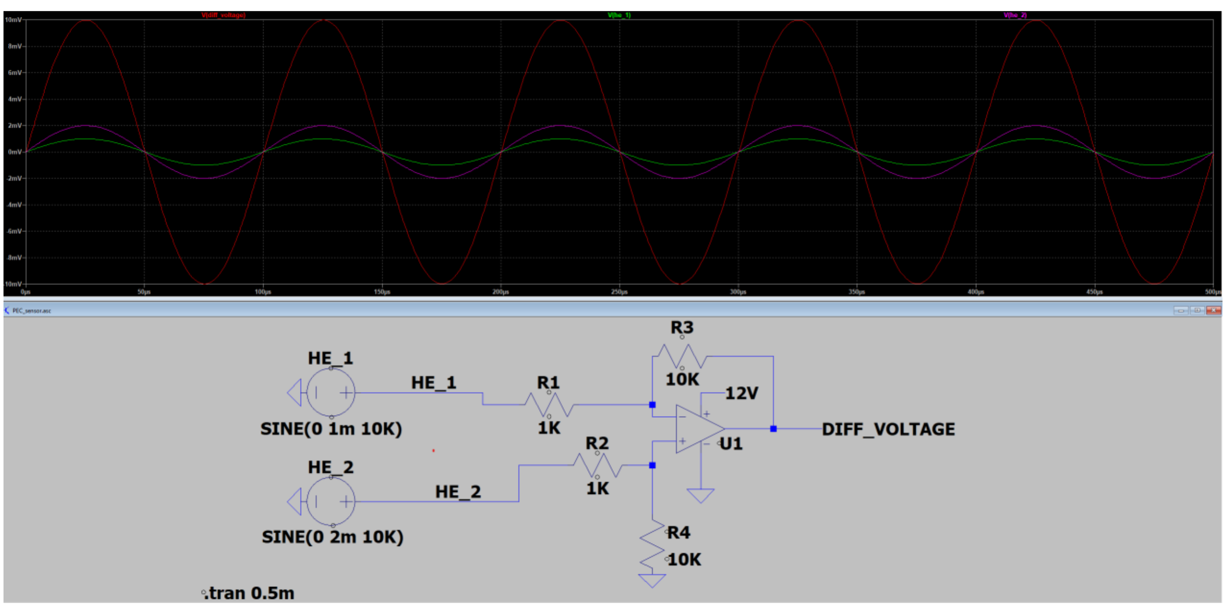

Figure 9: Simulated difference amplifier circuit for acquiring HE difference data from PEC sensor unit.

The amplification of this circuit from input to output adheres to

$$V_{out} = V_{in} * \left(\frac{R_3}{R_1}\right) \quad , if\ R1 = R2\ and\ R3 = R4.$$

The exact amplification needed is unknown at this time. Testing will reveal the amplification needed from the response of materials and sensor units. The gain can be adjusted easily through substitution of the sensors above and will be adjusted until the output range falls between 0 and 3.3V (based on microcontroller ADC voltage [4]).

5) *Bandpass Filter*

A bandpass filter will be needed at the output of the amplifier to mitigate noise cause by the sensor devices, power regulators, and the op amp itself. Testing is needed to determine the precise range of frequencies to filter, but the design will take the form of Figure 10.

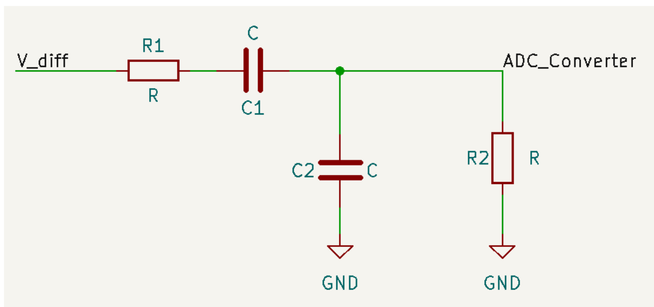

Figure 10: Bandpass filter design

The high and low cut off frequencies and band width equation for this circuit are

$$f_h = \frac{1}{2\pi R_1 C_1} \qquad f_l = \frac{1}{2\pi R_2 C_2} \qquad BW = f_h - f_l.$$

6) *PEC Array*

An array of PEC sensor units will be used to increase the scan area of the system. Each PEC unit will contain 2 HE sensor, an excitation coil, and the circuits described above (PWM control, difference amplifier, and bandpass filter). Each unit will be positioned as shown in Figure 11. A nominal lift off distance of 3mm was selected based on work from Kral J. which showed a decreased sensor response above 4mm [6].

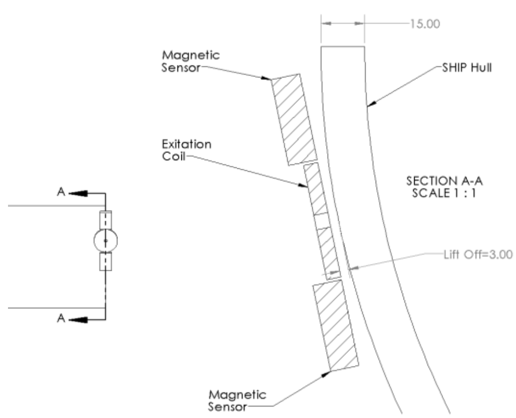

Figure 11: PEC unit scanning position on ship hull.

An array will be formed to maximize spatial resolution of HE sensors (Figure 12). The exact spacing may change if test reveal closer or farther spacing is required based on the excitation coil effect and HE sensitivity.

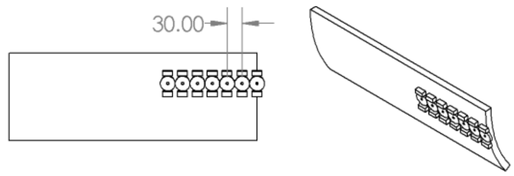

Figure 12: PEC array configuration

B. *Microcontroller*

The preliminary selected microcontroller is the PIC32MZ2064DAS176 [5]. This micro was selected for the properties

- **45 channel ADC (12-bit):** To read data from DAC
- **9 PWM Modules (250ns resolution):** To control excitation circuit
- **Integrated Graphics Processor**: For fast data processing and AI implementation
- **200MHz clock speed**: High speed processor for Real-Time functionality
- **128MB externally addressable DDR2 DRAM**: Large RAM for data processing
- **5 SPI and 6 I2C modules**: Interfaces for other peripheral devices.

This PIC32 device operates between 2.6 and 3.3V and requires a maximum of 500mA [5].

C. *Power and Charging*

The power needs of the system will change with additional peripherals including the wireless communication system. However, estimation may be made using common devices. The considered devices and their electrical specification are shown in Table 1. This table assumes 12 PEC detection units in the system. 12 units with a 40mm spacing covers 0.36m. This matches with some standard lengths of small underwater drones and AUV's [7].

Table 1: Electrical Characteristics of Components

Component	**DC Operating Voltage (V)**	**Max Current (mA)**	**Power (W)**
PIC32MZ2064DAS176	3.3	500	1.65
PEC Array (12 units)	12	(245)*12 (Figure 8)	35.28
UW-COM Unit	-	-	2.6W [8]
Under Water Camera			15.4W [9]
Additional Components*			10W (Generic)
		TOTAL	**64.88W**

* Other components are unknown at this time; however, compared to the main devices they will consume significantly less power. 10W is allocated as a large buffer.

64.88 W is the absolute maximum power draw of this system. A battery is selected with appropriate head room to extend the life of the system and operating time. The CSB HRL 1280W battery can provide 12V at 80W and has dimension small enough to mount to a AUV. Based on the data sheet, the battery could sustain 65W for over 90min [10]. The operating time may be less than this due to the pulsing power draw of the PEC array.

IV. DISCUSSION

The PEC array is the primary component of the sensor module and the focus of this analysis. Other components, such as underwater communication, have been addressed and are available for purchase [11]. A large portion of the final design will be software control and data analysis; however, an effective corrosion detection system is needed before these can be developed.

A. *Detection Method*

PEC detection offers many advantages over tradition EC detection. PEC can easily scan multiple depths in a surface with a single frequency pulse. Since the excitation signal is a pulse rather than a sinusoid, PWM signals from a microcontroller can control the sensor without the need for a sinusoidal function generator.

B. *Component selection*

A HE sensor is a common and widely used device. Equipment such as coils or magnetoresitive devices exist, but these have additional requirements or supporting hardware to function [1]. Some Magnetoresitive devices such as giant magnetoresistance (GMR) have been shown to have higher accuracy or lower noise. Should the HE be ineffective at these devices will be considered as a substitute.

The differential amplifier and filter circuit are common data acquisition circuits and need no comment.

The NMOS transistor may be ‘overkill’ for the performance requirements of the system. However, will allow multiple coils to be driven from the same circuit, potentially decreasing complexity and components. With a 200mA draw up to 50 coils could be driven by this transistor. Heat management will be essential in this configuration, and no more than 25 coils is recommended to maintain a 2x safety factor.

The inductor chosen for simulation has an inductance of 10mH. Likely, the actual value of the inductor will be significantly lower. Tests will show the required magnetic flux density to achieve the needed induced signal strength. Should a smaller inductor be needed, the driving voltage may need to be reduced to limit the current. A buck converter and filter circuit would serve this purpose. The power requirement of the PEC array will also decrease in this case.

A note should be made while programming the PWM input to the excitation circuit due to the potential resonance hazard. Frequency below 20kHz should be avoided as the resulting low impedance may result in unknown behaviour or damage.

C. Microcontroller selection

The main reason for selecting the PIC32 microcontroller was the large number of ADC channels and PWM outputs. The size of the array will require many HE sensors. Should the resolution requirements exceed the 45 channels available on the microcontroller, a switching methodology can be adopted. The array can be split into several sub array with enable switches. Multiple HE sensor can be wired to the same ADC port and read with a switching algorithm.

The integrate graphics processor on the PIC32 will allow for fast data and image processing. Real-time decision can be made locally with the analysis of this data and video feed.

D. Power Calculations

The value of 250mA used for the PEC system in Table 1 is an extreme maximum estimation. This current would be drawn if the excitation inductor was left fully power for more than 0.5ms. Since these inductors will be pulsed, the average current over time will be significantly lower and with proper capacitor usage, might be reduced significantly. This value will vary depending on the pulse width selected but will always be less than the full 250mA.

E. Recommendations

The next step in development will be to test the PEC array system. A Prototype should be built with the maximum value of components to collect initial data from corroded and non corroded samples. Based on these results the system can be tuned to the desired resolution and signal strength through iteration.

V. REFERENCES

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Appendix A. PROJECT BACKGROUND

Marine Monitoring Sensor Package: Project Background

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ENGR 446

Contents

I. BACKGROUND

Almost 70% of the planets surface is covered by oceans. From energy generation to commerce, the oceans are an essential part of human society. However, this environment is known for its harshness on materials and equipment. Steel is greatly affected by exposure to salt water by corrosion. Since most ocean assets are constructed with steels, this creates an enormous maintenance cost for ocean activities. In the early 2000's the cost of corrosion was estimated a 3.1 percent of the USA's GDP [1].

A. *Underwater Marine monitoring*

To combat corrosion and the other degrading effects of the ocean such a marine growth, detection techniques and constant monitoring is required. Historically, this inspection process was accomplished with dive teams or, in extreme scenario's, dry docking. In recent times, underwater drones, remote operated vehicles (ROV's), and autonomous underwater vehicles (AUV's) have become the more popular method of inspection. The drone system currently available have several sensors, but tend to require manual control, lack certain sensor systems, and consist of specialized configurations [2] [3]. Figure 1 show an example of the current monitoring drones available.

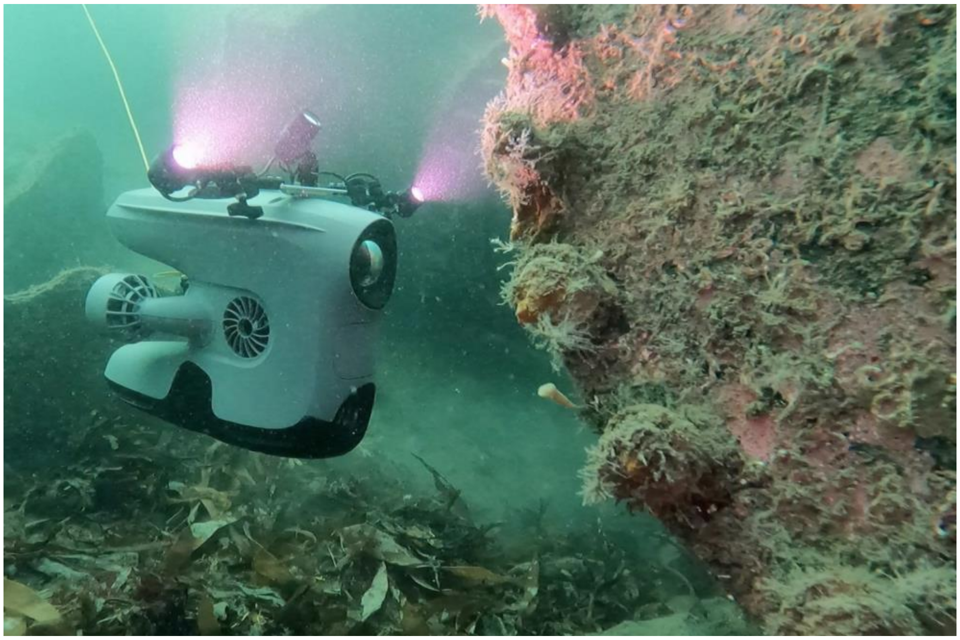

Figure 1: Underwater monitoring drone from Blueeye Robotics [2]

Thus, there is a market for modifiable, autonomous, and efficient marine monitoring system

B. *Corosion monitoring*

Perhaps the most sought-after monitoring system for marine equipment is for corrosion. Aqueous corrosion is constant, inevitable, and can be difficult to detect [4]. Several methods exist to detect corrosion. For monitoring in an ocean environment, these methods must work in and out of water, and detect beneath protective coatings [5]. Additionally, these methods must be non-destructive in nature. The available technology which fit these requirements are summarized in Table 1.

Table 1: Available Corrosion Detection Technology

Type	Description
Ultrasonic	Use ultrasonic emission in the water to detect different hull compositions at close range [5], [6]. Example sensor feedback shown in Figure 2.
AI based Visual inspection	Use AI and other algorithms to enhance non-invasive sensing equipment detection [7]
IR heat mapping	Use thermal wave propagation and infrared temperature field measurements to observe variation in coated steel [8].
Laser profilometry	Non destructive evaluation of a material surface profile to detect and monitor corrosion [9]
Magnetic Flux Leakage	Use magnetic coils to induce and measure magnetic fields in material to detect defects [10]
Eddy Current Detection	Use a probe and inductor to induce and measure magnetic eddy currents in materials and identify defects [11]. Example use shown in Figure 3.
Electrode Probe	Test the resistivity of the material via 2 electrodes to test for corrosion. Note requires a contact probe.

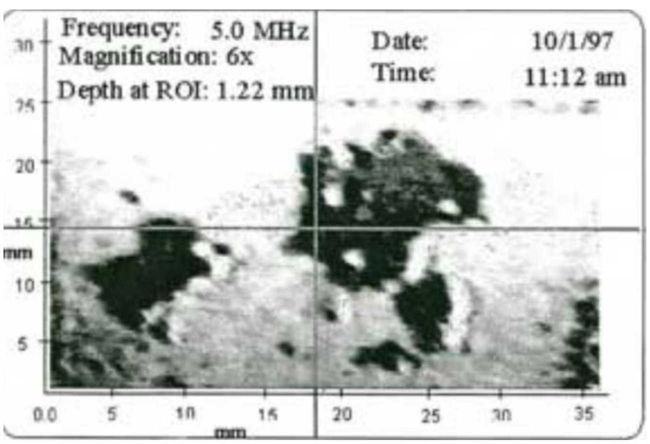

Figure 2: Ultrasonic reading from corroded aluminium plate [12]

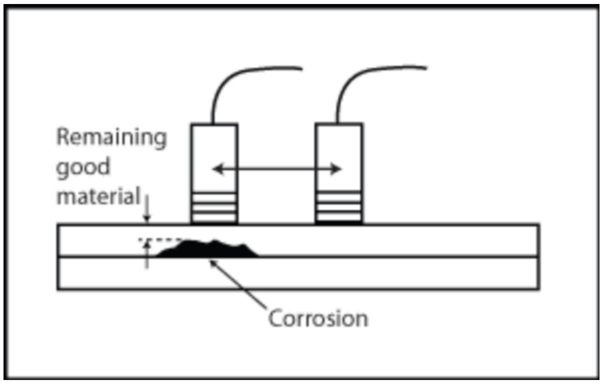

Figure 3: Eddy Current Corrosion Detection [11]

While these methods have proved viable for corrosion detection, work needs to be done to deploy this technology in an autonomous mobile system.

C. *Underwater Unmanned Vehicles*

Many underwater drones, ROV's, and AUV's exist for maneuvering inspection, and autonomous behaviour in the ocean. These range from remote operated tethered ROV's for focused inspection to magnetically attached hull crawlers [3], [13]. The broad selection of these devices more than meets the mobility needs of a static monitoring environment (such as a docked ship or ocean turbine). Therefore, a sensor and control system are needed for deployment on these vehicles.


Figure 4:DT640 hull crawler detection system [3].

II. OBJECTIVE

A. *Problem*

An online (real-time), integrated, and low management marine monitoring system is needed to combat corrosion and other degradation effect on marine assets. Corrosion in early stages is difficult to detect due to surface coating and large exposed areas of marine equipment. The battle against corrosion is constant and expensive. With a real-time and automated detection system, ocean equipment may be monitored constantly. This will increase the odds of early detection and prevent the need for manual inspection of hulls, potentially reducing corrosion cost significantly. Underwater drone and drone swarm technology has the mobility and capacity to achieve these goals; however, there is a need for an adaptable sensor array and data analysis system which can be deployed using the available drone technology.

B. *Purpose*

The objective of this work is to design a commercially producible sensor package which may be mounted to existing underwater drone technology. This system should scan marine assets for corrosion and damage, coordinate with multiple instances or devices, and analyze data for online display. Additionally, the system must offer an advantage over current marine monitoring technology in terms of speed, scale, and human resources.

C. *Aims*

The aims of this project are to develop a sensor package that:

1. Detects corrosion and defects on marine devices, vessels, and structures
2. Is configurable for specific needs and situations
3. Deploys and integrates on underwater drones, ROV's, AUV, and similar vehicles
4. Links with devices over a network to coordinate large scale monitoring
5. Does not require human attention while completing normal operation.

The scope of this report covers primarily aims 1 and 2.

D. *Limitations*

The capabilities of the mounted vehicle will not be considered unless extreme needs present themselves because they are assumed not to be the limiting factor. Additionally, the vehicle software interface is assumed to be compatible with the final design. Detection through excessive organic or other debris will not be considered since this is variable and requires additional attention. The project will be based on previous work and literature. Additional analysis may include:

- Communication range and throughput
- Power requirements
- Sensor range and required clarity.

III. POTENTIAL SOLUTIONS

All solution must integrate a variety of sensors for corrosion, damage, marine growth, and visual inspection. Different user may have different requirements regarding the monitoring needed; thus, the package must be modular in nature and allow for custom configuration. Additionally, since available power and communications on drone systems cannot be guaranteed, the system must be independent of the drone itself.

The difference in solution presents itself in terms of deployment and use case.

A. *Harbor/Port Wireless Based Swarm (Drone Linked)*

One solution includes a fleet of drone equipped with the sensor package. In this solution the drone is slaved to the sensor package itself. Communication with a central control and movement commands are handled by the sensor package and relevant instruction relayed to the drone.

Communication buoys would span the area of interest to allow for underwater wireless communication relay between the drones and a central control center.

The drones would systematically scan docked vessels, equipment, and structures with an algorithm to maximize scan time. Multiple drones may work squads to minimize the time each boat spend under inspection.

The drones would have a local hub to return for recharge and maintenance. Central control could also override the basic algorithm for high priority scans of vessels and objects.

B. *Ship based drone with wired package.*

This solution is for medium or large vessels which may set anchor outside of ports or harbors. This also applies to structure such as offshore oil rigs of wind turbines. These vessels would have one or multiple drones equipped with a sensor package. These systems would be tethered to the ships from which they may receive power and communication. The drones would be deployed at certain time when the vessel is stopped. They would quickly follow set paths to scan the entire ship and send data back to the command unit. This command unit may also be off site if a satellite or cellular network is available.

C. *Dedicated Tow Fish (Vessel Only)*

This device would operate constantly as the vessel is in motion. Attached to a tether, a tow fish would house the sensor package and adjust itself slowly across the entire hull of the ship. The tow fish would communicate and be powered through the tether connection to maximize deployed time. The difficulty of this method is obtaining accurate measurements with the disturbance of the vessel in motion. This system requires the ship to be in motion for positioning. Thus, it is not feasible on stationary platforms or structures.

D. *Large array position by multiple or large vehicle*

This system would attach multiple drones to a single, large, sensor package. The package would be positioned and moved under and along vessels and equipment and complete a scan in a few slow passes. The idea for this device is maximizing scan width and minimizing number of passes to decrease time for complete scan coverage.

IV. Initial Assessment

To select a potential solution, a weighted decision chart will be created with several criteria. These criteria will target qualities of a solution that will most fully meet the non functional requirements of the product. The primary non functional requirements of the product are

1. Product improves speed of detection for corrosion and other ailments on marine assets
2. Product can be configured for a specific task with different sensors and equipment.
3. Product reduces human resources needed to preform this task.
4. Product offer an advantage over current means of detection and monitoring through ease of use, quality of results, or quantity of scanning (total surface area scan per unit time).

A. *Criteria*

The following criteria will be weighted in order. The exact weights will be determined exactly when the discrepancy between the solutions is known.

The first criteria of this assessment will determine the types of viable sensing equipment for the solution. Should only some of the methods be usable (i.e. Only magnetic flux and eddy current), the ability of the system to fully detect and monitor will be examined closely. Since a requirement is configurability, a system that limits the available sensor will also receive a penalty.

The second selection criteria rates a systems autonomy and human resource needs. Should a system require a lot of attention it will receive a lower score than a one with lots of autonomy.

The 3rd criteria determines which solution would most effectively scan an entire vessel/platform completely once. This rating will help measure the potential speed of a solution.

The 4th selection criteria attempts to rate the scalability of a solution. This will consider the change in scenario from one to several vessels or platforms and compare the hardware, software, and maintenance requirements of the system.

The 5th criteria observes the potential operating times of the solution. If a solution only usable for small windows of time, it will receive a lower score than one available more of the time.

The 6th criteria will be a qualitative estimate of how easy the system may be to use and maintain. This may be subjective to the individual completing the assessment and thus will have the lowest weighting.

B. *Ratings*

Deployment Method — **Range = [0,5]**

Criteria	Autonomy	Score	Effective Scan	Score	Scalability	Score	Operating time	Score	Maintenance	Score	Total
Weight	0.3		0.3		0.2		0.1		0.1		1
Harbor Swarm	5	1.5	3	0.9	4	0.8	4	0.4	2	0.2	3.8
Ship Wired Drone	3	0.9	2	0.6	2	0.4	1	0.1	4	0.4	2.4
Tow Fish	3	0.9	1	0.3	3	0.6	4	0.4	4	0.4	2.6
Large Array	2	0.6	5	1.5	1	0.2	2	0.2	2	0.2	2.7

Corrosion Detection — **Range = [0,5]**

Criteria	Range	Score	Detection Depth	Score	Scalability	Score	Coverage Area	Score	Environment Immunity	Score	Total
Weight	0.2		0.4		0.1		0.1		0.2		1
Eddy Current	3	0.9	4	1.2	4	0.8	3	0.3	5	0.5	3.7
Ultrasonic	3	0.9	5	1.5	2	0.4	3	0.3	1	0.1	3.2

Magnetic Flux Leakage	2	0.6	2	0.6	4	0.8	2	0.2	5	0.5	2.7
Electrode Probe	0	0	3	0.9	5	1	5	0.5	5	0.5	2.9

Based on this analysis, a harbor swarm system with eddy current detection will be proposed.

V. References

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