UNIVERSITY OF PUERTO RICO AT MAYAGÜEZ

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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

# WaveSphere: Final Report

A REPORT SUBMITTED AS A PARTIAL REQUIREMENT OF THE MICROPROCESSOR INTERFACING COURSE ICOM-5217

by

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# 1. Introduction

Although waves are abundant at sea and everyone who has been near a shoreline has seen and interacted with a wave, most people don't think about the wave-breaking phenomena when enjoying their time at the beach. However, this topic is very important for the researchers at the Fluid Mechanics and Ocean Engineering Laboratories at the University of Puerto Rico at Mayagüez, which are directed by Dr. Miguel Canals. The natural physics and motion dynamics of the wave-breaking phenomena have not been thoroughly studied because of the difficulty encountered when trying to measure the characteristics of the waves.

A novel way to study these dynamics is by developing an instrument, also referred to from hereon as drifter, that will ride with the waves and take measurements during the wave-breaking process. This is the approach that the researches have taken as part of the NSF Funded project titled "Lagrangian Observations of Turbulence in Breaking Waves".

This work presents the design of a spherical drifter that will aid the researchers in taking the aforementioned measurements. A thorough explanation of the hardware and software design is presented along with supporting calculations where required.

# 2. Block Diagram

Figure 1 shows the block diagram for each of the drifters while Figure 2 shows the block diagram for the base station. Both diagrams contain the model numbers of the components and, in the case of the drifter block diagram, the types of connections required to the microcontroller unit (MCU) and the amount of lines needed for each connection.

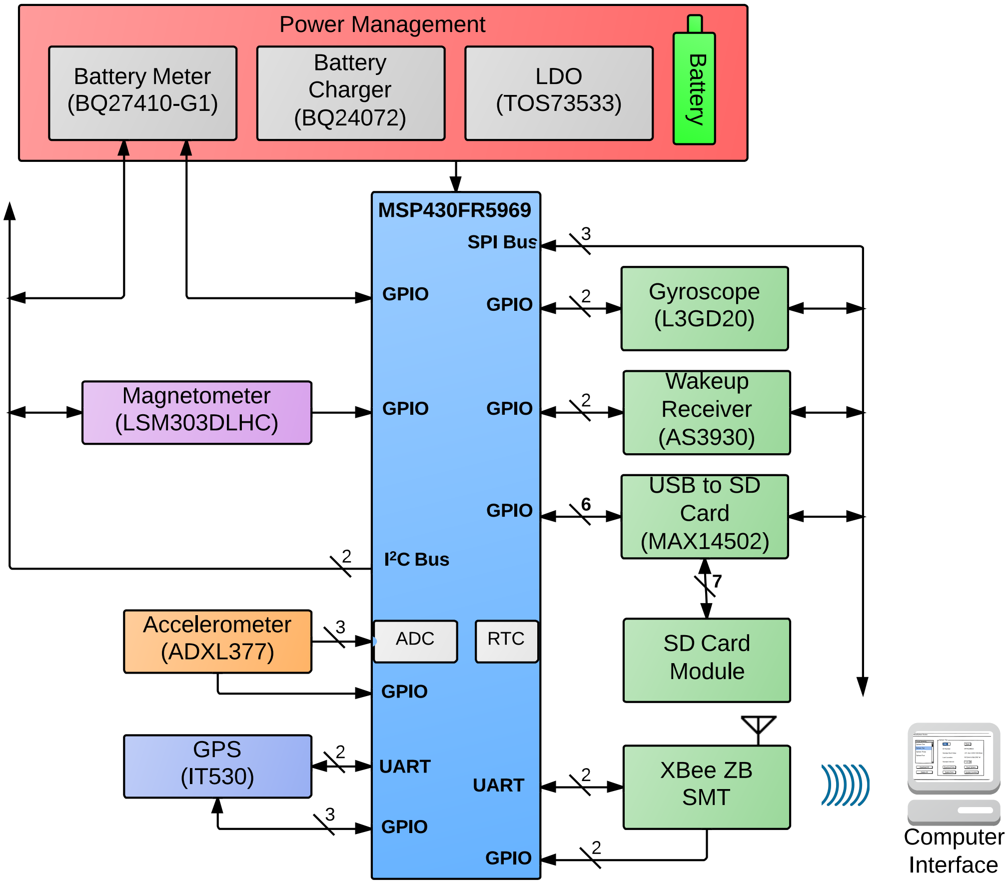


Figure 1: Block Diagram for the Drifter

1. **Microcontroller** - Needed in order to be able to control and establish the communication between components as well as process the output of the sensors.
2. **Battery** - Required to provide the necessary power to the drifters because the electrical components are enclosed by a sphere.
3. **Power Management Circuit** - Composed of an LDO, a battery charger and a battery meter. It is used to regulate the power provided by the battery, re-charge the battery once it has been depleted and to measure the amount of charge left on the battery.
4. **GPS Module** - Needed in order to know the precise location of the drifters when the user has to recover them after they have been thrown at sea for an experiment.
5. **Gyroscope** - Used to determine the rate of change of the orientation of the drifter while being carried by a wave.
6. **Accelerometer** - Used to measure the acceleration of the drifter while being carried by the waves.
7. **Magnetometer** - Used to determine the orientation of the drifter with respect to the Earth's magnetic north while it is being carried by a wave.
8. **Analog to Digital Converter (ADC)** - Needed in order to take the data from the accelerometer, which has an analog output, and convert it to digital signals so that the MCU can read them. It is integrated within the MCU.

9. **SD Card and SD to USB Converter** - The SD Card is used to save the data captured by the sensors during an experiment. The SD to USB converter will be used to allow the drifter to function as a mass storage device when connected to a Host computer via USB.
10. **XBee ZB Module** - Used to connect the spheres with a central base so that data can be retrieved without having to open the spheres.
11. **RF Wakeup Module** - Used to wirelessly wake up the drifter from low power mode via an RF signal.

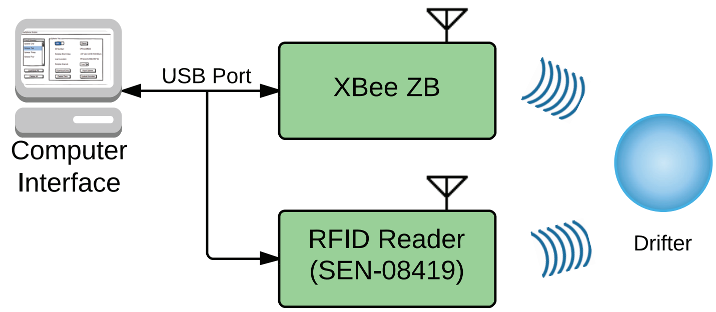


Figure 2: Block Diagram for the Base Station

1. **XBee ZB Module** - Used to communicate with the drifters in order to send commands to switch operating modes and retrieve collected data.
2. **RFID Reader** - Used to generate the 125kHz signal required by the RF Wakeup module in the drifters to wake them up from low power mode.
3. **Computer** - Used to run a custom application that will be used to send commands and data to the drifters through the XBee. A USB port in the computer will power the other devices in the base station.
4. **Power Management Circuit** - Composed of an LDO, a battery charger and a battery meter. It is used to regulate the power provided by the battery, re-charge the battery once it has been depleted and to measure the amount of charge left on the battery.

# 3. Power Analysis

The power analysis consists of four main parts: logic compatibility, driving capability, power supply design and battery life estimate. The purpose of this analysis is to ensure that power requirements for each component are satisfied in order to guarantee their proper functionality. A supporting thermal analysis will be performed on selected ICs.

## 3.1 Logic Compatibility

Table 1 shows all the digital components in the system along with their input and output digital voltage levels. Only two digital components communicate with each other: the SD Card to USB converter IC and the SD Card itself. It is easy to see from Table 1 that the logic voltage levels between these two devices are compatible. In addition to this, all components communicate with the MCU. It can also be seen that all the devices are logically compatible with the MCU except for the battery gauge, which communicates with the MCU through an $I^2C$ interface and has a $V_{DD}$ of 2.5V. In order to make them compatible, a bi-directional logic level shifter from Texas Instruments was used and can be found in the schematic. It can be seen in the table that by using the aforementioned level shifter, communication between the battery gauge and the MCU is now possible.

Table 1: Component Logic Levels and I/O Currents

| Component | $V_{DD}$ | $V_{IH}$ | $V_{IL}$ | $V_{OH}$ | $V_{OL}$ | $I_{OUT}$ | $I_{IN}$ | $I_{LEAK}$ |
|---|---|---|---|---|---|---|---|---|
| MSP430FR5969[1] | 3.3 | 2.1 | 0.75 | 3.2 | 0.2 | 45 mA[2] | 50 nA | 50 nA |
| Magnetometer[3] | 3.3 | 2.64 | 0.66 | 3.3 | 0 | 3 mA | 10 $\mu$A | 10 $\mu$A |
| XBee | 3.3 | 2.64 | 0.66 | 2.706 | 0.594 | 4 mA | 0.5 $\mu$A | 0.5 $\mu$A |
| RF Wakeup | 3.3 | 1.914 | 0.99 | 2.9 | 0.4 | 21 mA | 100 nA | 100 nA |
| Gyroscope | 3.3 | 2.64 | 0.66 | 2.64 | 0.66 | 100 $\mu$A | 10 $\mu$A | 10 $\mu$A |
| GPS | 3.3 | 2 | 0.8 | 2.4 | 0.4 | 8 mA | 10 $\mu$A | 10 $\mu$A |
| Battery Gauge[4] | 2.5 | 1.2 | 0.6 | 2 | 0.4 | 3 mA | 10 $\mu$A | 0.3 $\mu$A |
| SD Card[5] | 3.3 | 2.06 | 0.83 | 2.48 | 0.41 | 100 $\mu$A | 10 $\mu$A | 10 $\mu$A |
| Power Switch | 3.3 | 2.2 | 1.1 | 3.3 | 0 | 10 mA | 0 mA | 0.3 $\mu$A |
| SD Card to USB Converter | 3.3 | 2.06 | 0.83 | 2.48 | 0.41 | 100 $\mu$A | 2 $\mu$A | 1 $\mu$A |
| Level Shifter[6] | 2.5 | 1.7 | 0.7 | 2.5 | 0 | 100 $\mu$A | 20 $\mu$A | 10 $\mu$A |

## 3.2 Driving Capability

In order to ensure that no component draws more current than the one its driver can provide, a weakest driver analysis should be performed. Table 1 shows a list of the available currents found in the data sheets and other sources. The components and their connections are shown in the block diagram depicted in Figure 1.

[1] Values used are for the MSP430FR572x as they are not available for the selected microprocessor.

[2] In full-drive mode

[3] Currents obtained from [1]

[4] Input and output currents obtained from [1]

[5] Voltages obtained from [2]

[6] Values for $V_{OH}$ and $V_{OL}$ taken at 100 $\mu$A since the input and output current of the Battery Gauge does not exceed 10 $\mu$A.

Since $I^2C$ is a standard, there would be no problems if the level shifter was not present. However, since this component is the weakest driver, the analysis must be performed. The output current of this component is 100 $\mu$A in order to maintain the voltage levels specified in Table 1. It can be seen that this current is greater than the sum of input currents of the components connected to the bus: 10 $\mu$A for the Gyroscope and 50 nA for the MCU.

Since the components connected through UART and Software UART are point to point connections and since the MCU has such a low input and leakage current, the Xbee and GPS modules will not have a problem driving the MCU. Finally, for the SPI Bus, the weakest driver is the Gyroscope with an output current of 100 $\mu$A. It can be seen from Table 1, that this current is greater than the sum of input currents for the other components: 10 $\mu$A for the SD Card to USB Converter and 50nA for the MCU.

With this analysis, one can conclude that all ICs can drive their respective loads

## 3.3 Power Supply Design

In order to design the power supply that will be used by the system, the worst case quiescent current of each component should be taken into account. Although not all components will be operating at the same time, it is ensured that the system will continue to function properly for the worst possible case by performing the analysis in this manner. To ensure proper operation of the system, the Low-Dropout Regulator (LDO) must supply enough current for the entire system. Table 2 shows a list of components along with the worst case quiescent current of each of them. By adding all the current, a maximum current consumption of 181 mA was determined. The LDO is rated for a maximum output of 500 mA, which is well above the determined usage. In order to complete the power supply circuit, a USB Battery Charger and a Battery Meter were added as well. Note that since the level shifters are powered by the 2.5V regulated output of the Battery Meter, they have not been included in these calculations.

Table 2: Worst Case Quiescent Currents for components

| Component | $I_{DD(Active)}$ ($\mu$A) |
| --- | --- |
| MSP430FR5969 | 1600 |
| 3-Axis Accelerometer | 300 |
| Magnetometer | 110 |
| XBee | 45000 |
| RF Wakeup | 2.7 |
| Gyroscope | 6100 |
| GPS | 26140 |
| SD Card | 100000 |
| Power switch | 1 |
| SD to USB | 37 |
| LDO | 65 |
| Battery Charger | 1500 |
| Battery Meter | 103 |
| Total | 180958.7 |

### 3.4 Thermal Analysis

A thorough thermal analysis was performed on the MCU and all the power management ICs to determine whether they would exceed the thermal limits of their package under regular operation in our system. The expected operating junction temperature was calculated using the junction-to-ambient thermal resistance and the power dissipated by each IC. It was determined that no additional heat dissipation technique as needed to guarantee the proper operation of the ICs since all the calculated junction temperatures were well below the maximum operating junction temperature specified in the manufacturer's datasheets. The thorough and detailed analysis can be found in Section 3.4.

## 4. References


[1] "The $I^2C$-Bus Specification." `http://www.nxp.com/documents/other/39340011.pdf`.

[2] D. Ibrahim, *SD Card Projects Using the PIC Microcontroller*. IT Pro, Elsevier Science, 2010.

[3] M. Jiménez, R. Palomera, and I. Couvertier, *Introduction to Embedded Systems: Using Microcontrollers and the MSP430*. Springer London, Limited, 2013.

# Appendix A: System Specifications

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# Appendix B: System Schematics

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# Appendix C: Component Layout

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# Appendix D: User Guide

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# Appendix E: Bill of Materials

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# Appendix F: Extended Power Analysis

This section contains a more detailed explanation of how the battery life was estimated. It includes the assumptions made to generate the activity factors. In addition, it includes a thorough description of the calculations made in the thermal analysis.

Add Level Shifters and recalculate power. See if we can find a chart of Charge vs Voltage to determine the lower level of available charge to get a more real estimate

## F.1 Battery Life Estimate

In order to estimate the battery life, the average supply current was determined by using a weighted average based on the fraction of time each component is active. The weighted average formula used was: $I_{avg} = \alpha * I_{active} + (1-\alpha) * I_{LPM}$, where $\alpha$ is the activity factor or the fraction of time the component is active. The following assumptions were made when determining the activity factor.

- The drifters will spend 10 minutes in "Locate Mode" before they are retrieved from the water.
- The drifters will spend 30 seconds in sampling mode.
- The drifters will spend 3 minutes in stand-by mode before they are deployed.
- The drifters will spend about 10 seconds transferring a single data file. The following assumptions were made to determine this time:
  - File Size: 200 kB * 8 = 16,000 kbits.
  - 80% of XBee maximum Speed: 250 kbps * 80% = 200 kbps.
  - 16,000 kbits / 200 kbps = 8 seconds, which can be rounded up to 10 seconds.

Table 3 shows a list of the components along with their active and low power mode supply current, determined activity factor, and weighted average supply current. It also shows the total average current consumption of the system which was determined to be around 70 mA. This means that a chosen 500 mAh battery will last for about 7.23 hours. Based on the current assumptions, a single throw or experiment will last for about 13.66 minutes, which means that the drifters will be able to perform at least 30 experiment trials under the current assumptions.

Table 3: Activity Factors Used to Estimate Battery Life

| Component | $I_{DD(Active)}$ ($\mu$A) | $I_{DD(LPM)}$ ($\mu$A) | Activity Factor | $I_{DD(AVG)}$ ($\mu$A) |
|---|---|---|---|---|
| Connected To LDO | | | | |
| MSP430FR5969 | 1600 | 0.5 | 78.05% | 1248.91 |
| 3-Axis Accelerometer | 300 | 0 | 3.66% | 10.98 |
| Magnetometer | 110 | 1 | 3.66% | 4.9894 |
| XBee | 45000 | 0.5 | 96.34% | 43353.02 |
| RF Wakeup | 2.7 | 0.4 | 0.00% | 0.4 |
| Gyroscope | 6100 | 5 | 3.66% | 228.077 |
| GPS | 26140 | 5 | 73.17% | 19127.98 |

| Component | $I_{DD(Active)}$ ($\mu$A) | $I_{DD(LPM)}$ ($\mu$A) | Activity Factor | $I_{DD(AVG)}$ ($\mu$A) |
|---|---|---|---|---|
| SD Card | 100000 | 10 | 4.88% | 4889.512 |
| Power switch | 1 | 0.3 | 3.66% | 0.32562 |
| SD to USB | 37 | 1 | 100.00% | 37 |
| Connected Directly to Battery | | | | |
| LDO | 65 | 1 | 100.00% | 65 |
| Battery Charger | 1500 | 6.5 | 0.00% | 6.5 |
| Battery Meter | 103 | 4 | 100.00% | 103 |
| Total | 180958.7 | 35.2 | - | 69075.69 |
| Battery Capacity | 500 mAh | Hours of Use per battery charge | | 7.238436 |
| Est. time per throw (min) | 13.66 mins | Throws per charged battery | | 31.7785 |

## F.2 Thermal Analysis

Performing a thermal analysis on the system will reveal whether the operating temperature of the individual ICs is below their maximum rating. In order to perform this analysis, the junction temperature $T_J$ will be calculated for the MCU and the power management ICs. The junction temperature is given by [3, 419]:

$$T_J = T_A + \theta_{JA} \cdot P_{diss}$$

where $T_J$ is the estimated junction temperature, $T_A$ is the ambient temperature (taken here to be $27°C$), $\theta_{JA}$ is the junction-to-ambient thermal resistance and $P_{diss}$ is the estimated power consumption of the device.

This formula is applied throughout the following sections to determine whether the MCU and the power ICs will be operating at a safe temperature or if they require additional heat dissipation mechanisms such as heat syncs, fans, etc.

### F.2.1 Microcontroller

In order to estimate the average operating junction temperature for the MCU the power dissipated by the IC will first be calculated. The following formula, which was taken from [3, 419], will be used:

$$P_{diss} = V_{DD} \cdot \left( I_{DD(avg)} + \sum_{all pins} |I_{IO(avg)}| \right)$$

Although no information is available for the $\theta_{JA}$ of the MSP430FR5969, since this value depends on the package and the area exposed to the air, a device with the same package (48-pin QFN), the MSP430F5510, was found to have $\theta_{JA} = 28.6°C/W$ and this value was instead used. In the same manner, although no information on the IO currents is available, the ones for the MSP430F5510 will be used instead.

In full drive mode, the MSP430F5510 can output upto 45mA through its IO pins while still maintaining a valid $V_{OL}$. Table 4 shows the assumed IO currents for each components.

Table 4: Worst Case IO current for pins

| Pin | $I_{DD(Active)}$ ($\mu$A) | Qty | Total Current ($\mu$A) |
|---|---|---|---|
| SPI | 100 | 3 | 300 |
| $I^2C$ | 10 | 2 | 20 |
| UART | 1000 | 2 | 2000 |
| GPIO | 1000 | 21 | 21000 |
| | | Total | 23320 |

Assuming an IO current of 23.32mA and an average supply current of 1.6mA, the total power dissipation can then be calculated to be:

$$P_{diss} = V_{DD} \cdot (1.6m + 23.32m)$$

$$\boxed{P_{diss} = 82.24mW}$$

Using $\theta_{JA} = 47.8°C/W$, the total junction temperature is then given by:

$$T_J = 27 + 26.8 \cdot 0.08224$$

$$\boxed{T_J = 29.20°C}$$

The datasheet states that the maximum junction temperature is 95°$C$, which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

### F.2.2 Low-Dropout Regulator

The datasheet for the TPS73501 contains a section on power dissipation and provides the following formula for calculating the power dissipation across the device:

$$P_{diss} = (V_{IN} - V_{OUT}) \cdot I_{OUT}$$

The voltage provided by the battery charger circuit is 3.925 V and the required output voltage is 3.3 V. The estimated output current required is 180.96 mA. In order to leave a margin of error, a rounded value of 200 mA will be used in this calculation. Thus, the power dissipated by the device is given by:

$$P_{diss} = (3.925 - 3.3) \cdot 200m$$

$$\boxed{P_{diss} = 125mW = 0.125W}$$

Since for this device, $\theta_{JA} = 47.8°C/W$, the total junction temperature is then given by:

$$T_J = 27 + 47.8 \cdot 0.125$$

$$\boxed{T_J = 32.98°C}$$

The datasheet states that the maximum junction temperature is $150°C$, which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

### F.2.3 Battery Charger

The datasheet for the BQ24072 provides the following formula for estimating the power dissipation across the device.

$$P_{diss} = (V_{IN} - V_{OUT}) \cdot I_{OUT} + (V_{OUT} - V_{BAT}) \cdot I_{BAT}$$

The output voltage of the device is 5.5 V, while the input voltage is 5 V as dictated by the USB standard. The output current can be estimated to be 50mA by taking into account the two LEDs connected to this pin (at about 20mA per LED) and the LDO input (46 $\mu$A) and rounding up to leave a margin for safety. The circuit was designed for a battery voltage of 3.7 V and a current of 800 mA.

$$P_{diss} = (5 - 3.925) \cdot 50m + (3.925 - 3.7) \cdot 500m$$

$$\boxed{P_{diss} = 166mW}$$

Since for this device, $\theta_{JA} = 39.47°C/W$, the total junction temperature is then given by:

$$T_J = 27 + 39.47 \cdot 0.166$$

$$\boxed{T_J = 33.55°C}$$

The datasheet states that the maximum junction temperature is $125°C$, which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

### F.2.4 Battery Meter

Although the datasheet for the BQ27410 does not provide a direct formula for power dissipation and because the battery meter has an internal LDO, the formula used for the MCU IO pins will be combined with the power dissipation formula of the LDO to obtain a more robust estimate for the power dissipated.

$$P_{diss} = V_{DD} \cdot \left( \sum_{all\,pins} |I_{IO(avg)}| \right) + (V_{IN} - V_{OUT}) \cdot I_{OUT}$$

The IO pin output current for this device is between 0.5 and 1 mA. 1 mA will be used for the two $I^2C$ pins, which gives a total IO current of 2 mA. The maximum supply current is 103 $\mu$A and this will be used instead of the average supply current to leave a margin of safety. The input voltage is 5.5 V and the regulated output voltage is 2.5 V.

$$P_{diss} = 2.5 \cdot (2m) + (3.7 - 2.5) \cdot 0.103m$$

$$\boxed{P_{diss} = 5.12mW}$$

Since for this device, $\theta_{JA} = 64.17°C/W$, the total junction temperature is then given by:

$$T_J = 27 + 64.1 \cdot 0.00512$$
$$\boxed{T_J = 27.33°C}$$

The datasheet states that the maximum junction temperature is $100°C$, which means that in this application, the device is well under the maximum operating temperature rating and no additional heat dissipation mechanism is needed.

# Appendix G: Work Distribution

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