UNIVERSITY OF PUERTO RICO AT MAYAGÜEZ

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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

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WaveSphere: Final Report

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

by

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Abstract

Revise abstract at the end of the document

Wave post-breaking dynamics is a phenomenon that is not yet well understood. This article proposes a series of improvements for a device that is used to measure variables that are essential to the physics of wave breaking. The aforementioned device is a spherical drifter with a diameter of 7.5cm designed to closely imitate the dynamics of a particle in the water. It will be equipped with a 3-axis accelerometer, gyroscope and magnetometer, allowing the sphere to measure its motion to 9 degrees of freedom. This will allow the researchers to reconstruct the device trajectory in the wave via dead reckoning. A GPS module, on-board flash memory for data storage and a wireless communication module for data retrieval will also be integrated into the spheres in order to solve various problems currently faced by researchers in this area. It is expected that, when used in synergy, multiple units will be able to greatly help researchers understand the dynamics of wave breaking.

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1. Introduction

2. Block Diagram

Figure 1 shows a revised system block diagram. It contains the model numbers of the known components, the types of connections required to the microcontroller unit (MCU) and the amount of lines needed for each connection.

img/blockDiagram.pdf

Figure 1: Revised Block Diagram

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1. Microcontroller
   - The microcontroller is needed in order to be able to establish the communication between components, control the different components, and process the output of the sensors.

2. Battery
    - A battery is needed because the sphere has to be portable and it is the only way to provide the necessary power.
3. Power Conversion and Management Circuit
    - Power Conversion and Management is needed in order to give the necessary and adequate power to each component so that they can work properly and efficiently. It contains voltage converters and a battery meter.
4. GPS Module
    - A GPS Module is needed in order to know the precise location of the spheres when the user has to recover them after they have been thrown at sea for an experiment.
5. Gyroscope
    - The gyroscope will be used to determine the sphere's orientation while being carried by a wave.
6. LED
    - An LED will be used to help the user find the sphere when conducting experiments at night and to indicate battery and data transfer status.
7. Light Sensor
    - A light sensor will be used in order to only turn on the LED at night to conserve energy. The LEDs will still display battery and transfer status, but will not flash continuously as would be the case with the LED that aids in finding the spheres at night.
8. Real Time Clock
    - A Real Time Clock is needed in this system in order to track and record the time at which each sample measurement is taken in order to be able to match it with the measurements taken by different spheres.
9. Accelerometer
    - The accelerometer will be used to measure the acceleration of the sphere while being carried by the waves.
10. Analog to Digital Converter (ADC)
    - An ADC is needed in order to take the data from the acceleratometer, which has an analog output, and convert it to digital signals so that the microcontroller can read them.
11. SD Card
    - The SD Card will be used to save the data measured during an experiment.
12. Wireless Module
    - The wireless module will be used to connect the spheres with a central base so that data can be retrieved without having to open the spheres.

13. Computer Interface
    - A computer interface is needed in order to be able to wirelessly retrieve the data collected via wireless and save it for future analysis.
14. Magnetometer
    - Provides the extra 3 degrees of freedom that the researchers need in order to employ dead reckoning algorithms [1].

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, thus guaranteeing their functionality.

3.1 Logic Compatibility

Table 1 shows all the digital components in the system along with their input and output digital voltage levels. The table also includes a column labelled "Notes" that contains assumptions made for determining each value that was not available in their data sheets. 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. In order to make them compatible, a bi-directional logic level shifter using pass transistor logic was used and can be seen in the schematic. The interface was only added in the data lines because it is bi-directional, while the clock signal comes from the MCU and can be correctly interpreted by the battery gauge according to the data sheet.

Table 1: Logic Compatibility

Component	V_{DD}	V_{IH}	V_{IL}	V_{OH}	V_{OL}	Notes
MSP430FR5969	3.3	2.1	0.75	3.2	0.2	Values are for the MSP430FR572x as they are not available for the selected microprocessor.
Magnetometer	3.3	2.64	0.66	3.3	0	V_{DD}*0.8 and V_{DD}*0.2 Values assumed for V_{IH} and V_{IL} respectively, 0 and 3.3 for V_{OH} and V_{OL} because it uses CMOS technology

Component	V_{DD}	V_{IH}	V_{IL}	V_{OH}	V_{OL}	Notes
XBee	3.3	2.838	0.594	2.838	0.594	V_{OH} and V_{OL} assumed equal to V_{IH} and V_{IL}
RF Wakeup	3.3	1.914	0.99	2.9	0.4	N/A
Gyroscope	3.3	2.64	0.66	2.64	0.66	V_{OH} and V_{OL} assumed equal to V_{IH} and V_{IL}
GPS	3.3	2	0.8	2.4	0.4	N/A
Battery Gauge	2.5	1.2	0.6	2	0.4	Logic voltage Shifter was added to the schematic.
SD Card	3.3	2.06	0.83	2.48	0.41	Obtained from [2]
Power Switch	3.3	2.2	1.1	3.3	0	V_{IH} and V_{IL} were extrapolated from Data sheet. 3.3 and 0 were assumed for V_{OH} and V_{OL} because it uses CMOS technology
SD Card to USB Converter	3.3	2.06	0.83	2.48	0.41	N/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. However, due to a serious lack of information in the data sheets of the selected components, this was not possible. Table 2 shows a list of the available currents found in the data sheets. It can be seen that there is not enough information to perform the analysis on any component. This will be taken into account when initial prototyping begins and interfacing for the pins, in the form of transistors to amplify current, will be added as needed. Care will be taken when connecting components so that components are not damaged while prototyping: current will be limited by the power supply during the initial testing phase.

Table 2: List available of pin input, output and leakage currents

Component	I_{Out}	I_{In}	I_{Leak}
MSP430FR5969	2 mA	2 mA	Not Specified
Connected Through SPI			
XBee	4 mA	0.5 μA	Not Specified
RF Wakeup	21 mA	100 nA	100 nA
Gyroscope	Not Specified	Not Specified	Not Specified
SD Card	Not Specified	Not Specified	10 μA
Connected Through I^2C			
Battery Gauge	I_{OL} = 0.5 mA I_{OH} = -1 mA	Not Specified	Not Specified
Battery Charge	10 μA	1 μA	Not Specified
Magnetometer	Not Specified	Not Specified	Not Specified
Connected Through UART			
GPS	Not Specified	Not Specified	10 uA
Connected Individually			
3-Axis Accelerometer	Not Specified	Not Specified	Not Specified
Power Switch	10 mA	10 mA	0.3 uA
SD Card to USB Converter	2 μ A	2 μ A	1 μ A

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 3 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.

Table 3: Worst Case Quiescent Currents for components

Component	$I_{DD(Active)}$ (μA)
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 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 α 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 4 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 4: Estimate of Battery Life

Component	$I_{DD(Active)}$ (μA)	$I_{DD(LPM)}$ (μA)	Activity Factor	$I_{DD(AVG)}$ (μA)
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
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

4. 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 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 $27°C$), θ_{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.

4.1 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 θ_{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 5 shows the assumed IO currents for each components.

Table 5: Worst Case IO current for pins

Pin	$I_{DD(Active)}$ (μA)	Qty	Total Current (μA)
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:

$$T_J = 27 + 26.8 \cdot .08224$$

$$\boxed{T_J = 29.20°C}$$

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.

4.2 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.

4.3 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 μA) 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.

4.4 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 μA 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.

5. Timing Analysis

Old timing analysis, copied because it had a good format, however must be updated with the new information

The timing analysis consists of three main parts: Time bases, Point-to-point communication, and analog considerations. The purpose of this analysis is to ensure that no signal is transmitted at a faster frequency than the one its receiver can read, thus guaranteeing communications functionality and interoperability between all components and the MCU.

5.1 Time bases

This section compares the maximum external clock frequencies of all components and their communication ports to make sure that no component will be overclocked by the MCU and that all synchronous communication can be performed at the speed of the MCU's clock. Table 6 shows the frequency specifications for the components. Since the sample frequency will be a relatively low 256Hz, there is complete compatibility between the MCU and all components. The MCU can run at a clock frequency of up to 16MHz. For I^2C communications, the standard of 10-100kHz will be used, since all components are compatible with it. For SPI communications, a rate of up to 2MHz can be used, since the slowest device, the RF wakeup receiver, operates at this frequency. The only component that will be communicating with the MCU through UART is the GPS receiver, which will be communicating at a 9600 baud rate and tolerates a 10% error.

Timers Two timers will be needed for sampling. The first timer will control the sample frequency for all the components. In order to sample at an accurate frequency of 256Hz, an external crystal with a low frequency of 38.400kHz will be used. To achieve this, the crystal will be connected to one of the timers, and the terminal count will be set to 150 with a prescale divider of one. The second timer will control the sampling time of 30 seconds. The prescaler of this timer will be set to 1 and the terminal count will be set to 38,400. 30 counts of the terminal register will produce the interrupt that will conclude the sampling mode.

Crystal Oscillators The reason why a 38.400kHz crystal was chosen is because the GPS communicates through UART with a 9600 baud rate. If a standard 32.768kHz crystal is used instead, the frequency divider would be 3.4, which would produce an effective baud rate of 9637.65bps. This translates to a maximum error of 17.19%, which is unacceptable for maintaining a stable communication link with the GPS module. This problem is solved by using a 38.400kHz crystal, which would produce an effective baud rate of 9600bps with 0.00% error with a frequency divider of 4. The use of a 38.400kHz crystal will not affect real time keeping nor sampling rate, because a 256Hz signal can be obtained by counting 150 cycles of the crystal, and a second can be obtained by counting 38400, both of which fit into a 16bit timer compare register.

Additionally, a 12MHz crystal was added to comply with the USB-to-SD card reader specifications. The card reader comes preprogrammed to accept a 12MHz clock input that is used for the USB and SD subsystems.

Table 6: Components Frequencies

Component	Protocol	Frequency
MCU	-	4, 8, or 16 MHz
Crystal 1	-	38.400kHz
Crystal 2	-	12.000MHz
ADC	-	200ksps
Accelerometer	Analog	500Hz
Battery Gauge	I^2C	10-100kHz
Magnetometer	I^2C	0-100kHz
Gyroscope	SPI	0-10MHz
RF Wakeup	SPI	0-2MHz
SD card	SPI	0-25MHz
Xbee	SPI	0-5MHz
GPS	UART	9,600 baud

5.2 Point-to-point communication

This section outlines the minimum requirements for timing signals of the devices connected through GPIO. Table 7 shows the timing requirements for the components. These timing signals do not include forms of serial communication, including UART, SPI and I^2C. If a device requires a specific setup or hold time, the solution would be to set up a timer and count the specific number of clock ticks that the device requires. Unfortunately, many manufacturers do not specify these values in the device data sheets. Experiments on signal timing will be performed on such devices, and a 10% error will be added to ensure compatibility.

Table 7: Timing Requirements

Port	Time Required
GPS_DR (DR_INT)	Needs to be toggled by low-high-low with >10ms pulse length
GPS_FIX (UI_FIX)	Signal outputs 1s pulse every 2s during valid fix condition
GYR_CS (CS)	Setup time: 5ns, Hold time: 8ns
GYR_DR (DRDY/INT2)	Interrupt: enabled until acknowledged by the MCU
MAG_DR (DRDY)	Interrupt: enabled when a new set of measurements are available
RF_WK (WAKE)	Not specified
RFWK_CS (CS)	Needs to be high as long as data needs to be read. 65 clock cycles to calibrate
SD_CD (HCRD_PRST)	Active when card present
SD_CS (CS)	Asserted 74 clock cycles
SU_BERR (!BERR/INT)	Low when error occurs, stays until error is cleared
SU_BUSY (!BUSY)	>100ms to complete enumeration/de-enumeration
SU_MODE (MODE)	Active during simple control
XB_CS (SPI_!SSEL)	Not specified
XB_DR (!DTR/SLEEP)	Not specified
XB_SLEEP (ON/!SLEEP)	Not specified

5.3 Analog considerations

There is only one analog component in the system, the ADXL377 accelerometer. Care must be taken to ensure that the sampling rate of the MCU's ADC can be set to twice the frequency of the analog signal and that the input voltage range of the ADC is enough to allow for the output voltage swing of the ADXL377. The ADXL377 can output data at 1000Hz, but this system requires it to be 500Hz. This means that the MCU's ADC must be capable of sampling at a rate of at least 1ksps. The MSP430FR5969's ADC is capable of sampling at 200ksps, which is well above the required value. The acceptable input voltage range is specified to be from 0V to +Vcc. Since the ADXL377 output voltage swing ranges from 0.1V to 2.8V, the accelerometer's output can be sampled without suffering from clipping distortion. This makes the ADXL377 compatible with the MCU.

A second consideration should be made when interfacing with an analog component: slew rate compatibility. There is no documented specification of the ADC's slew rate in the MSP430FR5969's data sheet. However, since the ADC takes 200ksps, one can assume that at a relatively low signal frequency of 500Hz, the accelerometer's data will not suffer from distortion because of slew rate limitations.

6. Memory Usage Details

7. Hardware Reliability and Professional Component

8. Hardware Level of Completion

9. Theoretical Background

10. Conclusion

11. Future Work

12. References

[1] A. Amador, M. Canals, G. Guerrero, J. Cruz, and E. Ortiz, "Development of novel instrumented lagrangian drifters to probe the internal structure of breaking surface waves," in *Oceans, 2012*, pp. 1 –6, oct. 2012.

[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: Work Distribution

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