Oceanographic Instrument Simulator

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***Abstract*—The Monterey Bay Aquarium Research Institute (MBARI) established the Free Ocean Carbon Enrichment (FOCE) experiment to study the long term effects of decreased ocean pH levels by developing in-situ platforms [1]. Deep FOCE (dpFOCE) was the first platform, which was deployed in 890 meters of water in Monterey Bay. After the conclusion of dpFOCE, MBARI developed an open source shallow water FOCE (swFOCE) platform to facilitate worldwide shallow water experiments on FOCE [1][2]. A shallow water platform can be more ubiquitous than a deep-water platform as shallow water instruments are less expensive (as it does not have to be designed to withstand the pressure at deep ocean depths) and more easily deployed (they can be deployed right along the coast).**

The swFOCE experiment is an open source platform, and MBARI has made the plans available online to anyone interested in studying shallow water carbon enrichment. The Oceanographic instrument simulator (OIS), described in this paper provides the means for MBARI engineers to test the swFOCE platform without attaching the numerous and expensive oceanographic instruments. The Oceanographic Instrument Simulator simulates the various scientific instruments that could be deployed in an actual experiment.

Keywords—oceanographic; engineering; sensor; MBARI; open source; simulator

I. INTRODUCTION

As atmospheric CO_2 is rising, so is carbon sequestration in the ocean. The increase in CO_2 in our world's oceans will change its biological composition. In order to better monitor the effect of rising atmospheric CO_2 in the ocean, scientists and engineers at the Monterey Bay Aquarium Research Institute (MBARI) have been monitoring the ocean through the Free Ocean Carbon Enrichment (FOCE) experiment. Their first platform, Deep FOCE (dpFOCE) was deployed at 890 meters in Monterey Bay for 17 months from May 2011 to October 2012[1]. After the dpFOCE, shallow-water FOCE (swFOCE) was established as an open source platform to facilitate worldwide shallow water experiments on FOCE. A shallow water platform can be more ubiquitous than a deep-water platform as shallow water instruments are less expensive and more easily deployed.

When an open source platform is made available, it is also useful to make available an inexpensive means to test the platform to insure its operability and functionality. The Oceanographic Instrument Simulator (OIS), the topic of this paper, was designed to give test engineers the ability to test the functionality of swFOCE without the need for having the actual expensive oceanographic instruments connected to the system. The OIS simulates up to four oceanographic instruments by providing an equivalent electrical load and data stream as the real instrument. Thus, scientists and engineers can connect the OIS to the swFOCE, configure the OIS to simulate the oceanographic instruments they plan to deploy, and test the system to ensure 1. that the power limits of the system are not exceeded and 2. that the data from the 'sensor' accurately flows through the various modules of the system.

The rest of this paper is organized as follows: In section 2, we present the block diagram of the swFOCE platform and describe its purpose. In section 3, we describe the hardware and software design of oceanographic instrument simulator (OIS). In section 4, we describe the different tests we preformed to illustrate proper functionality of the OIS including electronic load oscillation testing, thermal testing and parallel testing. We present the power budget in section 5 and conclude in section 6.

II. SWFOCE PLATFORM

A block diagram of the swFOCE platform is shown in Figure 1. Each of the four sensor nodes, shown at the bottom of the figure, allows a user to connect four different sensors (three with a current limit of 2 Amperes and one with a current limit of 6 Amperes). The sensor node gathers readings from each of its attached sensors and sends the data back to a shore station through the gateway node. The swFOCE experiment could generate a large amount of data from a variety of instruments, including pH sensors, CTDs, O_2 sensors, water flow-meters, and ADCPs. This data propagates through a number of subsea housings prior to being stored on a local shore computer and disseminated over the web.

The sensor node module, designed by MBARI, is used to interface a wide range of scientific instruments. The sensor node provides power and serial communication to a maximum of three instruments. It also has a fourth high current port for devices such as lights or simple motors. The sensor node can provide a maximum of 75 watts and can be configured for 12V, 24V, or 48V. Port #3 can also be switched to interface a 4-20mA instrument.

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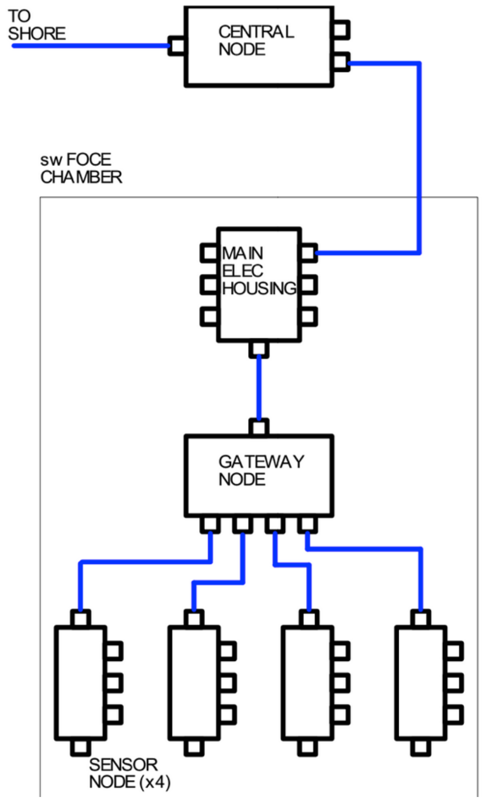

Figure 1: Block Diagram of swFOCE Implementation [1]

III. INSTRUMENT SIMULATOR

The purpose of the OIS is to provide the swFOCE platform a simple and portable test system to be used in a lab or office setting without the need of actual oceanographic instruments. The OIS connects directly to the Sensor Node Module and provides two major functions: hardware and software verification of the sensor node board and end-to-end testing of the data management architecture of the swFOCE experiment.

Because the sensor node was designed to connect to up to four oceanographic instruments (three with a current limit of 2 Amperes and one with a current limit of 6 Amperes) without exceeding 75W, the OIS instrument simulator was designed to simulate four oceanographic instruments (three with a current limit of 2 Amperes and one with a current limit of 6 Amperes) without exceeding 75W.

The OIS block diagram and its connection to the swFOCE sensor node is depicted in Figure 2. Electronic Loads #1, #2, and #3 simulate the three instruments with a current limit of 2 Amperes and Electronic Load #4 simulates an instrument with a current limit of 6 Amperes. Note that Port #3 can also be switched to interface a 4-20mA instrument per the sensor node's design. The three transceivers depicted below electronic loads #1, #2, and #3 emulate serial data transfer from each of the simulated sensors. The high current port #4 was not designed for serial interface as it is meant to interface to LEDs or motors. The Micro SD shield is connected to an SD card which stores simulated sensor data. The Arduino Due handles the configuration, the processing and the monitoring of the OIS. The USB Port on the Arduino Due connects to the personal computer (PC) for the user to have access to the terminal. The user can configure each load and each communication port to simulate a sensor of interest (either manually or from a drop down list of sensors such as the SeaBird SBE18s pH sensor [9]). Once the OIS is configured, the user can attach the OIS to the sensor node of the swFOCE for full system testing.

The OIS is designed to run on 12, 24, or 48V, because those are commonly used power supplies for oceanographic instruments. The following subsections describe the hardware and software design of the system in more detail.

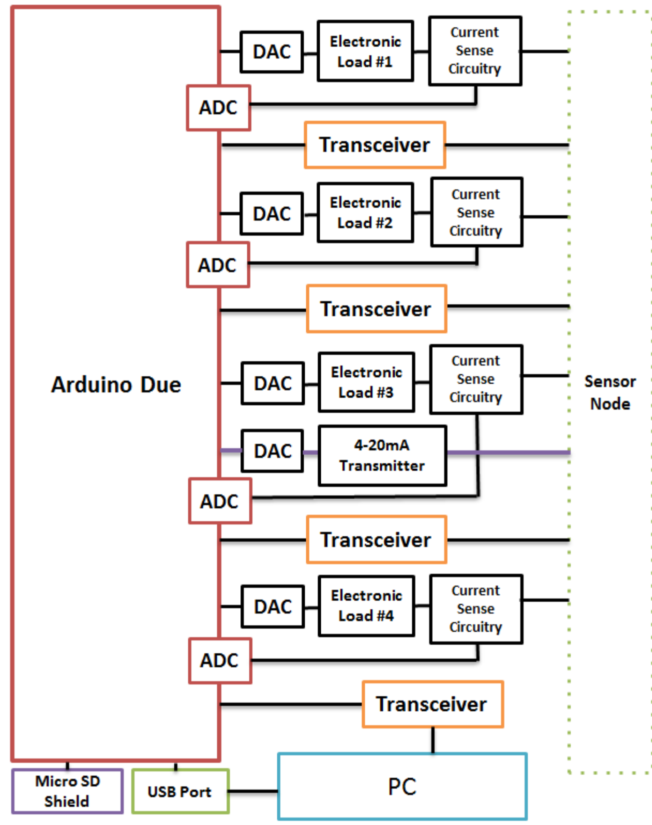

Figure 2: Oceanographic Instrument Simulator Block Diagram

A. Hardware Design

The hardware design of the OIS includes the design of the electronic load, DAC interface, current sense circuitry, the 4-20mA current loop transmitter and the ADC interface.

The Arduino Due controls the electronic loads and monitors the OIS with user control available through a terminal window. The Arduino Due was selected because unlike other Arduino boards, it contains four UART ports. The Arduino board sets the output voltage of the DAC, takes in feedback from the current sense circuit via the ADC and verifies the functionality of the UART ports.

The electronic load includes the DAC, the op-amp, the MOSFET and a resistor, shown in Figure 3.The DAC is controlled by the Arduino and provides fixed voltage to the positive terminal of the op-amp. The MCP4921 is selected, based on the supply voltage of 3.3V, which is compatible to the output voltage from the Arduino Due. The DAC controlled programmable current sink circuit is shown in Figure 3. The op-amp creates a negative feedback loop from the gate of the MOSFET via the resistor then back to the negative terminal of the op-amp. Depending upon the input voltage from the DAC, the current conducted by the MOSFET and resistor varies. The output voltage from the Arduino goes up to 3.3V; therefore the range of the DAC output is set to vary from 0V to 3V. To sink in 0A to 2A, a resistor with value 1.5Ω is selected. The op-amp and the 1.5Ω sense resistor form an integral control that forces the MOSFET's current to be exactly Vin/1.5Ω. This value assumes stable loop and op-amp with zero offset. LM358 was chosen for its ground-sensing capabilities [3] and the MOSFET FDP050AN06A0 for its large current and power dissipation capabilities [4].

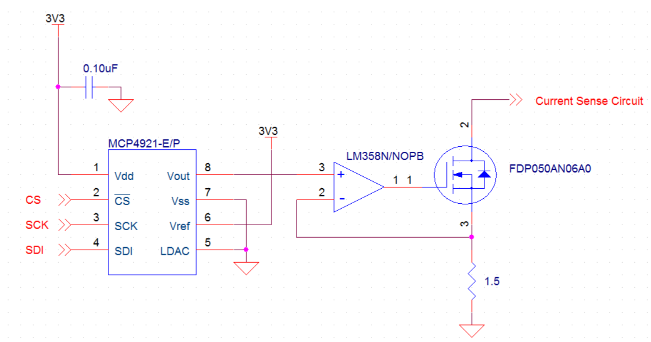

Figure 3: DAC Controlled Electronic Load Schematic

The current sense circuit, as shown in Figure 4, is used to monitor the output current and shut down the circuit should the current exceed 75W. The LT1999 is selected due to simplicity. To increase the resolution of the current sense circuit, the offset of the V_{REF} is set at 1V. The current sense circuit can sense voltages ranging from 1-3Vdue to the offset of the V_{REF}. The LT1999 chip has an offset of 2.5V at V_{REF}, shown in Figure 5. In order to lower the V_{REF}, an additional 52.3k resistor is added to lower the V_{REF} to 1V. Due to the range of the ADC on the Arduino Due, we were able to sense voltages from 1V to 3V.

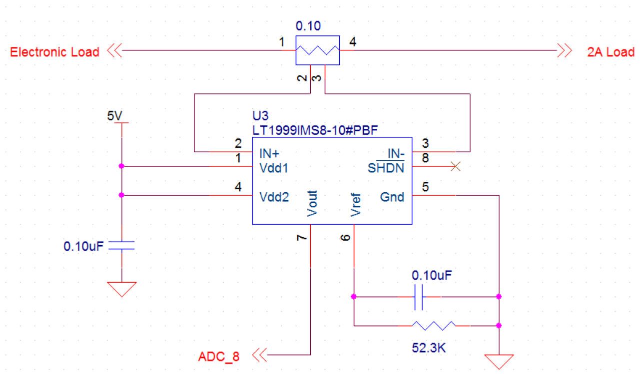

Figure 4: Circuit Sense Circuit Schematic

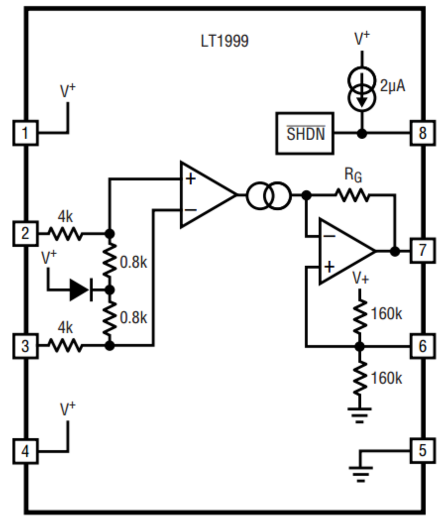

Figure 5: LT1999 Block Diagram [8]

A single 4-20mA current loop transmitter is designed for OIS at load #3 to communicate with 4-20mA instruments on the Sensor Node. The 4-20ma current loop transmitter, XTR117 [7], shown in Figure 6, from Texas Instrument is selected due to the simplicity of the design. According to the datasheet, the chip is built around Eq. (1). Since the output of the DAC was originally range from 0V to 3V, Eq. (1) is used to calculate the resistance of 15k.

$$I_o = \frac{100V_{in}}{R_{in}}(1)$$

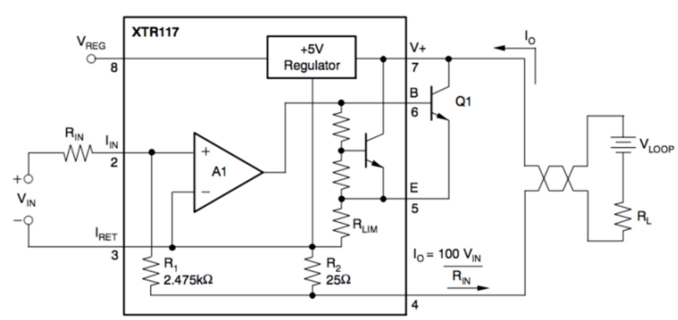

Figure 6: 4-20mA Transmitter Loop Schematic [7]

B. Software Design

The software for the OIS is a terminal based program that allows the user to configure and run the simulator. The main menu screen for the terminal program is shown in Figure 7. Option 1 allows the user to specify the sensor node's DC-DC converter's voltage (12, 24, or 48V). Option 2 allows the user to configure each port with a desired electronic load and data stream to simulate the desired sensor and Option 3 allows the user to check any ports that have already been configured. Option 4 can test each individual port's electronic load and Option 5 can test each port's serial communication. Option 6 can run or stop individual ports. Option 7 is currently used for testing individual commands to simulate the SBE18s pH sensor. In the future, these commands will be incorporated into Option 5 for testing the serial communication.

```
Main Menu
Please choose an option:
   1 - Select DC/DC converter used in Sensor Node
   2 - Configure individual port
   3 - Get port Configuration
   4 - Test individual port load
   5 - Test SD communication
   6 - Run/Stop port
   7 - Read pH command
Select:
```

Figure 7: Main Menu Screen

Figure 8 shows the software design in more detail - illustrating the sub menus/selections that appear after each main menu option is pressed.

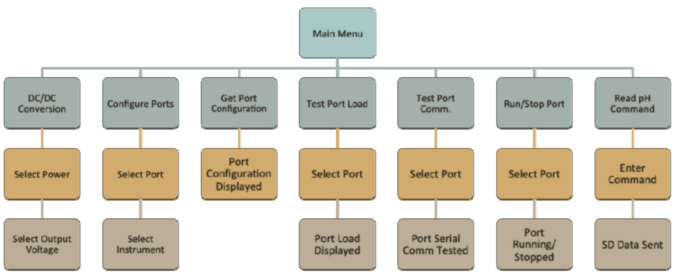

Figure 8: Software System Diagram [2]

When all ports have been configured and are running and the OIS is connected to the sensor node, the OIS will respond to any serial commands sent from the sensor node. The OIS software program streams simulated data and monitors the current consumption on all active ports to ensure they do not exceed the system's maximum power, 75W. Figure 9 shows an example of the OIS responding to the sensor node's command of "gethd" directed toward the SBE18s pH sensor. The OIS interprets the command and responds back with the appropriate information (in this case, hardware device information) which is stored on the OIS' SD card.


```
[plugged in instrument]
<POWERON/>
S> gethd<HardwareData DeviceType='SBE18S' SerialNumber='01801065'>
   <Manufacturer>Sea-Bird Electronics, Inc</Manufacturer>
   <FirmwareVersion>V1.2.0</FirmwareVersion>
   <FirmwareDate>Oct 21 2013</FirmwareDate>
   <PCBAssembly PCBID='64217' AssemblyNum='41819D'/>
   <PCBAssembly PCBID='62222' AssemblyNum='41817'/>
   <MfgDate>May  2 2013</MfgDate>
   <FirmwareLoader>SBE 18S FirmwareLoader V 1.0</FirmwareLoader>
   <PCBType>0</PCBType>
   <InternalSensors>
      <Sensor id='Water pH'>
         <type>PH0</type>
         <SerialNumber>01801065</SerialNumber>
         </Sensor>
      </InternalSensors>
_  </HardwareData>
```


Figure 9: Data Format for pH Sensor [2]

IV. TESTING

In order to test the accuracy and stability of the OIS, the following tests were performed: 1. Accuracy of the electronic load, 2. Thermal testing of the electronic loads and 3. Parallel testing of the electronic loads.

A. Electronic Load Testing

In order to ensure the OIS accurately simulates the electronic load it was configured to simulate, electronic load testing must be performed. The scope capture shown in Figure 10 has an input of 1Vpp square wave with an offset at 500mV. The yellow waveform represents the input square wave to the op-amp and the blue waveform represents the gate of the MOSFET. The gate voltage would vary due to the feedback loop and the input voltage. When the circuit is in ON-state, high-frequency oscillation develops. The oscillation is seen here as a thick "band" in the gate voltage waveform.

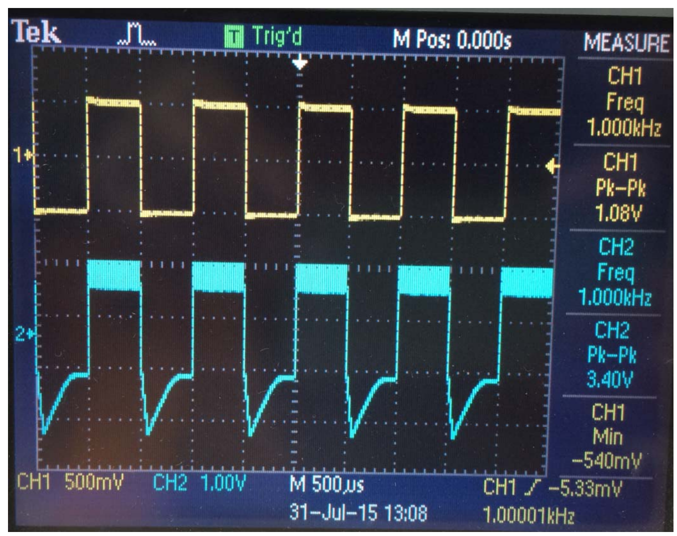

Figure 10: Scope capture of input of 1Vpp and V_G of the MOSFET. Yellow square wave on the top represents the input of 1Vpp. Blue waveform on the bottom represents the V_G of the MOSFET.

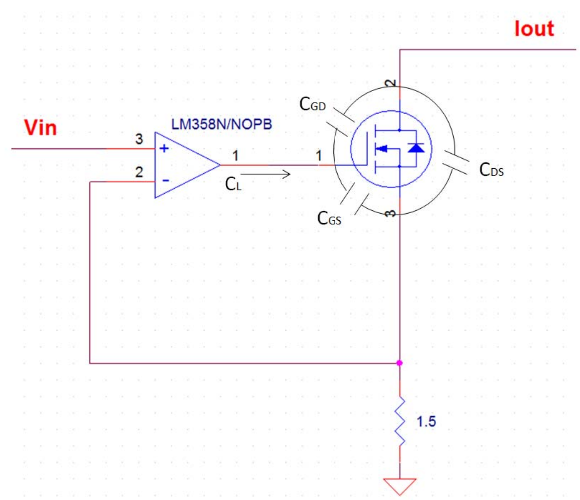

Figure 11: Schematic of electronic load with small signal capacitance

The reason high frequency oscillation develops can be explained as follows. In Figure 11, the parasitic capacitors associated with the MOSFET are explicitly depicted. The C_{GD} is effectively connected at the output of the op-amp, because the 12V DC source biasing the drain terminal acts as an "AC-short". The op-amp therefore experiences capacitive loading C_L where $C_L > C_{GD}$. The parasitic pole formed by R_{OUT} of the op-amp and C_L introduces phase lag and compromises the stability of the loop.

There are many ways to resolve the issue [6]. The approach chosen is to increase the bias current of the output stage thus lowering the output resistance of the op-amp and pushing the parasitic pole at higher frequency.

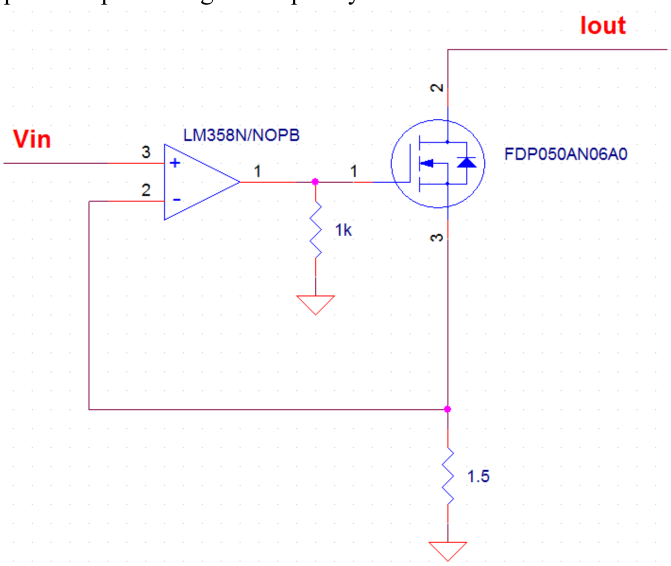

Figure 12: Schematic of the current-sink circuit with addition resistor

The resistor R_{BIAS} in the Figure 12 increases the bias current of the output stage of the op-amp. Larger bias current leads to smaller output resistance. The functional block diagram of the LM358 [3] is shown in Figure 13. Notice that the Darlington Pair of the push-pull stage as biased at approximately 50uA. At this current the output resistance of the last stage and hence the op-amp is estimated to be no less than 1kΩ. Several scope captures were taken after the additional resistor 1k was added. As seen in Figure 14, connecting bias resistor of 1kΩ resolves the issue.

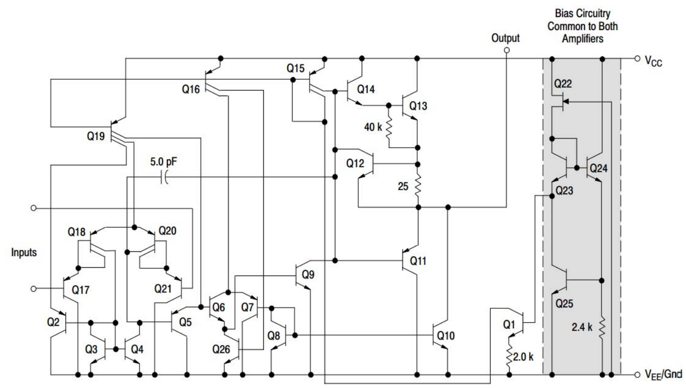

Figure 13: Schematic Diagram of one-Half of LM358 [3]

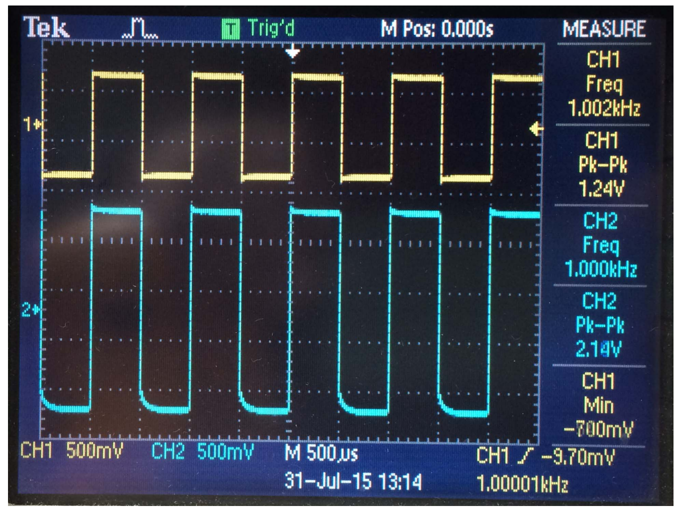

Figure 14: Scope capture of input of 1Vpp and V_G of the MOSFET. Yellow square wave on the top represents the input of 1Vpp. Blue waveform on the bottom represents the V_G of the MOSFET.

B. Thermal Testing

The purpose of the thermal test is to ensure proper functionality of the OIS under a fully loaded condition. Excessive heat can cause instability of the system or even overheat the components used in the simulator. A sudden and excessive rise in temperature could cause failure of the electronic load. Figure 15 depicts such a scenario, suggesting the need of forced-air cooling. Without the fan, a load up to 6A would go over 100^{o}C in less than 7 minutes. A load up to 2A would go over 80^{o}C within 5 minutes.

Two fans were selected to accommodate the anticipated heat. Each fan is 92x92x25mm, covering the surface of the heat sinks.

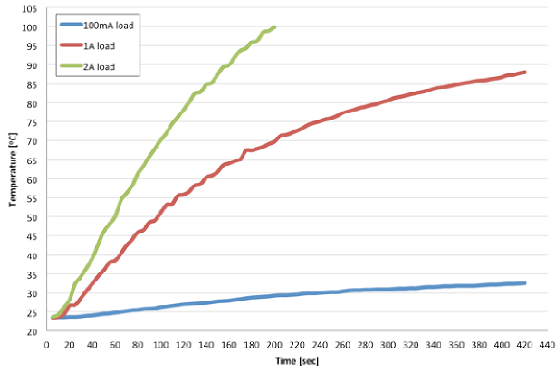

Figure 15: Thermal Test without Fan

With the fan on, as shown in Figure 16, a load up to 6A would remain around 45°C over a long period, thus providing the necessary stability of the entire system.

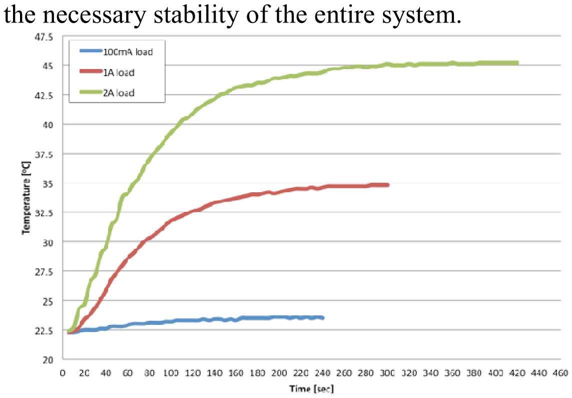

Figure 16: Thermal Test with Fan

C. *Parallel Testing*

The purpose of the OIS is to simulate multiple oceanographic sensors simultaneously, thus parallel testing of multiple sensors is necessary to insure the accuracy of the system. As shown in Figure 17, Figure 18, and Figure 19, the parallel testing result demonstrates the accuracy of the OIS. The expected current is the current the user would input to the OIS and the output current is the current that is displayed on the power supply. To ensure the system does not exceed 75W power rating, three loads of 2A and the single 6A load are tested separately. Figure 17, Figure 18 and Figure 19 show that the overall OIS system remains linear and accurate when all loads are running.

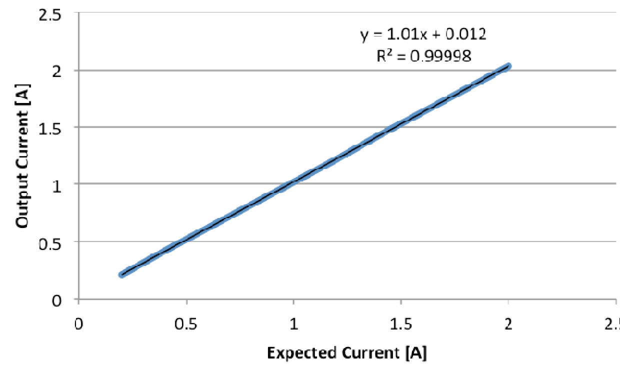

Figure 17: Single load test

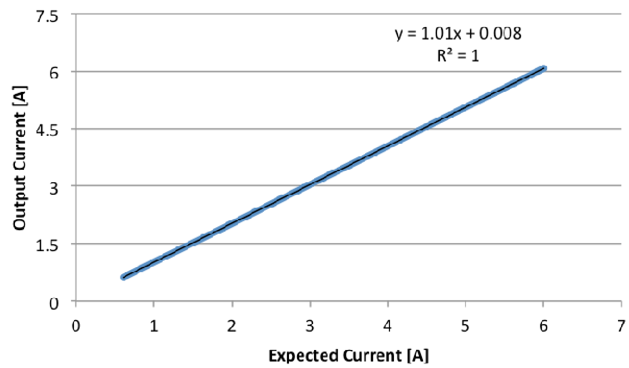

Figure 18: Parallel testing for three loads at the same time

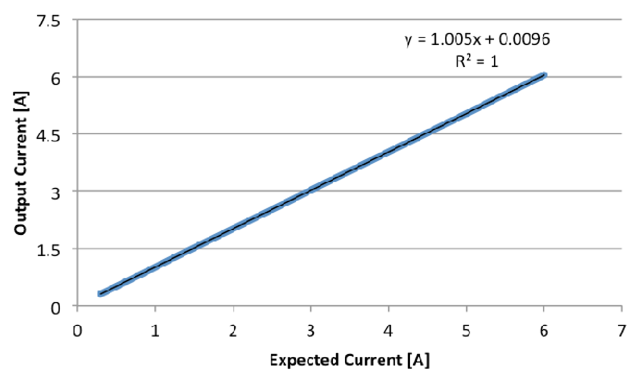

Figure 19: Parallel testing for Load #4

V. POWER BUDGET

The following is the estimated power budget for the OIS. The OIS will be supplied with 3.3V and 5V from the Arduino Due and supplied with 12V from an external power supply (Hewlett Packard 6028A DC Power Supply 0-60V/0-10A, 200W). The estimated power budget matched the experimental power supply, shown in Table 1. The R_{BIAS} shown in Figure 12 would increase the power consumption of the op-amps.

TABLE I. POWER BUDGET

Circuit	Part number	Voltage [V]	Current [mA]	# Used
DAC	MCP4921	3.3	0.35	5
Current-Sense Amplifier	LT1999	5	1.55	4
Dual Op-amp	LM358	12	6	5
Interface Circuit	Max3323	3.3	1	4
Fan	259-1464-ND	12	165	2
LED	WP710A10CGCK	3.3	20	1
	Estimated Value [mA]		Actual Value [mA]	
Total Current from 12V	360		378.47	
Total Current from 5V	6.2		6.17	
Total Current from 3.3V	25.75		28.5	

VI. CONCLUSION

Currently, the hardware and software design of the OIS are working properly and the OIS is providing MBARI engineers with an inexpensive means to test the swFOCE platform. The hardware design of the OIS could be improved to further increase the stability of the electronic load output and the software design could be improved with a graphical user interface. After the improvements, the OIS can then be interfaced with the swFOCE platform.

Although the OIS was designed specifically to test the swFOCE platform, the OIS can be used as a general oceanographic instrument simulator for other applications as it can be manually configured to emulate many different electronic loads and serial data stream. The OIS can serve as an excellent testing platform for the entire oceanographic community.

ACKNOWLEDGMENT

The David and Lucille Packard Foundation support this project. Jim Montgomery (MBARI) has also made significant contribution to the development on the Oceanographic Instrument Simulator.

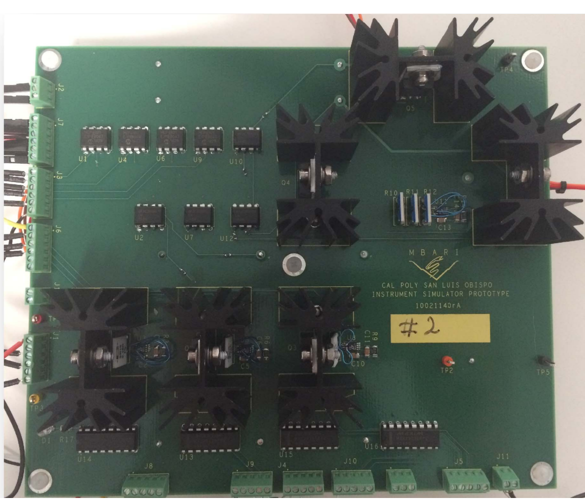

Figure 20: The Oceanographic Instrument Simulator circuit board

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