Advances in Wave Sensing Using MEMS

Semiconductor sensors enable a new generation of wave sensing applications

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***Abstract*—Advances in semiconductor technologies have enabled a new generation of small, accurate, low power sensors. The capabilities of these sensors, combined with similar advances in microprocessing capabilities, have enabled the integration of sensors and on-board processing algorithms that bring a wealth of possibilities. This paper will explore the use of one such sensor-microprocessor combination and its application to buoy-based directional wave sensing for weather and oceanographic applications. The basic design of this sensor, some of the algorithms used, and the limitations, implications and possibilities for this approach will be explored.**

Keywords—wave sensor; magnetometer; wave height; significant wave height; MEMS; inertial wave sensor, IMU; dominant period

I. Introduction

The use of Micro-Electrical Mechanical Systems (MEMS) accelerometers for such diverse mass markets as cell phones, game controllers and automotive applications has resulted in tremendous investment and subsequent improvements in the power consumption, accuracy, and cost of these sensors. The resulting availability of low cost sensors has driven a range of applications.

Early work with MEMS based accelerometers, most notably Brown and Meadows [1], identified buoy-based wave sensing as a likely application area. But early MEMS accelerometers were limited by drift and inaccuracy. This inaccuracy necessitated various computational corrections in order to get workable wave statistics as cited by various National Data Buoy Center (NDBC) documents including [2]. Among the techniques proposed and implemented in various forms was frequency domain filtering based on the work of Lang [3] from the NDBC.

In 2011 Brown and Meadows, working at the University of Michigan's Ocean Engineering Laboratory, produced a small, low power circuit that combined the accelerometers needed to perform wave sensing, a magnetometer for sensing the heading of a buoy that is able to spin freely, with the electronics needed to perform computational corrections. This enabled practical wave sensing in a compact package with relatively low power consumption and with reasonable accuracy. Some of the inaccuracy concerns about sensor drift could be eliminated by looking at statistics of waves rather than individual wave height data. However, there were limitations including a requirement to place the wave sensing accelerometers as close as possible to the roll center of the buoy. Any displacement from this position would result in measurements that would be swamped by spurious movement as the buoy rocked with the waves it was meant to measure.

But as the technology for accelerometers and magnetometers has advanced, driven mostly by other applications, many of the initial limitations and performance metrics have improved. The result is a vastly improved landscape of possibilities for the use of these sensors in other applications such as wave sensing and suggests the possibility of significant improvement in wave sensing applications when compared with the sensors of only a few years earlier.

II. Improved Sensors Open New Algorithmic Possibilities

With the advancing sensor technology, combined with power efficiency and the possibility to incorporate increased processing power, MEMS-based sensors enable more accurate measurements as well as increased algorithmic capability which can compensate for non-ideal buoy hulls or mounting conditions. The inclusion of explicit measurement of pitch and roll angles allows for more complex algorithm implementations and thus more flexible sensor placement, reducing the importance of placement at the buoy roll center.

SeaView Systems has been actively developing electronics for various oceanographic and hydrographic survey applications. This paper presents work that has been done on advanced wave sensor design and explores the implications of advancing sensor capabilities and how these could impact the use of MEMS sensors for various applications from buoys to autonomous vehicles to drift buoys. This paper will explore some of the considerations that went into a comprehensive wave sensor design and present some measurement results as well as exploring the implications for broader application of the technology.

A. *Limitations of Previous Techniques*

In the initial implementation of this technique as devised and published by Brown and Meadows [1], the sensors used offered only acceleration measurements and a magnetometer for determining heading, a so-called 6 degrees of freedom. As a result, it was essential that the sensor be placed at or near the roll center of the buoy in order to avoid spurious accelerations produced by buoy pitch and roll. However, by placing the sensor at the roll center, the effects of pitch and roll could be minimized and good results could be achieved.

And, while the size and power consumption of the initial designs for this type of sensor were impressive by comparison with previous techniques, new sensors enable the possibility of improvements in these and many other areas.

In addition, while the early implementation of this technique included using the on-board processor to perform a fast Fourier transform (FFT) of the data set in order to perform filtering operations and calculate wave statistics, there are other possible data manipulations that might be beneficial but that press the limits of the processing capabilities used in early sensors.

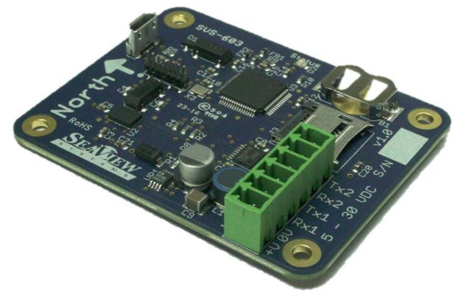

Fig. 1. At just 53.5 x 68 x 23mm, the SVS-603 can fit into very small platforms.

B. New Sensor Outputs Create Richer Palette of Algorithmic and Feature Support

Subsequent advances in available sensors added both pitch and roll angle and angular velocity as possible outputs. The availability of these parameters allows for a variety of useful enhancements to the algorithmic possibilities. The combination of improved sensors, improved processing capabilities, and the target of adding algorithms to enable support for a much broader set of platforms motivated SeaView Systems to design a new sensor to exploit the latest capabilities as well as incorporating a list of enhancements based on experience with early sensors in the field.

The list of desired features for a new sensor included:

- Use the latest, most accurate sensors with the richest set of possible outputs
- Reduce the overall power consumption of the system
- Increase the processing power of the system to support more elaborate algorithm implementations needed for non-ideal buoy hulls or mounting positions
- Add flexible control to output streams to enable use in both low data support and high data support environments
- Add data logging capabilities to easily support thorough logging of all measured data for retroactive analyses
- Implement new algorithms to reflect specialized requirements such as non-ideal buoy hull shapes or non-ideal mounting position

The resulting sensor design, the SVS-603 addresses each of these considerations and is shown in Figure 1.

Figure 2 shows the raw sensor output including pitch and roll angles, heading and accelerations as seen in the sensor's frame of reference. In particular, the pitch and roll angles open new algorithmic possibilities.

Among the algorithmic improvements included in the SVS-603 are the translation of the measured accelerations into an earth frame reference. This translation is readily accomplished as a result of the availability of the pitch and roll angles output by the newer sensors used in this design.

In addition, by taking into account angular velocities algorithmically, the sensor's firmware is able to compensate for the centrifugal acceleration and extract the resulting buoy vertical acceleration including the consideration of the motion of the sensor when offset from the roll center of the buoy [4]. This eliminates one of the primary limitations from early designs: the requirement for either a buoy with very low maximum deployed pitch and roll angles, or alternatively, the requirement that the sensor be placed at the roll center of the buoy to avoid accelerations that were not representative of the movement of the buoy's roll center.

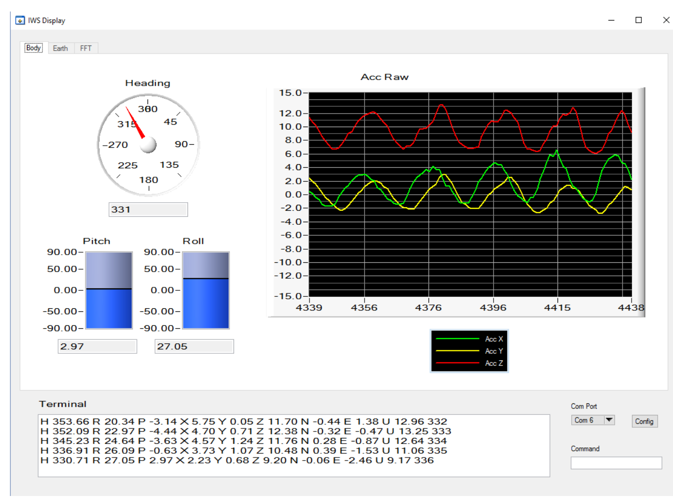

Fig. 2. Graphical display of the raw output from the SVS-603 showing pitch and roll angles, compass heading, and acceleration in 3 dimensions in the sensor's reference frame.

Translating the accelerations into an earth referenced frame allows for the resolution of the vertical motion of the sensor independent of pitch and roll angle, thus dramatically reducing the effect of spurious motion that is created when the sensor is located away from the roll center of the buoy platform. The algorithms employed can take this into account and can greatly reduce the impact of buoy pitch and roll on the resulting wave statistics. Figure 3 shows a graphical display of the accelerations following transformation into an earth reference frame.

Once the accelerations have been translated into an earth reference frame, the SVS-603 performs a spectral analysis similar to that described by Brown and Meadows.

Figure 4 shows the resulting power spectrum for a motion test with a period of three seconds. The display also shows the calculated wave parameters that have been extracted from the spectrum.

Some figures of merit and characteristics of the resulting sensor design, the SVS-603, are given below:

- Supply voltage: 4.5 to 30V
- Power consumption: 150mW at 12V, 136mW at 5V
- Mass storage support: micro-SD card slot
- Size: 53.5 x 68 x 23mm
- Ports: USB and RS-232
- Wave statistical summary or full spectrum output
- User configurable through command line inputs

The SVS-603 also includes algorithms to take into account movement of the sensor based on position relative to the buoy roll center. This enables the on-board algorithms to calculate the vertical motion of the buoy's roll center even when the sensor is mounted some distance vertically away from it.

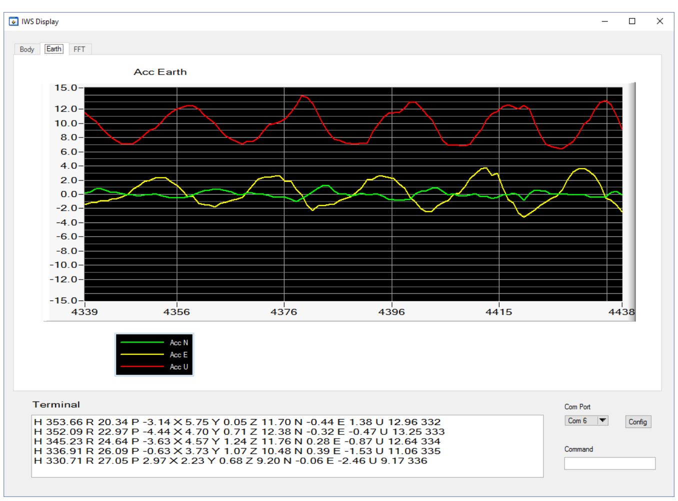

Fig. 3. Graphical display of sensor acceleration when translated into an earth frame reference.

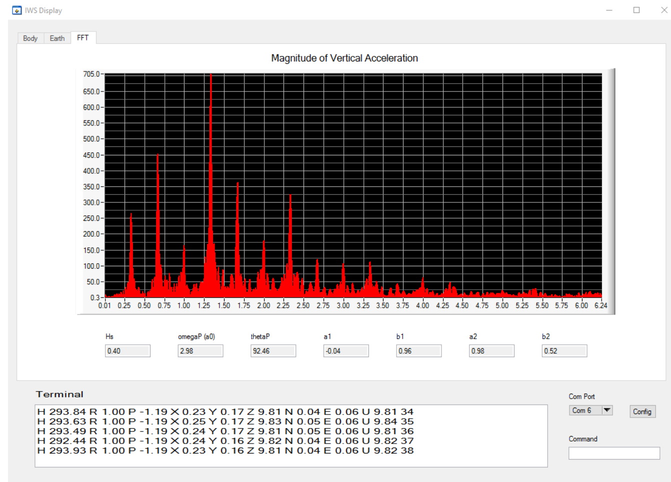

Fig. 4. Display of the frequency spectrum produced on board the SVS-603 for a test for motion with dominant period of about 3 seconds (corresponding to 0.33 Hz peak in the display) and clearly visible harmonic peaks at multiples of this frequency.

III. Deployed Sensor Results

A test deployment of the SVS-603 was performed in a buoy similar to that shown in Figure 5.

Data for significant wave height from a deployment of the SVS-603 mounted on a buoy in the Great Lakes is shown in Figure 6. The graph also shows data produced by an acoustic waves and currents (AWAC) sensor that was co-located with the buoy on which the SVS-603 was mounted for comparison.

Fig. 5. A buoy of the type used for the test deployment.

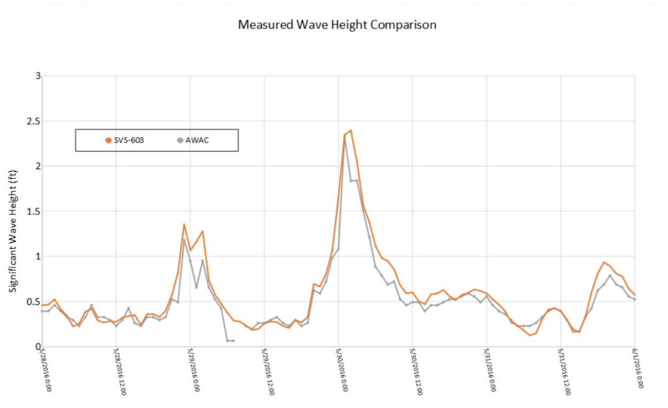

Fig. 6. Measured data comparing the significant wave height as measured by the SVS-603 with measurements produced by a co-located AWAC sensor.

IV. Conclusions and Directions for Future Work

The use of the most recent MEMS sensors enables very low power wave sensing in a small package that enables wave sensing on smaller platforms and with reduced power budgets. The inclusion of onboard processing capabilities enables detailed calculations for wave statistics or enhanced algorithmic analysis. Among the possibilities that open up with these capabilities are more complete response amplitude operator (RAO) analyses and more thorough investigations of differing wave conditions that can be accomplished using the on-board processing capabilities. One of the areas that could exploit these capabilities are non-ideal (from a wave riding perspective) hull shapes such as those employed by unmanned surface vehicles.

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References

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