A Miniature, Sourceless, Networked, Solid State Orientation Module

CP Townsend BSEE, DC Guzik MSBME, SW Arms, MSME
MicroStrain Inc., 294 North Winooski Ave., Burlington, VT 05401
URL: www.microstrain.com, Email: info@microstrain.com

ABSTRACT

A device to accurately measure inclination and/or heading in a static or dynamic environment would be useful as a feedback element for vibration and position control in adaptive structures. Our goal was to develop a miniature, sourceless angle measurement system, which utilizes triads of accelerometers and magnetometers as well as an onboard microprocessor (3DM). The microprocessor calculates pitch, roll, and yaw based on Earth's magnetic and gravitational field vectors. The microprocessor also incorporates a digital user programmable infinite impulse response (IIR) filter. This paper describes the ability of 3DM to accurately measure angle in static and dynamic environments. Static as well as four dynamic test configurations were performed: 100, 500, 1000 Hz and Gaussian white noise. The IIR cutoff frequency was set at 0.5, 5, and 30 Hz for each test. Results indicate that implementing an IIR filter can improve measurement accuracy. When the 3DM was oscillated at 100 Hz, error on the pitch axis changed from 1 degree to 0.15 degrees peak to peak using IIR filter cutoff frequencies of 30 and 0.5 Hz respectively. The roll axis responded similarly. Its error was reduced from 2 degrees to 0.1 degrees peak to peak when the IIR cutoff frequency was reduced from 30 Hz to 0.5 Hz.

INTRODUCTION

Miniature orientation devices may be used for a variety of structural and biomedical applications, including: measurement of structural angular displacement and orientation, computer input and pointing, virtual reality head and body tracking, camera stabilization, vehicle navigation, downhole drilling, feedback for functional electrical stimulation, and body position and inclination tracking.

Sourced trackers use fixed magnetic field coils as a reference for magnetic sensors to detect position. (Raab et al., 1979) The source magnetic field coil is required to be relatively close (<10 feet) to the measurement coils. This greatly limit's these devices suitability in smart structure applications as it is often not practical to locate a source coil within this limited range.

Sourceless trackers utilize earth's gravitational and magnetic field vectors, and do not limit a user's range of operation in any way.

Our goal was to develop and test miniature, sourceless trackers with analog and digital signal conditioning, embedded microprocessor, and RS-232 output (3DM). Pitch, roll and yaw angles will be computed in real time, which eliminates the need for bulky external processing units, and facilitates networking.

Our objectives were:

1) to design a solid state, programmable, pitch, roll, and yaw sensor
2) to characterize performance: resolution, linearity, accuracy, and temperature stability
3) to accurately measure inclination in a vibration environment

Our target specifications were:

1) outputs: RS-232, RS-485, and analog
2) range: 360 degrees of pitch, 360 degrees of yaw, and +/-70 degrees of roll
3) programmable digital filter: Infinite Impulse Response (IIR)
4) adaptive filter (static & dynamic)
5) PC based software which will collect, save, display angles or raw sensor data, and allow the user to program the IIR filter

Methods:

3DM's use three orthogonal accelerometers and three orthogonal magnetometers (Figure 1) to measure Earth's gravitational and magnetic field vectors, from which we resolve pitch, roll, and yaw (heading) in real-time (Figure 2). Accelerometers provide a faster response than other sourceless trackers, which may rely on electrolytic fluid (Durlack et al.,1995) or thermal tilt sensors.

Figure 1 3DM board

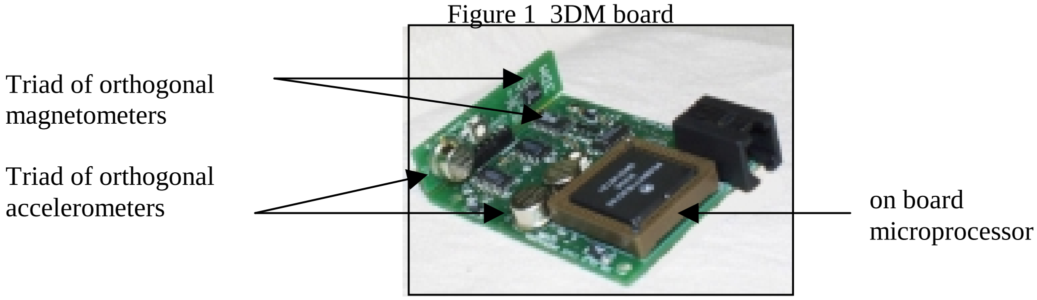
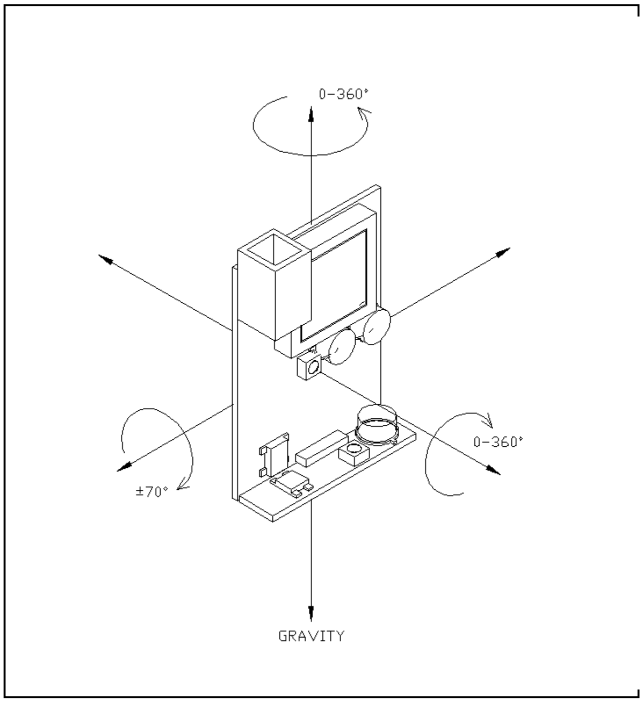


Figure 2 3DM axes of rotation



By implementing filter algorithms that are programmable by the end user, the 3DM device response can be tuned to fit a particular application.

Analog low pass filters were implemented to help to minimize effects due to inertial inputs to the accelerometers. These analog filters dampen the effect of other inputs that have a dynamic response.

To supplement analog filtering we implemented an Infinite Impulse Response (IIR) low pass recursive digital filter. The digital low pass filter function is described by the following equation:

$$x(n) = K*u(n) + (1-K)*x(n-1) \quad (1)$$

The transfer function of this filter in the digital domain using the z-transform relation can be reduced to:

$$H(z) = K/(1-(1-K)z^{-1}) \quad (2)$$

Where K is the filter gain, which for computational reasons is always a factor of a power of two. The filter gain parameters, which are proportional to the filter cutoff frequency, are programmable from the PC by the user.

Typically, use of a filter with a lower cutoff frequency will produce a measurement with fewer artifacts due to noise. The tradeoff is that there is a sacrifice in the systems dynamic response to achieve this lower noise measurement. To try to reach a balance between static vs. dynamic response, an adaptive low pass filter was also implemented, and can be programmed on or off by the user. The adaptive filter works by continually calculating

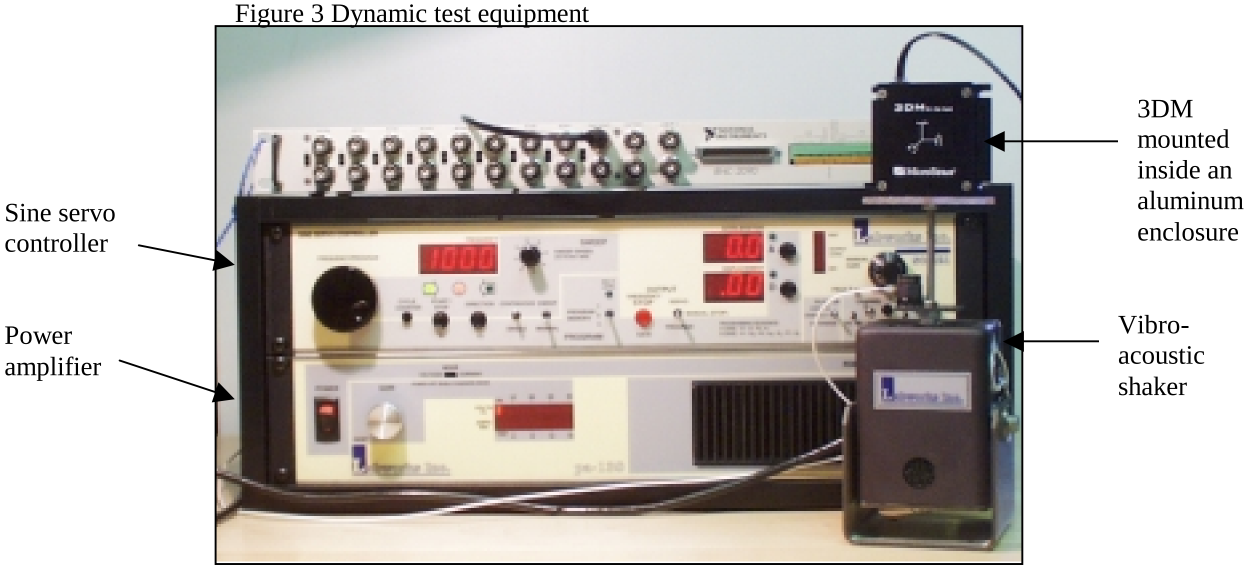
low pass filter readings with separate filter cutoffs on all the sensors in parallel. The software monitors the first derivative of the magnetometers to determine which filter coefficients to apply to the output data. The ramifications of this are that when the device is in a relatively static condition (or moving slowly) a more aggressive filter is applied to the data, because the first derivative of the magnetometer data is small. This results in a lower noise measurement when the device is in this mode. When the first derivative of the magnetometer is above a preset (programmable by the user) level the system reverts to a filter that has a faster response. This is useful for applications such as posture control, when a stable static measurement is important, while retaining the ability to make dynamic measurements if required.

Static tests were performed on five 3DM's to quantify temperature drift, repeatability, nonlinearity, accuracy, and resolution. Temperature tests were run in a thermal chamber ranging from 70 to -20 degrees Celsius. Repeatability tests were performed by placing each 3DM in a position, removing it, and replacing it in the exact same position. Each unit was calibrated against an optical encoder (40,000 counts/revolution), and the nonlinearity was computed. Accuracy was defined as the root mean square of the errors. Resolution was determined by sampling over time, and measuring changes.

Dynamic tests were performed using a vibro-acoustic shaker (LabWorks Inc., Costa Mesa, CA) controlled by a sine servo controller for fixed sine excitation and LabVIEW 5.0 (National Instruments, Austin, TX) for white noise excitation (Figure 3). Data was collected using a high-speed data acquisition card and LabVIEW software.

The 3DM was subjected to four excitation frequencies (100, 500, 1 KHz, and Gaussian white noise) at a magnitude of 1.5g for 20 seconds. Each frequency test was performed using three different IIR filter cutoff frequencies: 30 Hz, 5 Hz, and 0.5 Hz. Adaptive filtering was turned off.

Figure 3 Dynamic test equipment



RESULTS

Static test results from five 3DM's are presented in TABLE I.

TABLE I Static test summary

	Pitch	Roll	Yaw
Temp. Drift (%/deg. C) (mean, std.dev.)	0.009+/-0.008	0.033+/-0.025	0.019+/-0.019
Repeatability (degrees)	+/- 0.07	+/- 0.07	+/- 0.26
Nonlinearity (% FS)	+/- 0.23	+/- 0.23	+/- 0.15
Static Accuracy (deg.)	+/-1.0	+/-0.3	+/-0.5
Resolution (deg, filter off/max)	0.275 / 0.1	0.225 /0 .1	0.5 /0 .1

Dynamic test results showed that angular measurements could be made in the face of vibrations about the pitch and roll axes (yaw is inherently immune to vibrations) using the IIR filter (TABLE II). When the 3DM was oscillated at 100 Hz, error on the pitch axis changed from 1 degree to 0.15 degrees peak to peak at IIR filter cutoff frequencies of 30 and 0.5 Hz respectively. The roll axis responded similarly. Its error was reduced from 2 degrees to 0.1 degrees peak to peak when the IIR cutoff frequency was reduced from 30 Hz to 0.5 Hz.

TABLE II Dynamic test summary

	Pitch (f=30 Hz)	Roll (f=30 Hz)	Pitch (f=5 Hz)	Roll (f=5 Hz)	Pitch (f=0.5 Hz)	Roll (f=0.5 Hz)
100 Hz	1	2	0.4	0.65	0.15	0.1
500 Hz	0.75	0.75	0.6	0.4	0.15	0.05
1 KHz	1	0.5	0.2	0.25	0.15	0.05
White Noise	0.5	0.75	0.2	0.4	0.1	0.2

f= IIR filter setting,
All values are in degrees peak-peak

Typical test data is shown in the following graphs for the Roll axis. Figure 4 is a graph of roll output with the IIR set to 0.5 Hz and Figure 5 is a graph of roll output with the IIR set to 30 Hz.

Figure 4 Roll Output with IIR at 0.5 Hz

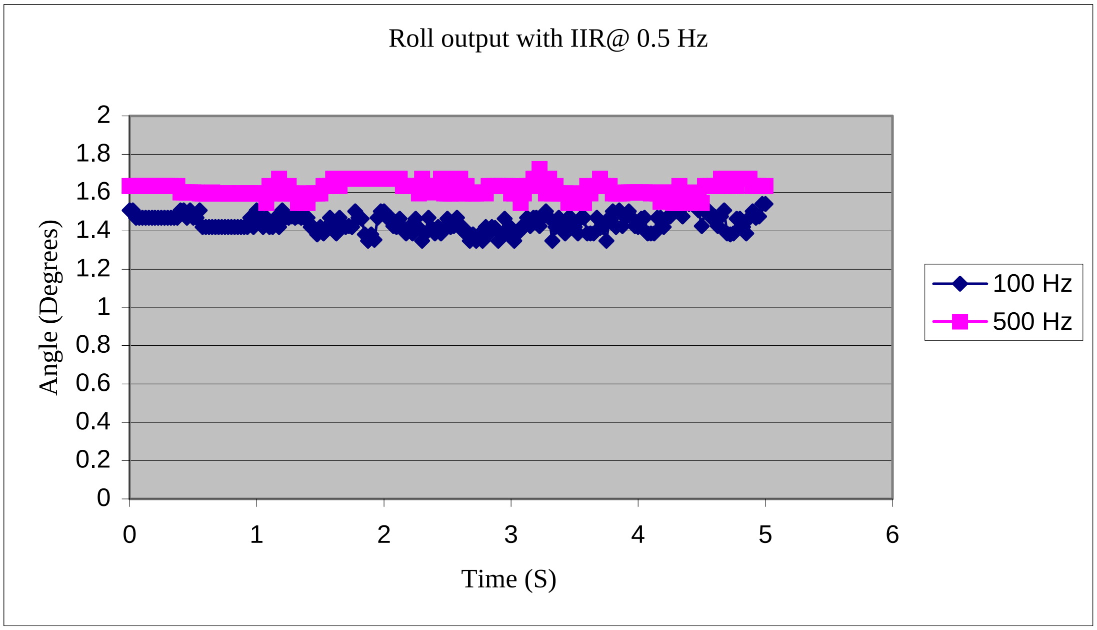
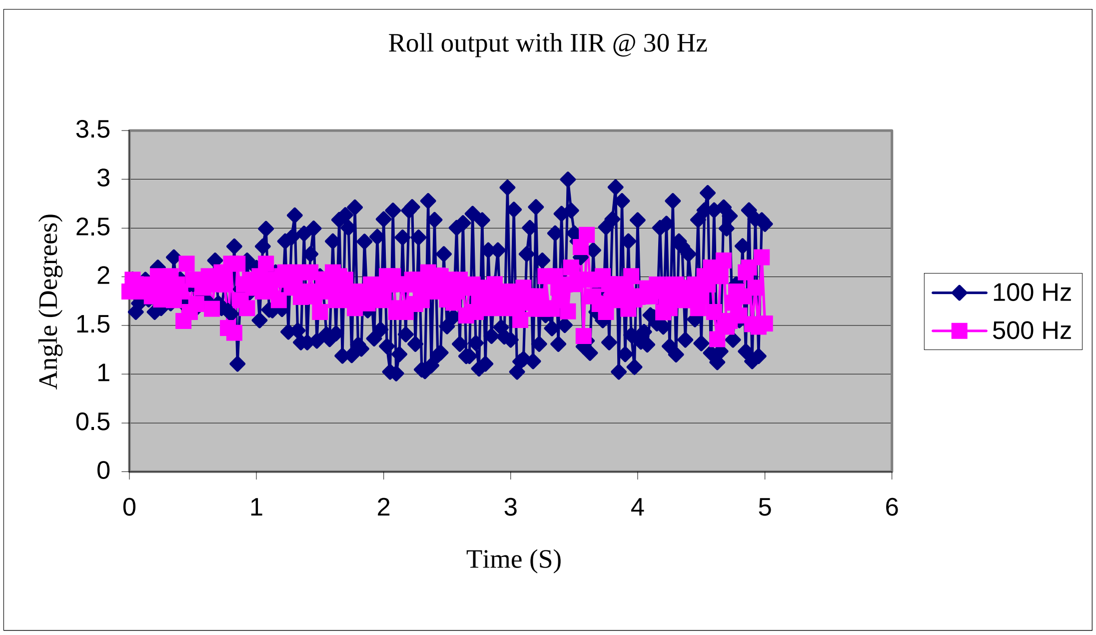


Figure 5 Roll Output with IIR at 30 Hz



CONCLUSION

3DM's provide accurate wide-angle measurement capabilities, for both static and dynamic applications. It has been shown that the 3DM is a valuable tool for measuring inclination angle in the presence of vibration. The use of digital filtering is necessary to reduce errors in inclination measurements when used in a vibrating environment.

For adaptive structures, 3DM's could be employed as feedback elements for vibration and position control. For structural health monitoring, 3DM's could be used for detection of changes in inclination and orientation that exceed safe limits.

Future research will focus on using the networking capabilities of 3DM for adaptive structures, improved algorithms for adaptive filtering, and datalogging capability to record the long term structural integrity of large civil structures.

REFERENCES

Durlack, N and Mavor, A.. 1995. "Virtual Reality of Scientific and Technological Challenges," National Academic Press, Washington.

Raab, F.H., Blood, E.B., Steiner, T.O., and Jones, H.R. 1979. "Magnetic Position and Orientation Tracking System," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-15, No. 5, pp.709-717.