

Sensor Development for the iMote2 Smart Sensor Platform

Jennifer Rice

March 7, 2008

SPIE Smart Structures/NDE 2008



Introduction

- Aging infrastructure requires cost effective and timely inspection and maintenance practices
- The condition of a structure following an extreme loading event must be quickly assessed
- Structural health monitoring systems must provide **relevant** information without data inundation
- The local nature of damage requires a dense array of sensors to adequately assess the structural condition

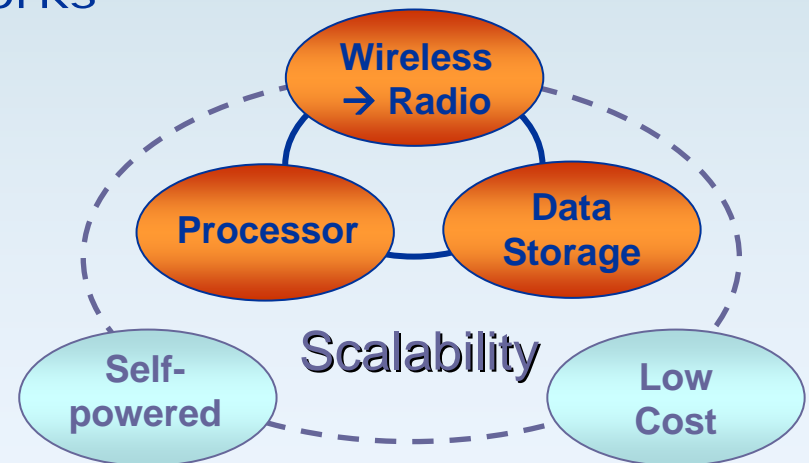


Smart Sensors

The evolution research on sensor networks for structural health monitoring

Wired sensors → Wireless sensors → Smart Sensors

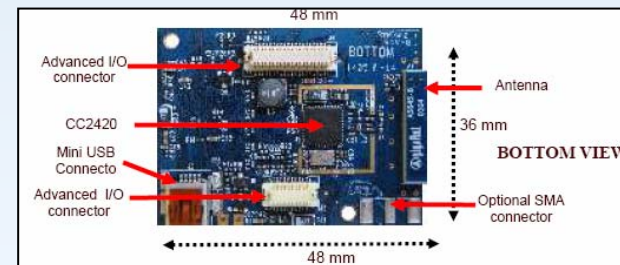
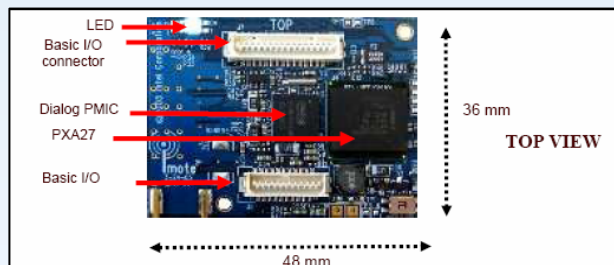
- Advances in microprocessor and MEMS technology have led to the potential for highly adaptable, densely distributed smart sensor networks
- Features of a smart sensor:
- Utilize the computational power of the smart sensor nodes to realize distributed computing
- Limit the amount of raw data that is shared amongst sensors



Intel's iMote2

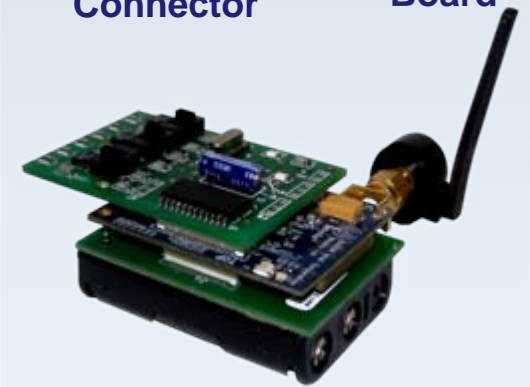
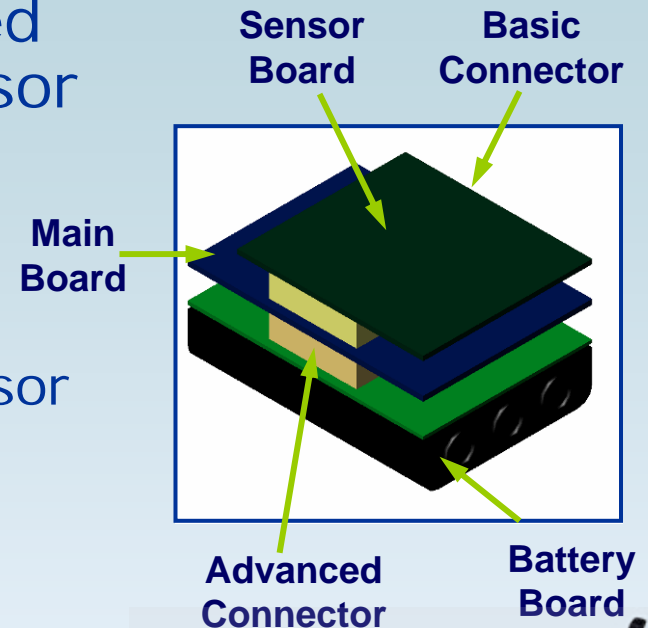
- ❑ Second generation of Intel mote
- ❑ Geared toward higher bit-rate applications
- ❑ Low-power 32-bit XScale processor (PXA271)
- ❑ Scalable processor speed to improve power consumption
- ❑ 802.15.4 radio (ChipCon 2420)
- ❑ Data storage
 - 256KB SRAM
 - 32MB External SDRAM
 - 32MB Flash

	Mica2	iMote ²
Microprocessor	ATmega128L	XScalePXA271
Clock speed (MHz)	7.373	13-416
Active Power (mW)	24 @ 3V	44 @ 13 MHz, 570 @ 416 MHz
Data rate (kbps)	38.4	250
Program flash (bytes)	128 K	32 M
RAM (bytes)	4 K	256 K + 32 M external
Nonvolatile storage (bytes)	512 K	32 M (Program flash)
Size (mm)	58 x 32 x 7	48 x 36 x 7



Sensing with the iMote2

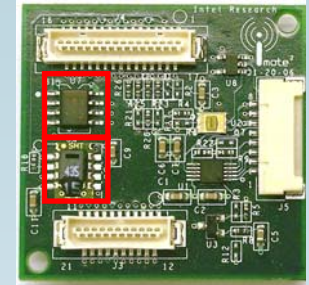
- The iMote2 has all of the desired characteristics...except the sensor
- Sensor Interface
 - Connect to main board via two connectors
 - Interface allows flexibility in sensor applications
 - Digital I/O options only
- Two options...
 - Utilize the *Basic Sensor Board* created by Intel
 - User/developer must provide the sensor board(s)



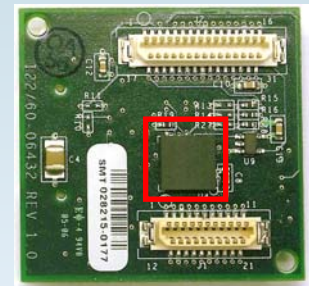
Intel's *Basic Sensor Board*

- Original *Basic Sensor Board* features
 - Light Sensor
 - Temperature/Relative Humidity Sensor
 - ST Microelectronics Digital Accelerometer
 - 3-axes
 - $\pm 2g$ measurement range
 - 12-bit resolution
 - Anti-aliasing filters with selectable cutoff frequencies

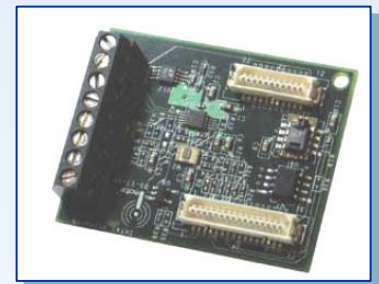
- ITS400 Sensor Board (Crossbow) additional features
 - Additional temperature sensor
 - General purpose ADC
 - 4-channel
 - 12-bit resolution



Top



Bottom

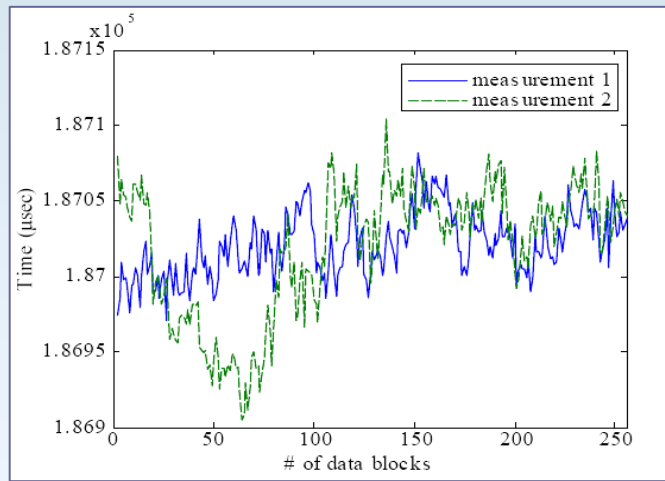


Intel's *Basic Sensor Board*

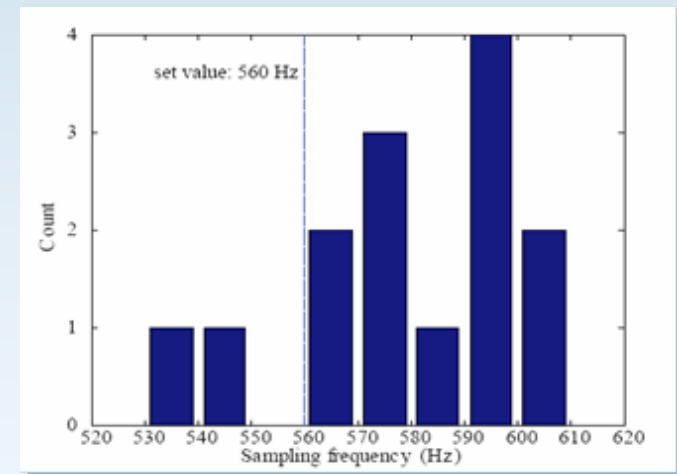
□ Limitations:

- Low ADC resolution
- Limited signal processing capabilities
- Inaccurate sampling rate
- Clock jitter (sample rate fluctuation)

Decimation factor	Cutoff frequency (Hz)	Sampling rate (Hz)
128	70	280
64	140	560
32	280	1120
8	1120	4480



Sample rate fluctuation on a single sensor



Variation in sample rates amongst sensors

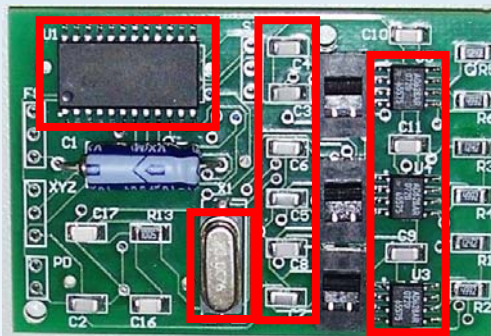
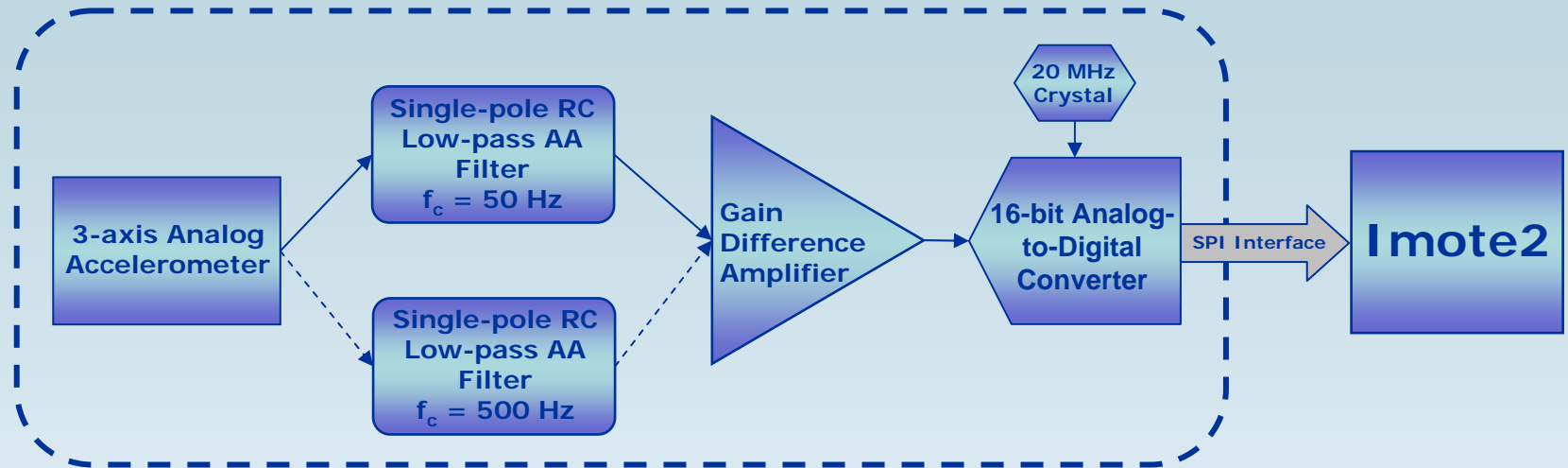
iMote2 SHM-A Board

Designed specifically for vibration based structural health monitoring applications

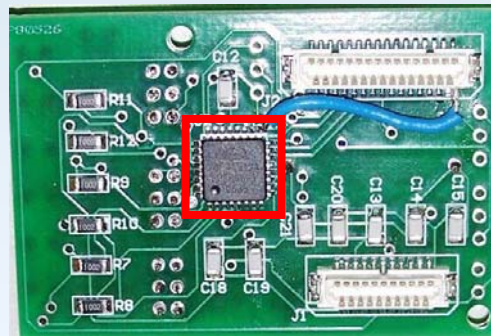
- Motivation
 - Typical civil structures exhibit low frequency response but damage is often evident in higher modes
 - Flexible measurement bandwidth
 - Vibration based SHM is often limited to ambient excitation
 - High resolution, low-noise data is required
 - Distributed SHM requires synchronization of signals from each sensor node to a high degree of accuracy
 - Accurate clock and timing components are required

- Primary design goals
 - Provide flexible, user-selectable anti-aliasing filters and sampling rate options
 - Utilize commercially available, low-cost MEMS components
 - 3 axes acceleration
 - High ADC resolution
 - High sensitivity

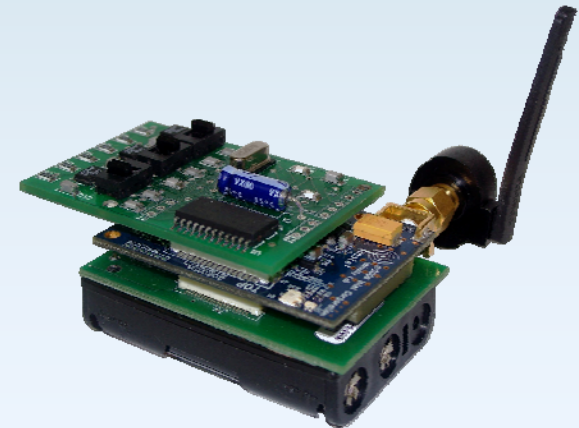
iMote2 SHM-A Board Components



Top

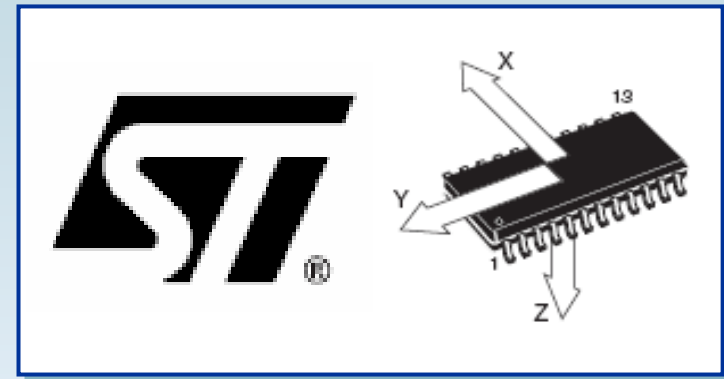


Bottom



iMote2 SHM-A Board Components

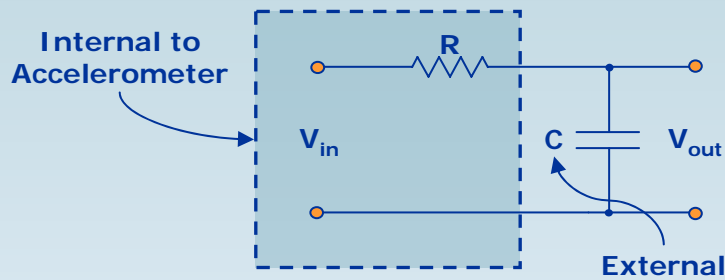
- ST Microelectronics Analog Accelerometer
 - 3-axes acceleration
 - 0.66 mV/g resolution
 - Low-power
 - Moderate noise ($50\mu\text{g}/\sqrt{\text{Hz}}$)
 - Cost: ~\$12 per chip



- Design limitations
 - High output impedance (110 k Ω)
 - High margin or error in output resistor ($\pm 20\%$)

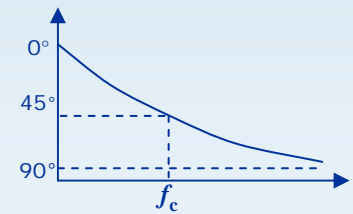
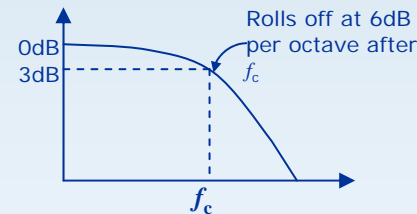
Filter Considerations

- Accelerometer internal resistor + external capacitor create a single-pole low-pass RC filter



$$f_c = \frac{1}{2\pi R_{out} C_{load}} \quad \phi(f) = \tan^{-1}(-2\pi fRC)$$

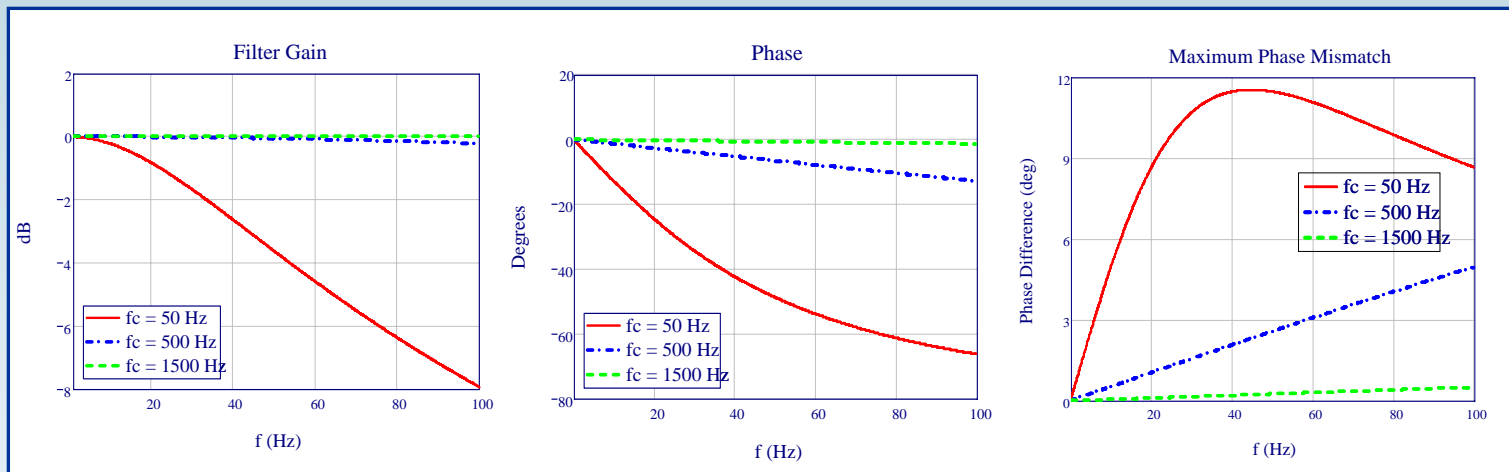
- Not effective anti-aliasing filter
 - Very slow roll-off
 - Non-linear phase response



- Potentially large error introduced to signal by resistor error – different for each channel

Filter Considerations

- Capacitor chosen sets the “cut-off”
- Consider three potential cut-off frequencies: 50 Hz, 500 Hz, and 1500 Hz (maximum allowed)

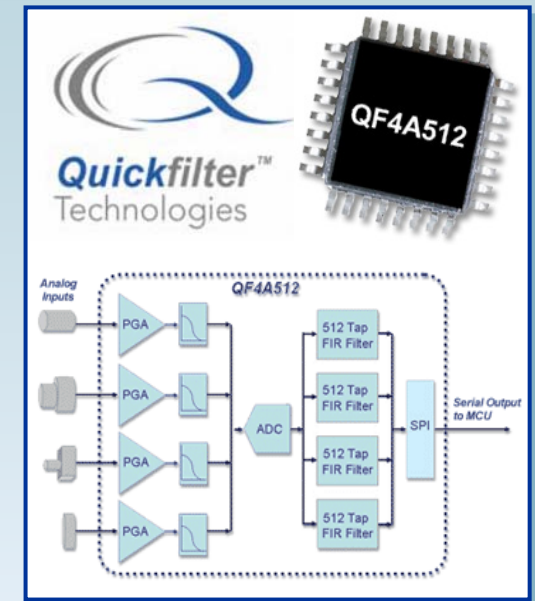


- Phase mismatch occurs when channels have different values of output resistance (due to resistor error)
- To avoid potential phase mismatch and signal distortion, use the highest possible cut-off frequency
- Address aliasing in another way...

Digital Signal Processing

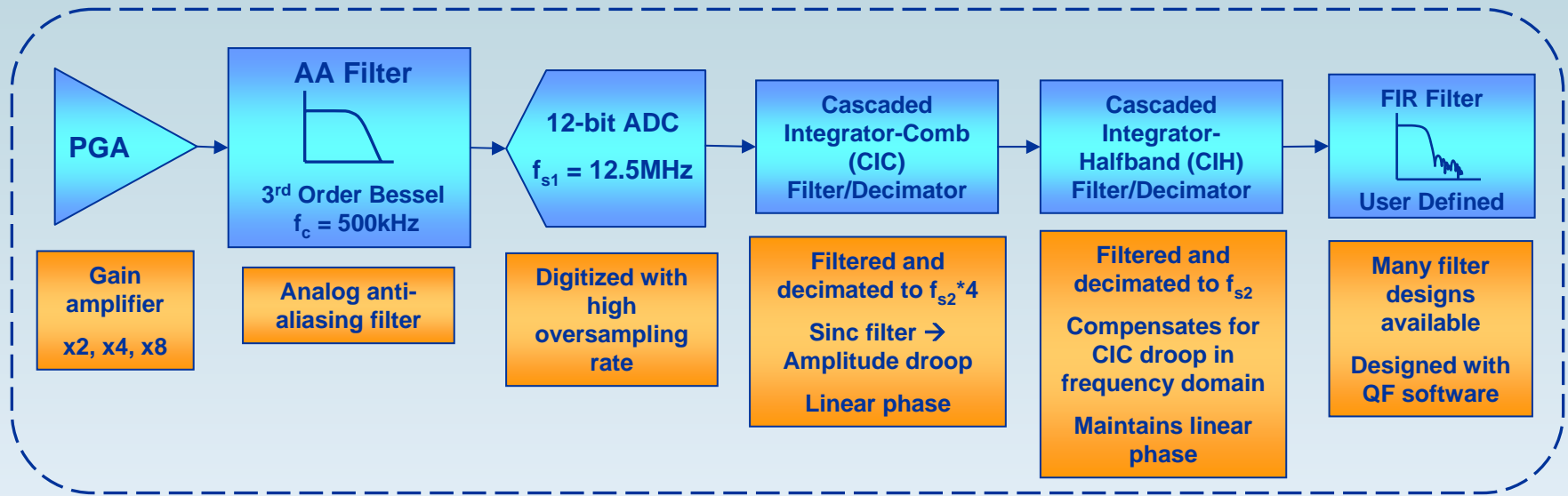
- Quickfilter Programmable Signal Conditioner
 - 4-channels, single- or double-ended
 - 16-bit analog-digital-converter (ADC)
 - Programmable gains
 - Built-in anti-aliasing filters
 - Individually programmable digital FIR filters
 - Digital SPI output
 - Cost: ~\$18 per chip

- Flexible signal processing
 - User-selectable anti-aliasing filters, sampling frequency
 - Oversampling-filtering-decimation provides sharp roll-off and linear phase response
 - Similar to PC-based analyzers



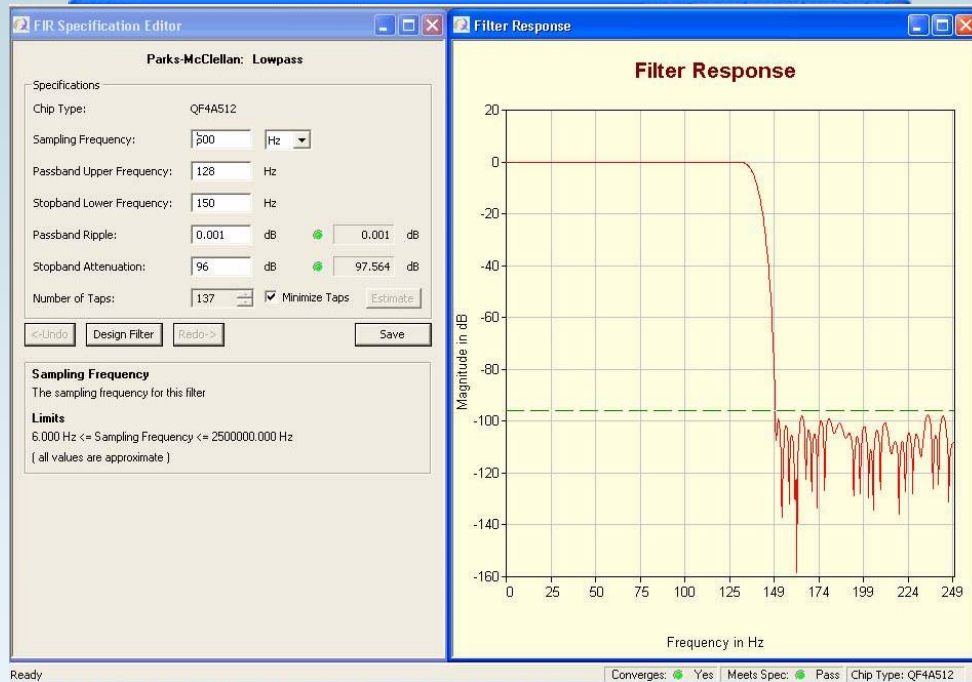
Quickfilter

□ Block diagram of QF4A512



- Oversampling-filtering-decimation serves two purposes
 - Increases resolution by reducing quantization noise
 - In conjunction with simple analog anti-aliasing filters, produces un-aliased signal

FIR Filter Design



- ❑ Built-in digital signal processing
- ❑ Software allows for many filter design options
- ❑ User specifies characteristics such as sampling rate and cut-off frequency
- ❑ Filter design is optimized and header file created
- ❑ Included when sensing application loaded on the iMote2

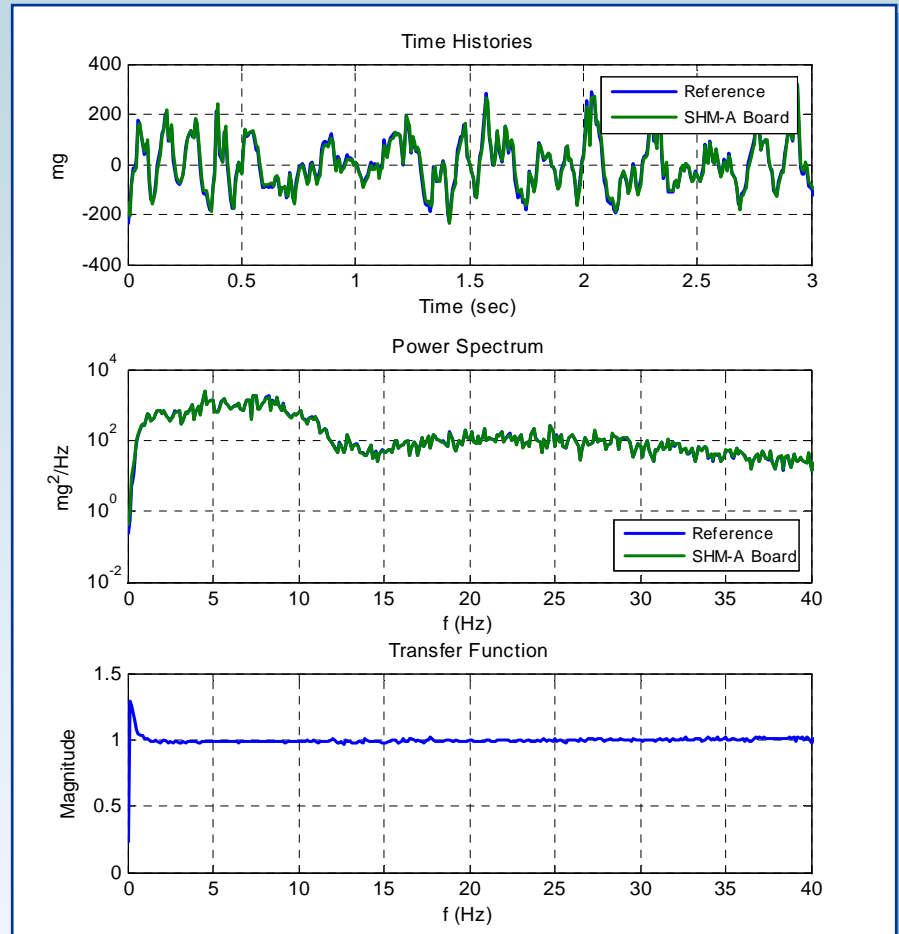
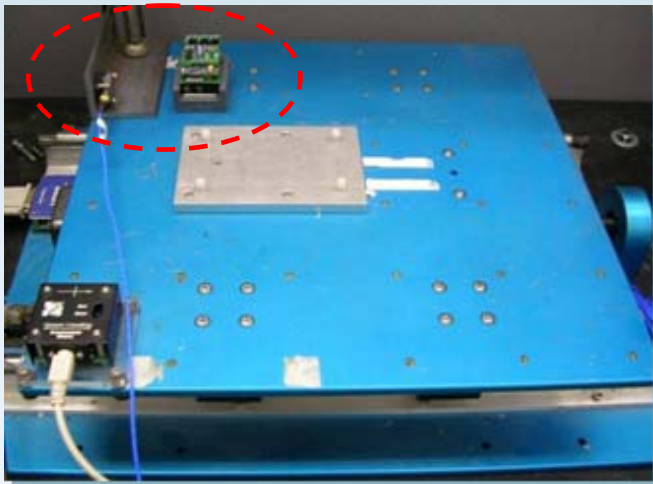
Software

- TinyOS is the operating system for many smart sensors including the iMote2
 - Small memory footprint
 - Power efficient
 - Large user community

- Driver was developed in TinyOS to control the functions of the ADC
 - Allocate memory
 - Load FIR filter coefficients
 - Set sampling rate
 - Do timestamping
 - Write data

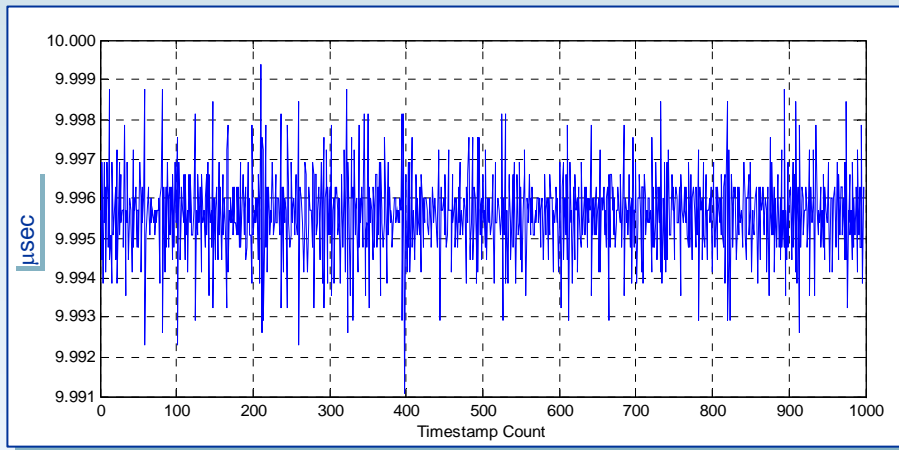
Design Validation

- Calibration testing performed on bench-scale uniaxial shake table
- Signal compared to wired sensor
- Excellent agreement in time and frequency domains



Clock Accuracy

- Sampling rate accuracy estimation:
 - Sample rate set to 1000.32Hz ($dt = 9.997e-04\text{sec}$)
 - Record timestamp from processor every 10th sample
 - Subtract consecutive timestamps and divide by ten to get average timestep over ten data points



Measured sampling rate:
1000.44Hz (0.012% error)
Standard deviation of
sample rate fluctuation:
0.11 μs (0.011% error)

- Performance may be better than measured because timestamping itself may interfere with hardware timing

Ongoing Work

- Test Structure
 - Historic bridge in Mahomet, Illinois
 - Truss bridge built in 1912
- Environmental hardening
- Antenna testing
- Multi-scale sensor board for iMote2
- Network optimization/fault tolerance



Conclusion

- Smart Sensors, which incorporate wireless sensing with computational capability, allow for distributed SHM scenarios
- The iMote2 provides data storage and computational capability required for SHM applications
- A versatile accelerometer board has been designed for vibration-based SHM applications

Acknowledgement

This work is sponsored in part by the National Science Foundation, Dr. Shih-Chi Liu, program manager

Additional support was provided by the Vodafone Graduate Fellowship program