Sensor Development for the iMote2 Smart Sensor Platform

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Introduction

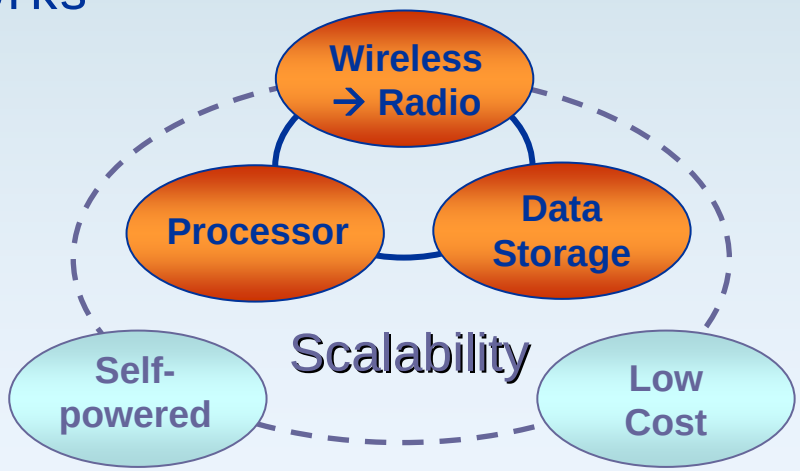
- Aging infrastructure requires cost effective and timely inspection and maintenance practices
- The condition of a structure following an extreme loading event must be quickly assessed
- Structural health monitoring systems must provide **relevant** information without data inundation
- The local nature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

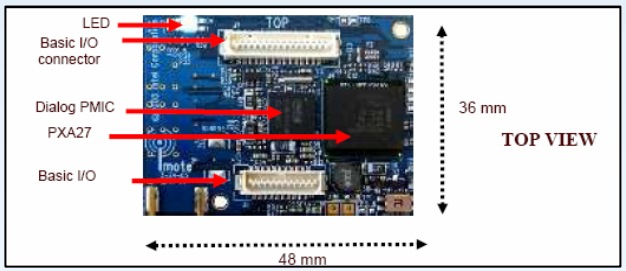
- Advances in microprocessor and MEMS technology have led to the potential for highly adaptable, densely distributed smart sensor networks
- Features of a smart sensor:
- Utilize the computational power of the smart sensor nodes to realize distributed computing
- Limit the amount of raw data that is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

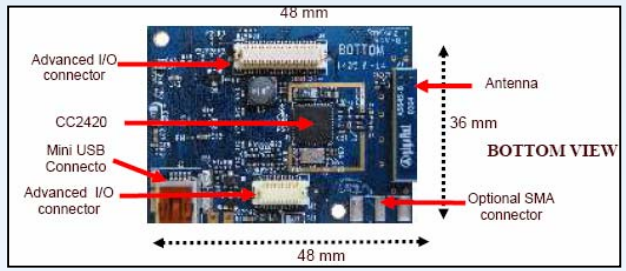


Intel's iMote2

- 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

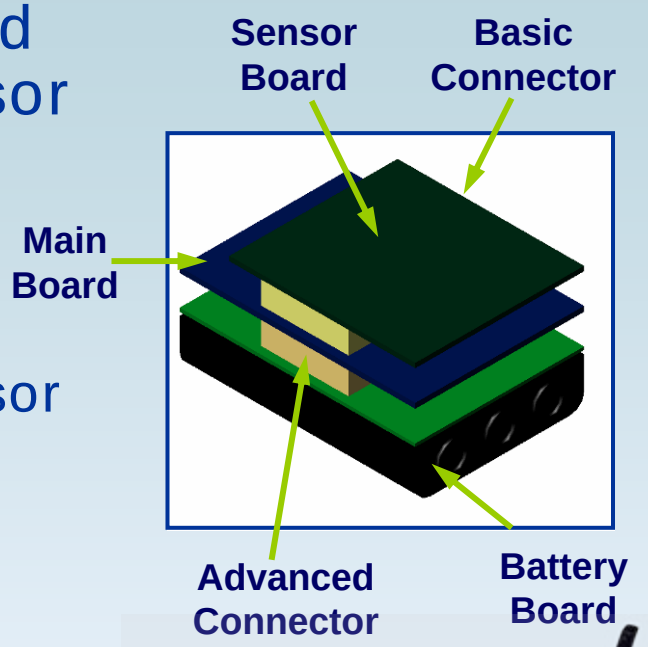
	Mica2	iMote^2
Microprocessor	ATmega128L	XScalePXA271
Clock speed (MHz)	7.373	13-416
Active Power (mW)	24 @ 3V	44 @ 13 MHz, 570 @ 416 MHz
Data rate (kbps)	38.4	250
Program flash (bytes)	128 K	32 M
RAM (bytes)	4 K	256 K + 32 M external
Nonvolatile storage (bytes)	512 K	32 M (Program flash)
Size (mm)	58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

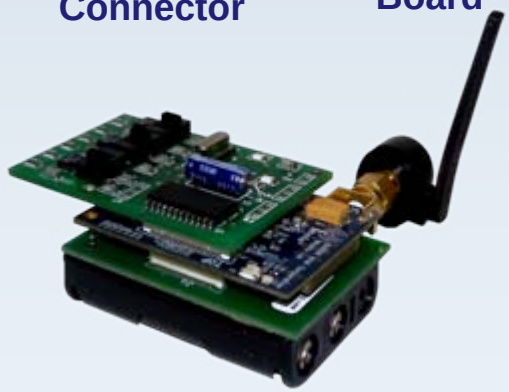




Sensing with the iMote2

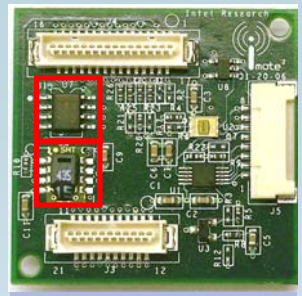
- The iMote2 has all of the desired characteristics…except the sensor
- Sensor Interface
  - Connect to main board via two connectors
  - Interface allows flexibility in sensor applications
  - Digital I/O options only
- Two options…
  - Utilize the *Basic Sensor Board* created by Intel
  - User/developer 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
    - ± 2g measurement range
    - 12-bit resolution
    - Anti-aliasing filters with selectable cutoff frequencies



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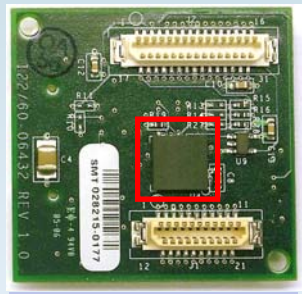
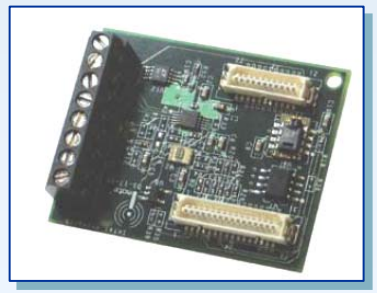


Bottom

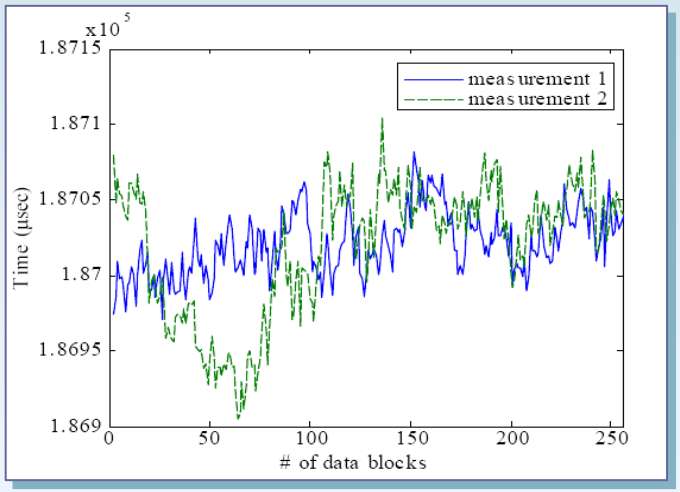
- ITS400 Sensor Board (Crossbow) additional features
  - Additional temperature sensor
  - General purpose ADC
    - 4-channel
    - 12-bit resolution



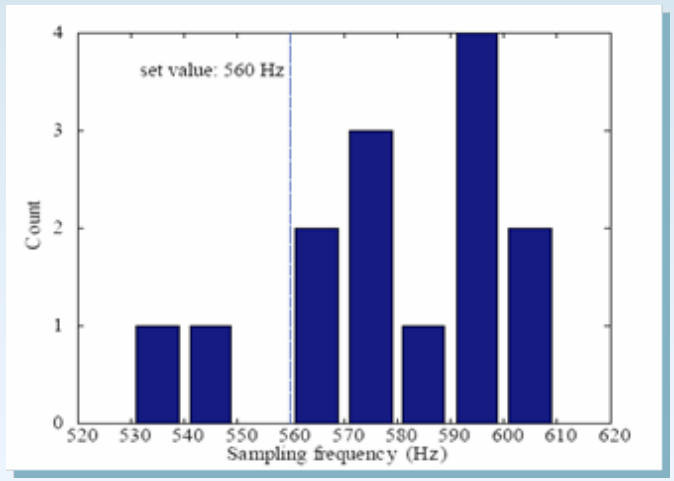
Intel's *Basic Sensor Board*

- 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

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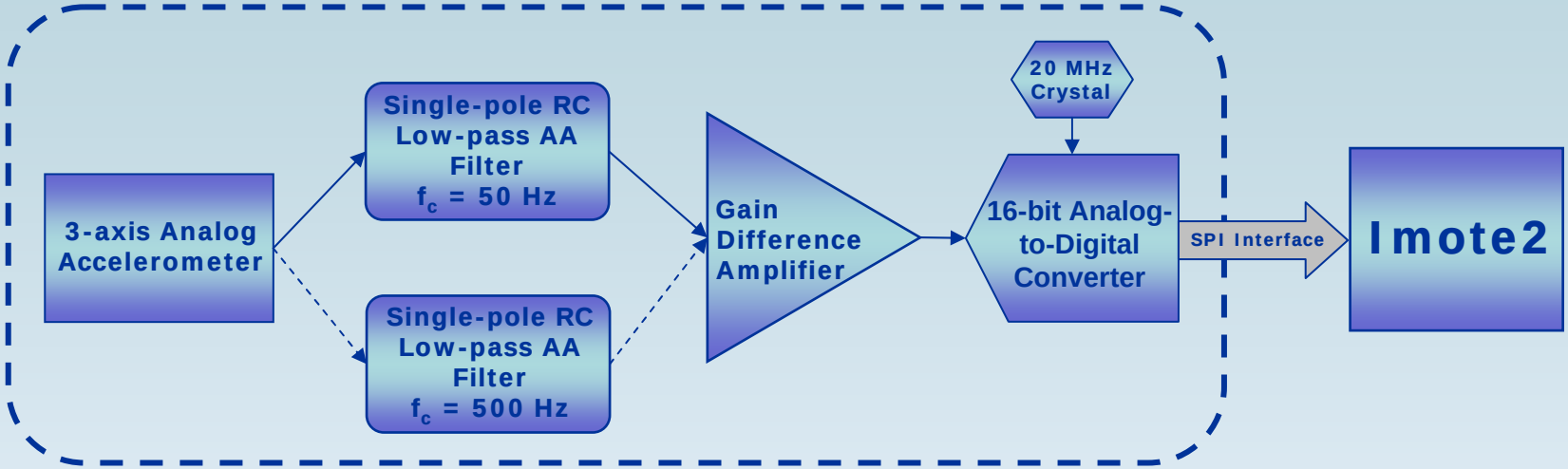
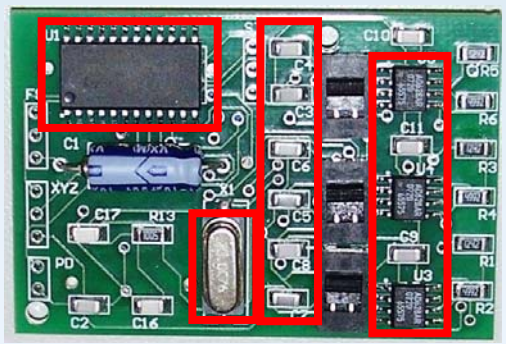
iMote2 SHM-A Board

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





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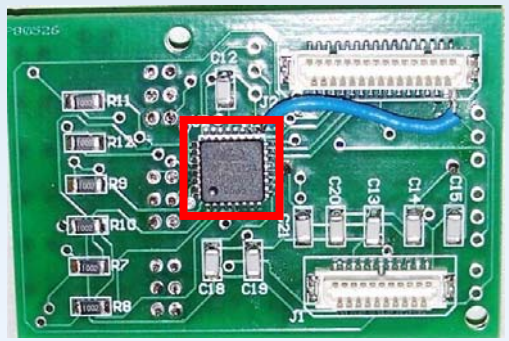

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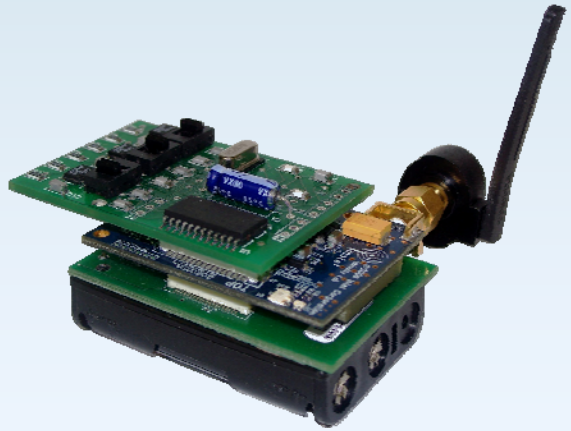
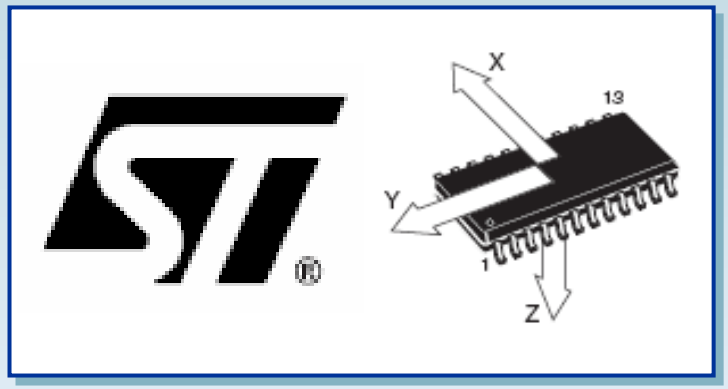


iMote2 SHM-A Board Components

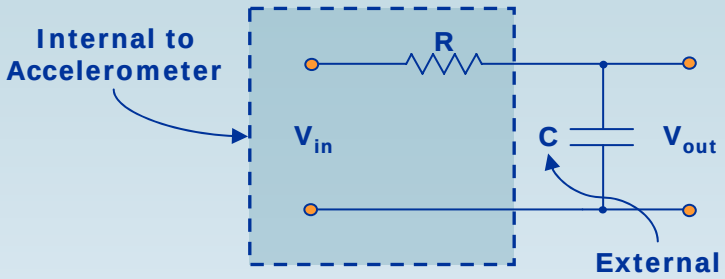
- ST Microelectronics Analog Accelerometer
  - 3-axes acceleration
  - 0.66 mV/g resolution
  - Low-power
  - Moderate noise ($50\mu g/\sqrt{Hz}$)
  - Cost: ~$12 per chip



- Design limitations
  - High output impedance (110 kΩ)
  - High margin or error in output resistor (±20%)

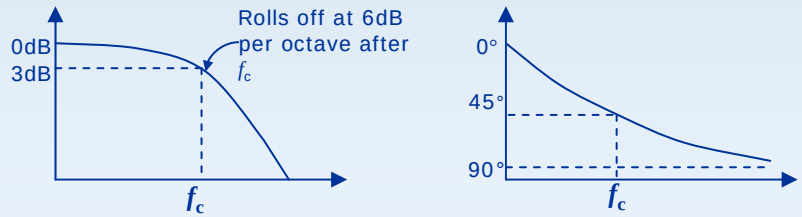
Filter Considerations

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



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

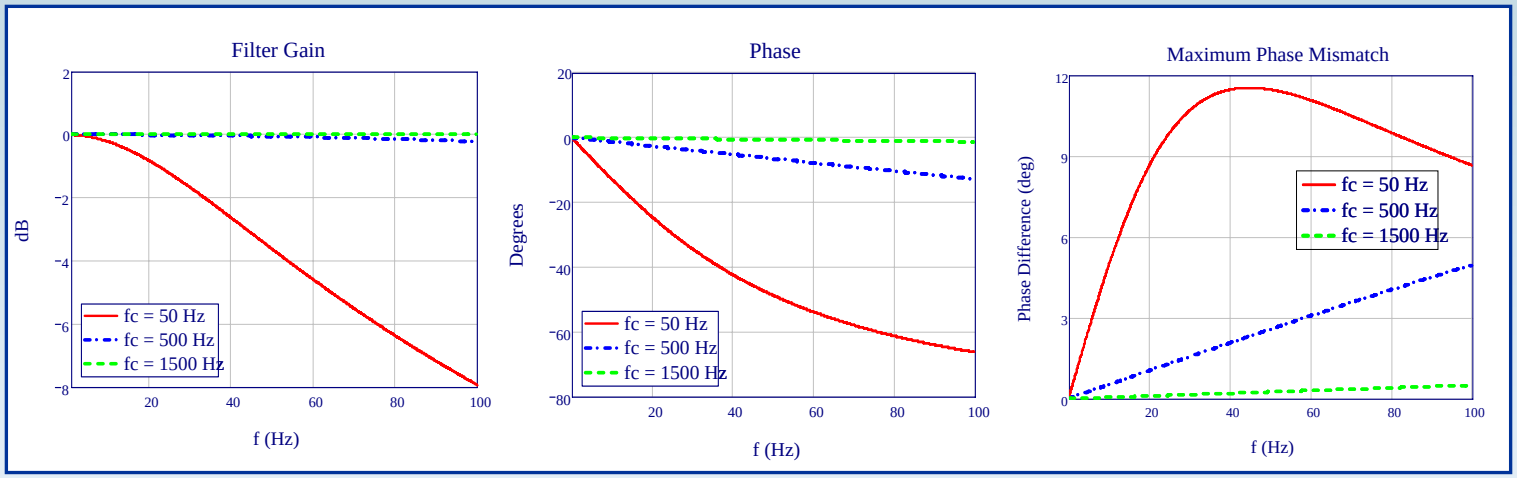
- Not effective anti-aliasing filter
  - Very slow roll-off
  - Non-linear phase response



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

Filter Considerations

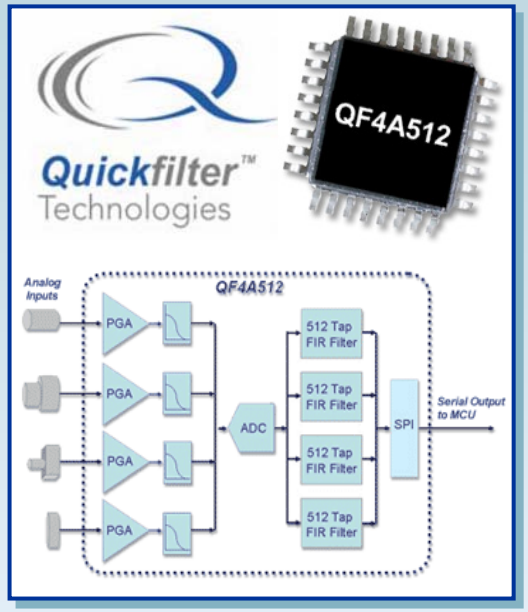
- Capacitor chosen sets the “cut-off”
- Consider three potential cut-off frequencies: 50 Hz, 500 Hz, and 1500 Hz (maximum allowed)



- 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

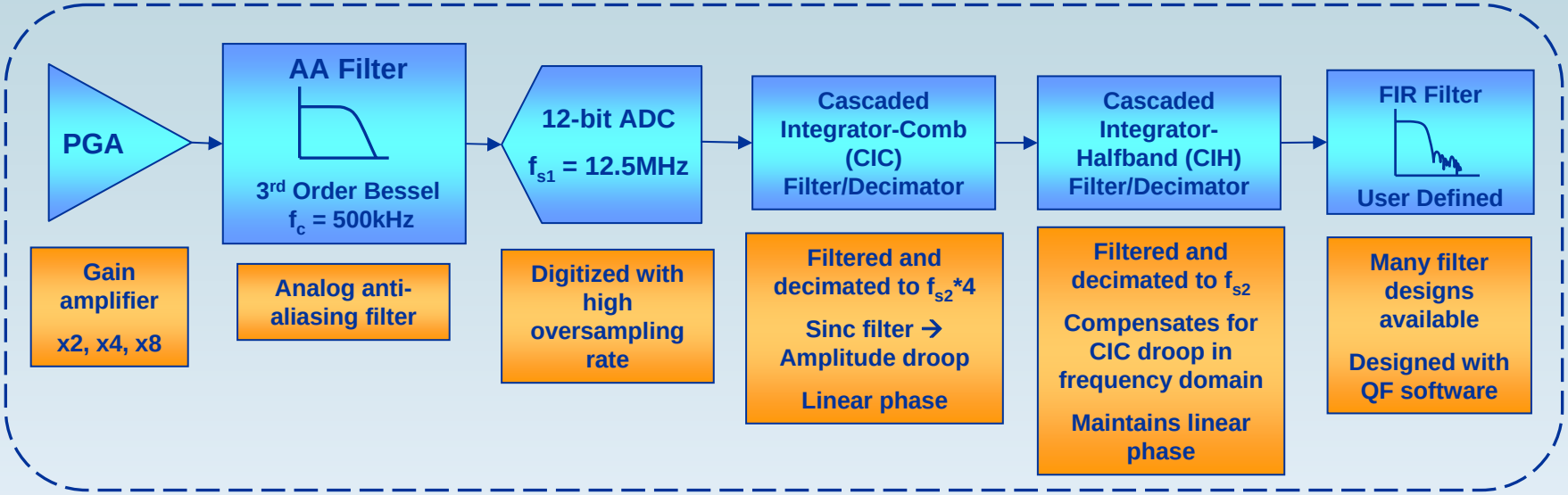
- Quickfilter Programmable Signal Conditioner
  - 4-channels, single- or double-ended
  - 16-bit analog-digital-converter (ADC)
  - Programmable gains
  - Built-in anti-aliasing filters
  - Individually programmable digital FIR filters
  - Digital SPI output
  - Cost: ~$18 per chip



- 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

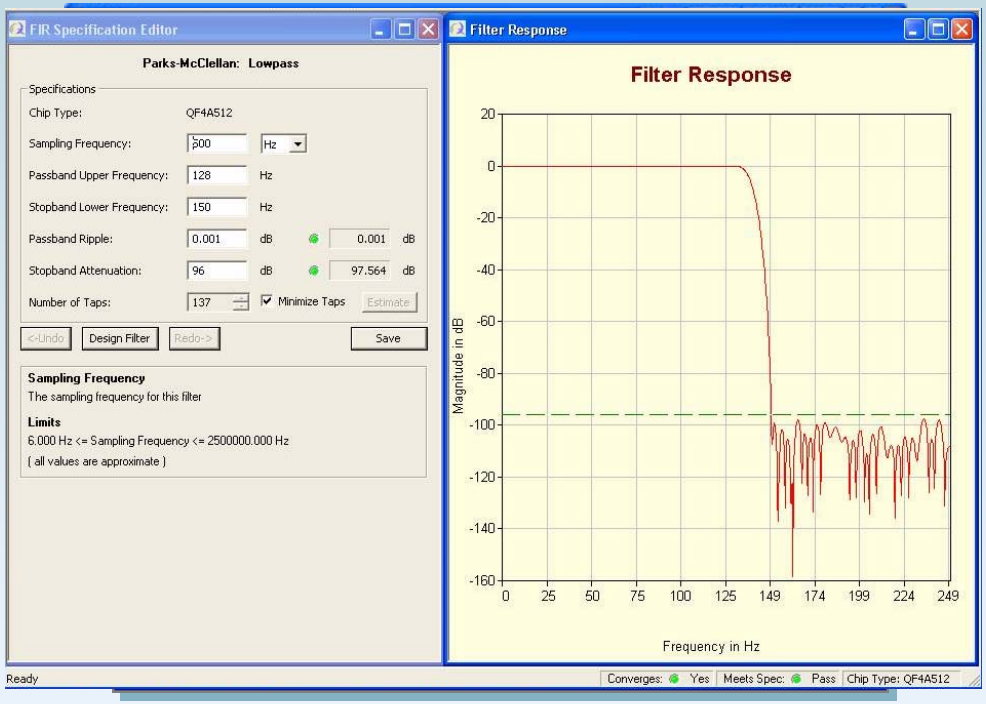
Quickfilter

- 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

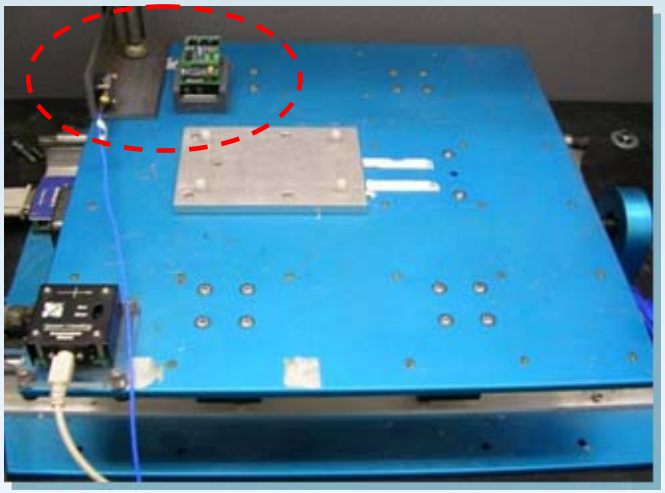
Software

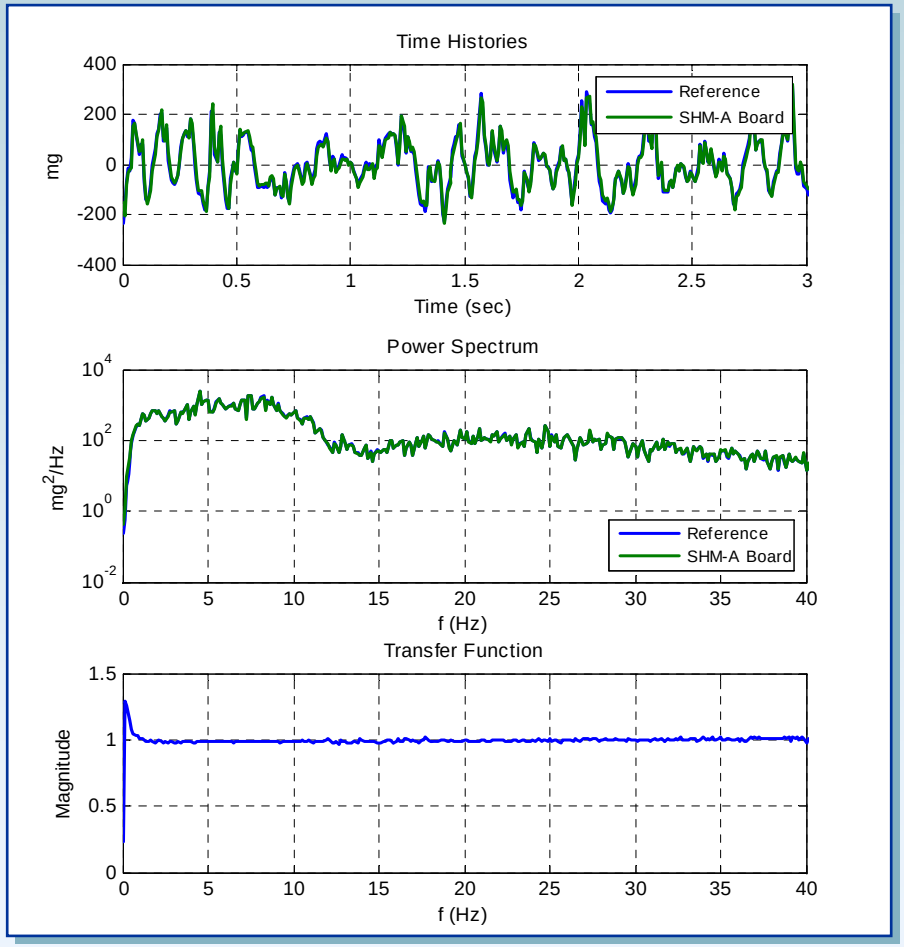
- TinyOS is the operating system for many smart sensors including the iMote2
  - Small memory footprint
  - Power efficient
  - Large user community

- 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

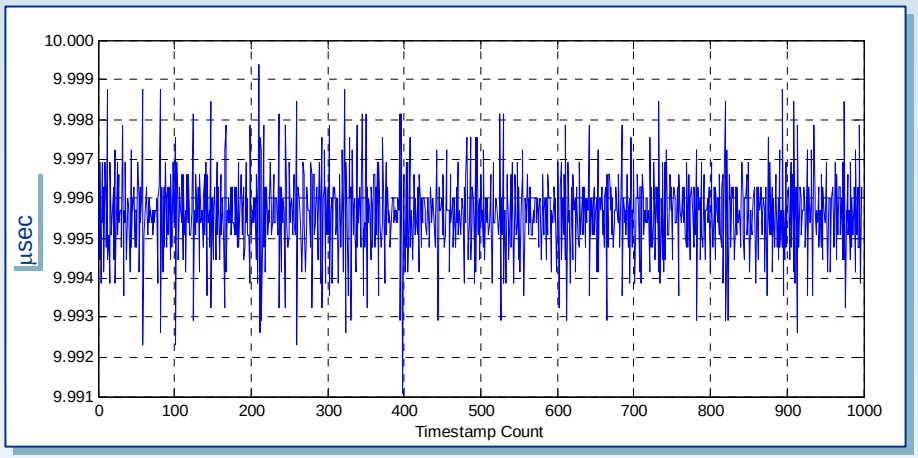
- Calibration testing performed on bench-scale uniaxial shake table
- Signal compared to wired sensor
- Excellent agreement in time and frequency domains





Clock Accuracy

- Sampling rate accuracy estimation:
  - Sample rate set to 1000.32Hz (dt = 9.997e-04sec)
  - 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:

0.11µs (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

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