Application Note

PIR Motion Detector Using Integrated Smart Analog on MSP430FR2355

TEXAS INSTRUMENTS

ABSTRACT

Motion detection is valuable in many battery powered building automation applications, from basic security sensors to fully interactive camera systems. These systems rely on accurate, low power motion detection to maximize battery life by keeping powerful processors and wireless radios shut down when not needed. This design provides a low power, high-performance, and very cost competitive motion detection solution using an analog passive infrared (PIR) motion sensor and the MSP430FR2355. The MSP430FR2355 has integrated Smart-Analog Combos (SACs) that include operational amplifiers (OpAmps) and digital to analog convertors (DACs). The SACs can provide the PIR sensor's entire signal chain, integrated inside the MSP430. The SACs are software configurable, allowing the signal chain to be easily adjusted for higher sensitivity and range, digital feedback loops, and optimized for low power performance. This application report addresses ultra low power, high performance PIR design theory and test results using the MSP430FR2355.

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Trademarks

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1 PIR Design Description

1.1 PIR Sensor

There are several different types of sensors that can be used to detect basic motion, but the most common solution for the last decade has probably been using PIR sensors. PIR sensors are based on Wien's displacement law, which states that black-body radiation curve for different temperature will peak at different wavelengths that are inversely proportional to the temperature. Basically, if you monitor the infrared spectrum, objects of different temperature will radiate different levels of energy. Figure 1-1 shows what you see in images taken with infrared camera.

Figure 1-1. Infrared Photos

PIR motion detectors are passive sensors that used to detect general motion of people or animals. Instead of all the pixels seen in the IR images above, the PIR motion detectors typically generally only have only two sensing elements, as seen in Figure 1-2. These two sensing elements will be physically offset from each other, giving each of them slightly different fields of view (FOV). Each sensor will respond to general changes in temperature in its FOV. Only two sensors may sound limiting, but analyzing the combined signal from both sensor elements can provide a decent amount of information to be captured.

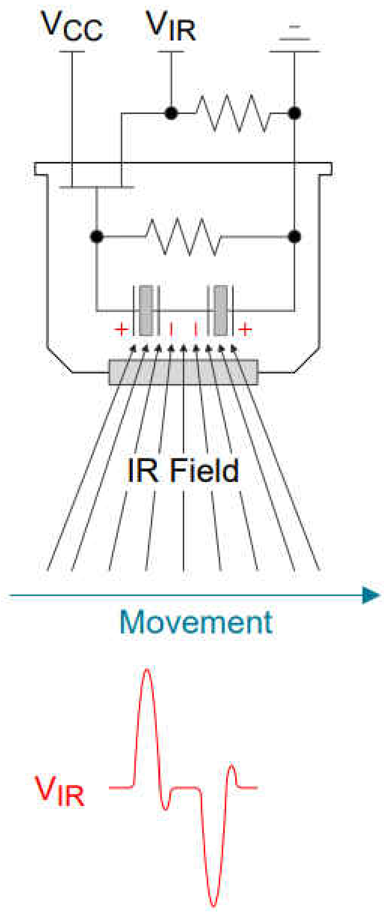

Figure 1-2. PIR Motion Sensor Illustration

As a person moves across both fields of view, the sensor will output a wave form from the sensing elements as the person passes from one sensor elements FOV through the next one. This waveform can be seen in Figure 1-3. As seen in Figure 1-3(a), The direction of this signal can tell us the direction of motion. In Figure 1-3(b). The amplitude of the signal can indicate the distance of the object or possibly the size of the individual/animal. Finally, in 3C, the speed of motion will also affect the speed of the waveform seen. In a given hallway, a walking person will have a different signature than a running person. An adult will have a different signature than that of a child or pet.

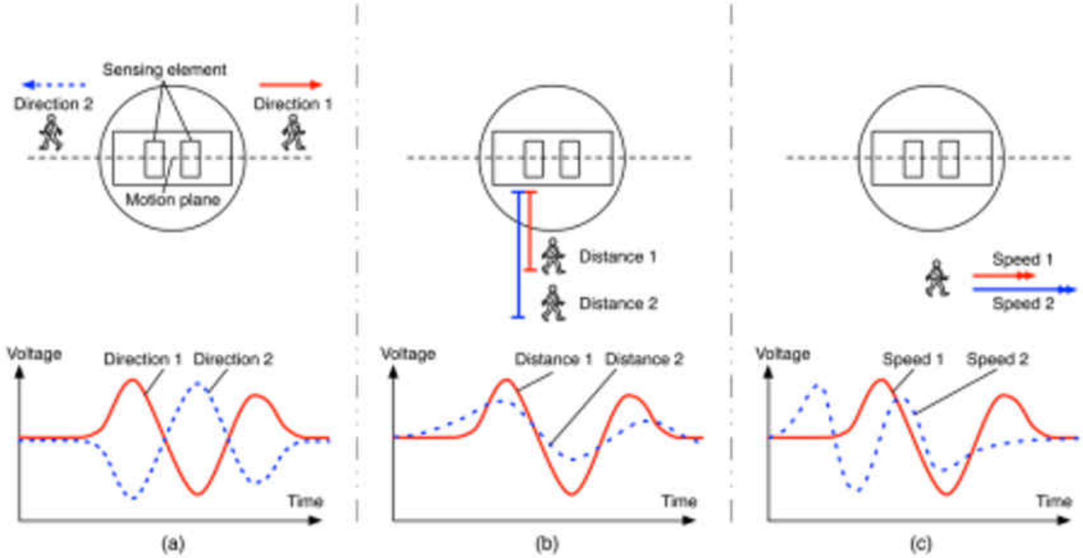

Figure 1-3. PIR Sensor Output Signal

There are usually two main specifications that are chosen when designing a motion detector for a specific application, maximum range and minimum motion speed. Generally, PIR motion detectors try to detect up to 10-12 meters and the motion frequency range is usually .7 Hz to 30 Hz. The exact performance needed for the application will affect how sensitive the system will need to be, from signal conditioning but also in software thresholding. The further away you want to monitor, the smaller the amplitude of the signals and the lower the signal to noise ratio. Typical signal levels at the output of a PIR sensor are in the micro-volt range for motion of distant objects, so it is necessary to amplify and filter the signal. The lower the minimum speed, the harder it will be to slowly slip past the monitor but the system will be more susceptible it to false triggers from environmental variation.

False detections are very undesirable, especially in battery powered applications. Typically the PIR Motion detection is monitoring while an application is in a low power mode. False detections will wake the rest of the system or trigger false alarms. This risk vs the sensitivity stated above must be weighed when designing a system. Traditionally a PIR's signal chain was designed with a specific use case in mind and designed with a fixed gain and bandwith in hardware, which means it had a fixed detection distance and speed. Fortunately, using the MSP430FR2355 with integrated SACs, the signal chain can actually be configured via software offering much greater flexibility without changing anything in hardware.

Finally, there are both analog and digital PIR sensors on the market. The digital sensors have the signal chain and detection algorithms integrated in them. They are easier to integrate into applications, but usually come with a significant added cost that makes them unsuitable for low cost applications. This document focuses on analog PIR sensors as they reduce overall system cost and can easily be integrated with the built-in SAC signal chain.

1.2 PIR Signal Chain

1.2.1 Traditional Motion Detection Signal Chain Design

Figure 1-4 illustrates the traditional PIR motion detector signal chain. The signal from the PIR sensor is fed through a series of gain band-pass filters, that usually include DC blocking caps, and then fed to a set of comparators for low and high side waveform detection, acting as a window comparator.

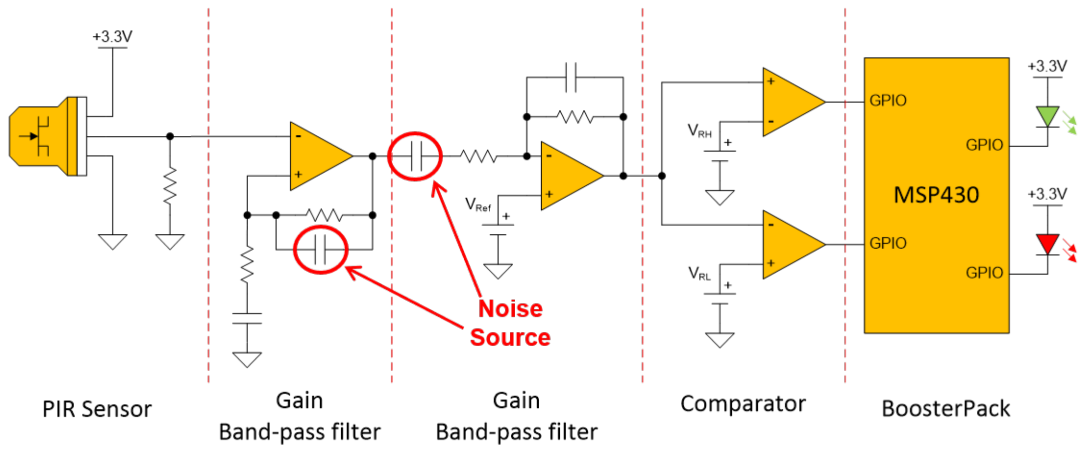

Figure 1-4. Traditional PIR Signal Chain

As mentioned in the introduction, this signal chain is fixed and limited. For the band-pass filters, the gain and cutoff frequencies are configured specifically for a particular detection range and motion speed. Typical cutoff frequencies are around .7 – 30Hz and overall signal gain may be as high as 1000x.

Another downside of this signal chain we found during our investigation, is that these DC filter caps actually end up being very large noise sources for the signal chain. Ceramic surface mount capacitors are usually made of barium titanate, which has a piezoelectric effect, meaning any noise or vibration actually generates small noise signals on the caps. Tantalum capacitors at such low frequencies can also introduce noise onto the signal. Coupling this noise with up to 1000x gain in the signal chain can return a very poor signal to noise ratio. In Figure 1-5, the signal from a PIR sensor was fed into the above signal chain and a capacitor free signal chain using the MSP430FR23355 in parallel. It is much easier to see the motion signal with the capacitor free circuit.

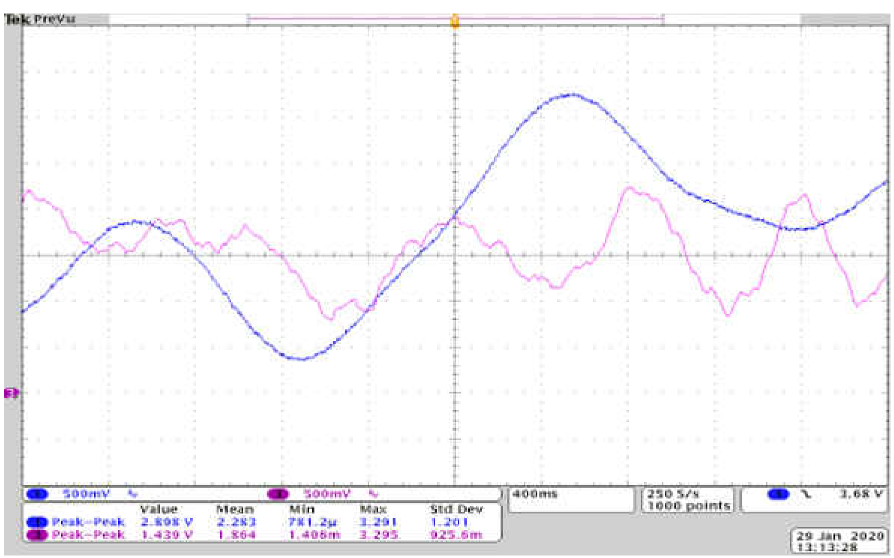

Figure 1-5. Traditional vs Capacitor-Free Signal Chain

1.2.2 Capacitor-Free Signal Chain Design

Figure 1-6 shows a simplified version of our capacitor-less signal chain. The signal chain now is mostly purely buffering and gain stages. To remove DC blocking capacitors in the traditional circuit that were adding noise to the system, the stages are being biased using DACs. Instead of using comparators, the signals are fed into an analog-to-digital converter (ADC) which enables a feedback loop for the DAC for tracking changes to environment and ambient temperature and allows digital filtering of the signal.

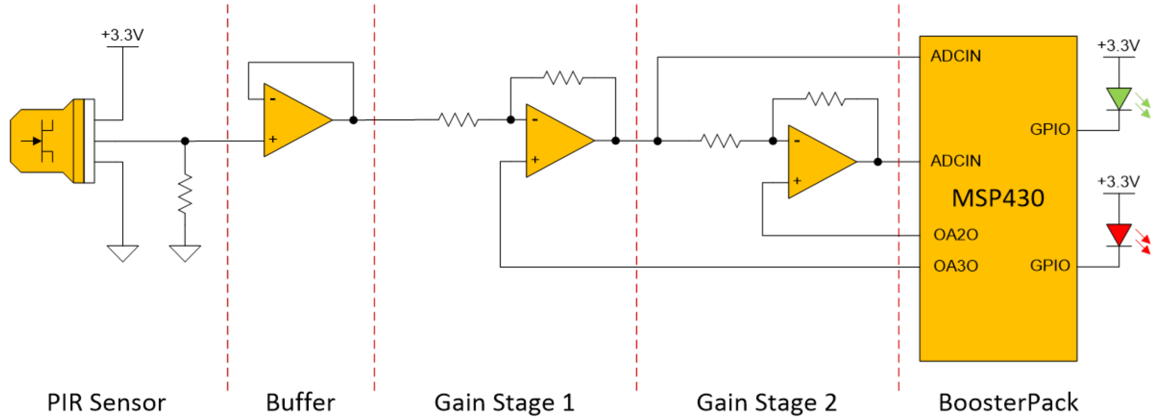

Figure 1-6. Capacitor Free Signal-Chain

The biggest benefit of the MSP430FR2355 is that this entire signal chain is integrated into the MCU and is software configurable. The MSP430FR2355 includes four smart analog combos (SACs). Each of these SACs include an general purpose op-amp with configurable gain from 1-32x and a 12-bit reference DAC. Figure 1-7 illustrates the simplified interface to the PIR sensor leveraging the full signal chain inside the MSP430FR2355. The SACs can be chained together inside the chip, connected directly to the internal ADC, and can be shutdown for lowest possible sleep currents.

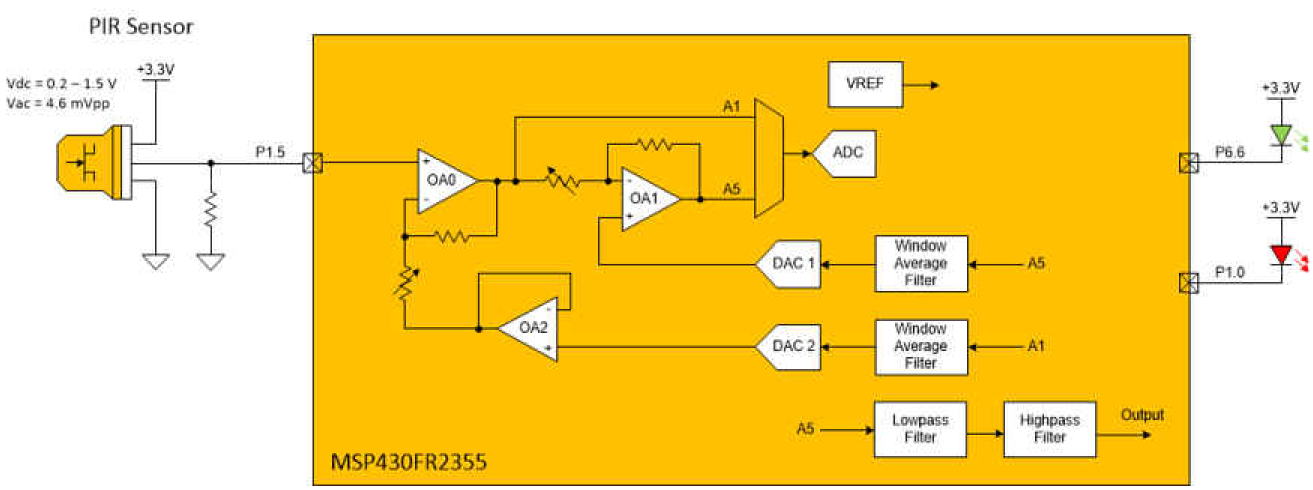

Figure 1-7. PIR Signal-Chain Integrated Into MSP430FR2355

2 Software

Software is a powerful piece of the MSP430 PIR Motion Detector. As mentioned, the software controls the analog signal chain and feedback loops. The signal is also being sampled via the ADC, which allows digital filter techniques to be applied to the detection and feedback loops. This application note includes source code for the PIR motion detection demo. This demo software is intended to accelerate the development of a PIR solution using MSP430FR235x MCU, but this software is only a part of a complete system and is intended to be used only as a reference.

2.1 Software Architecture

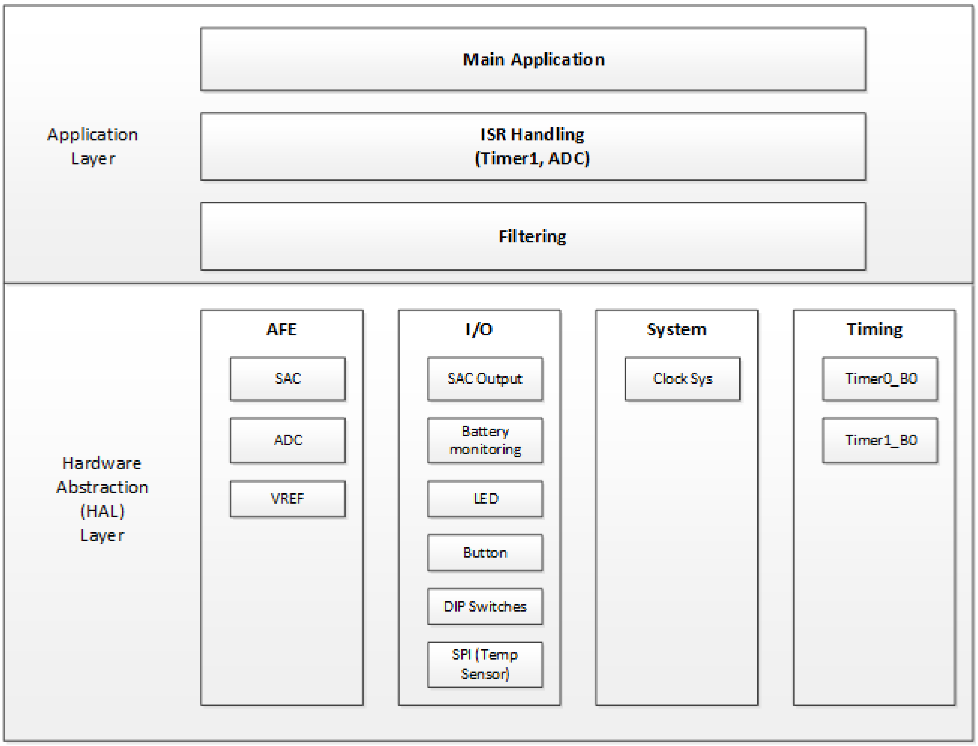

Figure 2-1. Software Architecture

The software was architected in two layers:

- The application layer implements the main functionality, with a default configuration, and handles the initialization and processing of the data.
- The HAL layer provides hardware-abstraction to interface with different peripherals of the MSP430FR2355 and allow for a modular, flexible and portable solution.

2.2 Software Flow Chart

Figure 2-2 shows a flow chart of the software's overall behavior. The demo software wakes up and performs this full loop 20 times a second. The loops takes approximately 250 µs - 300 µs. The other 99% of the time, the analog is shut down and the MSP430 is sleeping in low power mode 3. This flow chart is explained somewhat further in the power profile section.

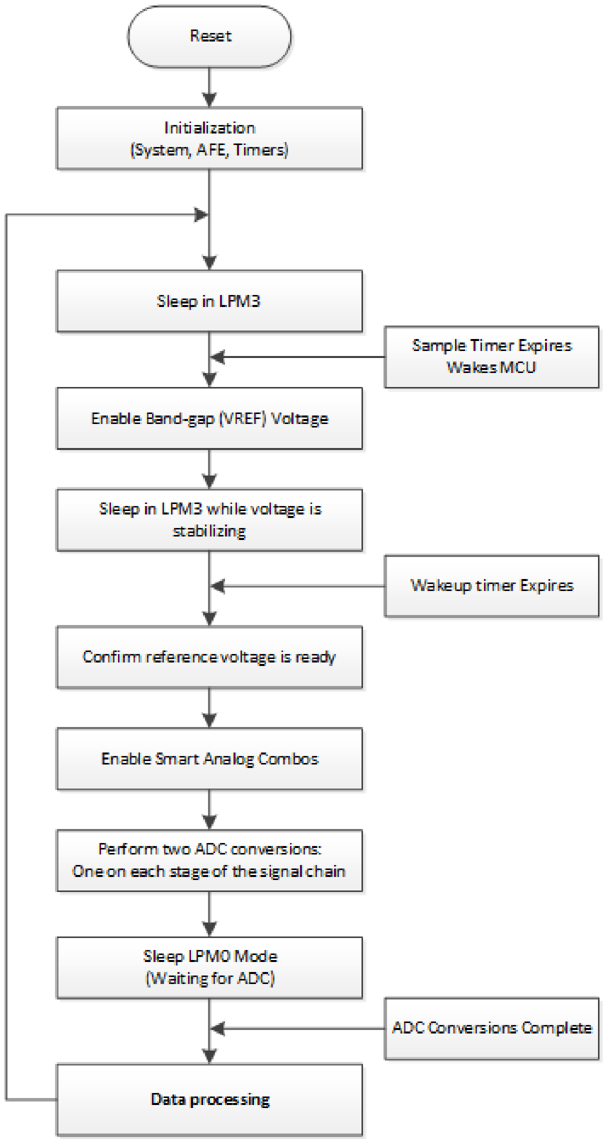

Figure 2-2. Software Flow Chart

2.3 Power Profile

The software flow is also what controls the system's power profile. The first current spike is where the MSP430 wakes to enable the analog circuits, then goes back to sleep while the reference voltages are stabilizing. After a short period of time, the MSP430 wakes back up to check the Vref reference voltage and that the SACs are ready. Two ADC measurements are made from each stage of the signal chain. Finally, there is some data processing on the new samples to determine if there was motion before the MSP430 shuts down the analog circuitry and returns back to sleep where the system it spends 99% of it's time.

This software flow gives us an average current of approximately 6 µA with a 20 sps measurement rate.

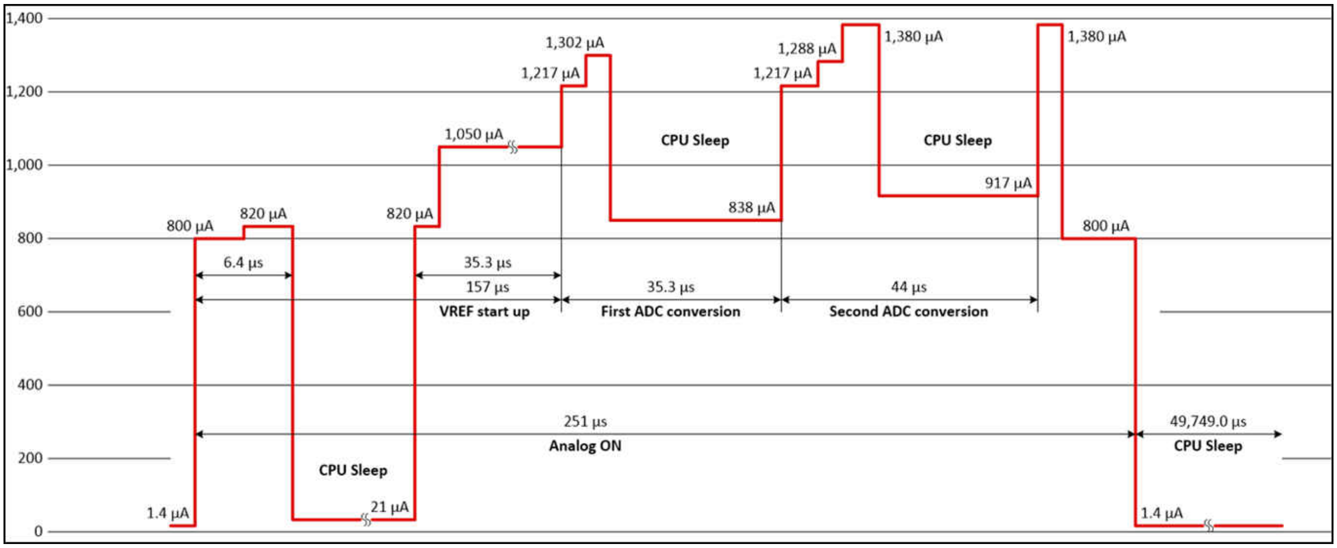

Figure 2-3. Power Profile of MSP430 PIR Demo Software

2.4 Data Processing

2.4.1 Digital Signal Conditioning

2.4.2 Low-Pass Filter for Temperature Drift

Figure 2-4 shows what the PIR signal looks like over time as the ambient temperature and the PIR sensor body temperature are fluctuating. There is no motion detect events here, just the signal drifting. A digital low-pass, moving average filter is applied in software to the collected data samples. Based on this moving average filter, the DACs are adjusted to compensate for this baseline trend over time and this removes most of the DC component of the signal. This allows you to achieve a higher dynamic range from the MSP430's 12-bit ADC since the signal chain is actively being compensated for the ambient temperature, it keeps the signal centered within the ADC measurement range. The software can use both the ADC's reading and the current DAC compensation values to determine the absolute digital output code.

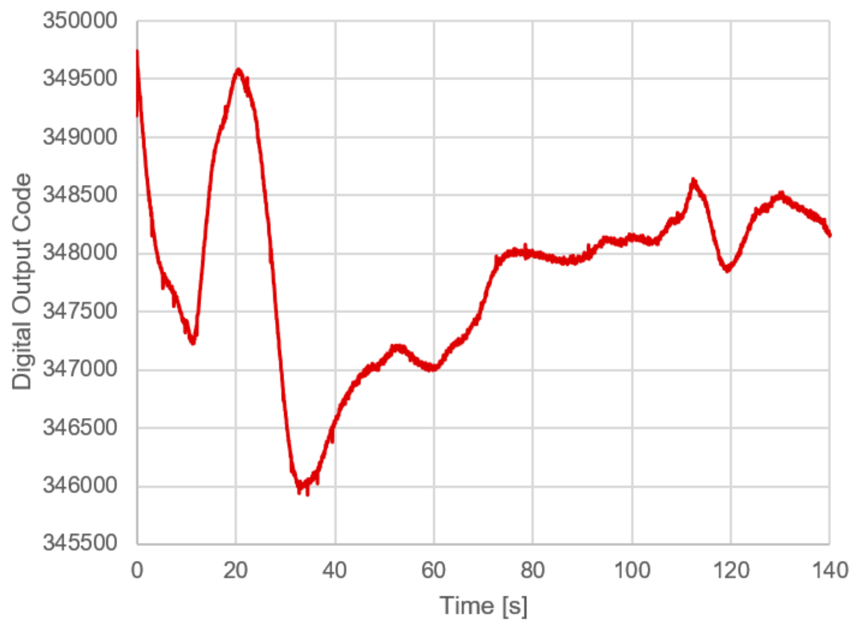

Figure 2-4. PIR Sensor Signal Drift Over Time

2.4.3 Spikes and Noise

If you zoom in on the data waveform, you will see that the signal is still quite noisy. The more noise that can be removed, the better the signal to noise ratio will be. The signal chain has already been improved to reduce the noise, but because you are sampling the signal with an ADC, it is possible to perform additional data processing on the signal. For the software, this noise is characterized as two different types: spikes and ripples.

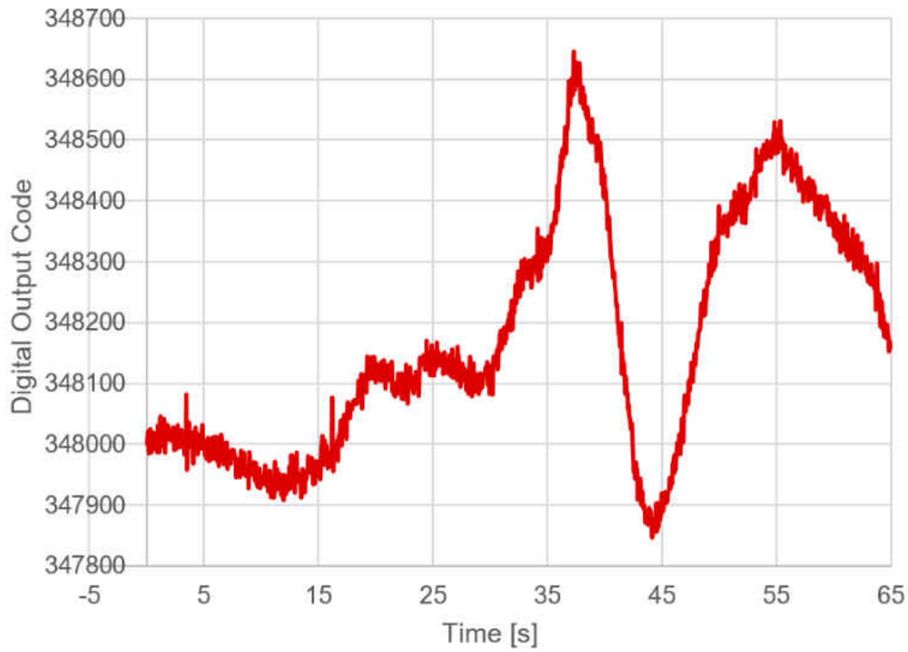

Figure 2-5. PIR Sensor Signal Zoomed In

Figure 2-6 shows two fairly large, random high-frequency spikes in the data. The samples are run though a “de-spiking” function that attempts to identify and remove these spikes and improve performance. This function basically looks at the last several samples captured in a window, and removes maximum and minimum values and therefore smoothing out any extreme "spikes" seen in the data.

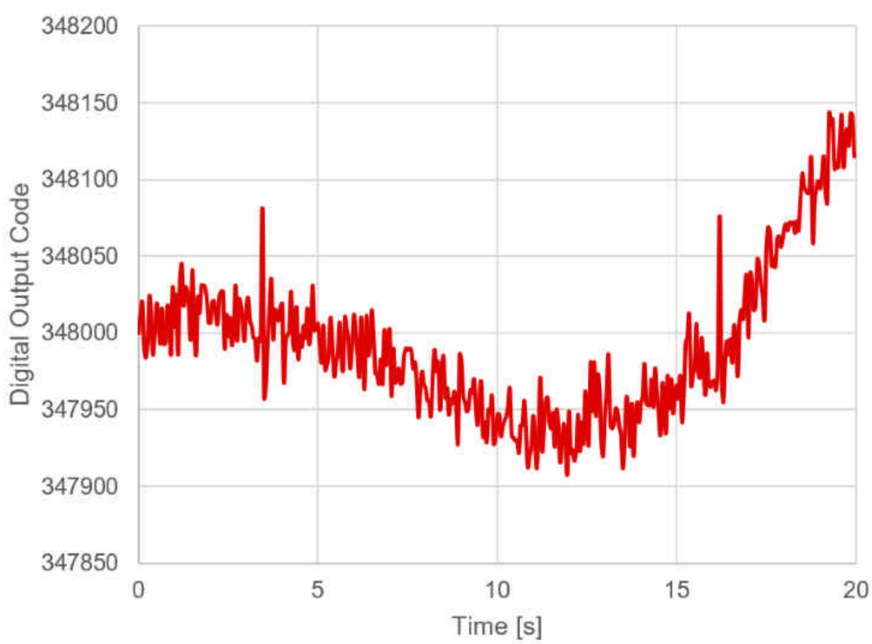

Figure 2-6. PIR Signal Spikes

Figure 2-7 shows ripples and white noise. There is a place holder for a“de-rippling” function, but the current example software has not implemented this. All the data below was captured without it.

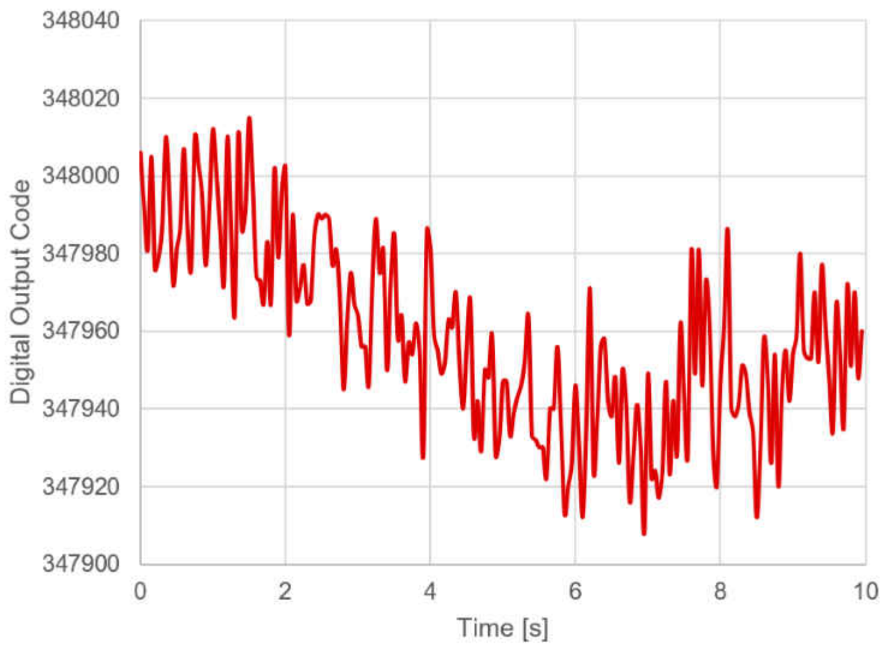

Figure 2-7. PIR Signal Ripples/Noise

2.4.4 Motion Detection Function

To detect if there has been motion, the software sends the latest sample to a signal analysis function after it has been run through the filtering functions. This function uses previous samples in an exponential moving average filter. This filter is used to output a reference level. There are a few more functions that then compare the sample to this reference output from the moving average filter. If the delta between these two samples becomes large enough and faster enough, then it decides that motion has been detected. This is the main place in software where the overall behavior and sensitivity of the solution can be tuned.

3 Hardware and Schematic

3.1 MSP430FR2355

The main MCU leveraged to enable this innovative PIR Motion Detector Design is the MSP430FR2355. The MSP430FR2355 is part of the MSP430™MCU value line portfolio of ultra-low-power low-cost devices for sensing and measurement applications. MSP430FR235x MCUs integrate four configurable signal-chain modules called smart analog combos, each of which can be used as a 12-bit DAC or a configurable programmable-gain Op-Amp to meet the specific needs of a system while reducing the BOM and PCB size. The device also includes a 12-bit SAR ADC and two comparators. The MSP430FR215x and MSP430FR235x MCUs all support an extended temperature range from –40°C up to 105°C, so higher temperature industrial applications can benefit from the devices' FRAM data-logging capabilities. The extended temperature range allows developers to meet requirements of applications such as smoke detectors, sensor transmitters, and circuit breakers.

- Microcontroller
  - 16-bit RISC architecture up to 24 MHz
  - Extended temperature: –40°C to 105°C
  - Up to 48-MHz clock speed
- Low-power ferroelectric RAM (FRAM)
  - Up to 32KB of nonvolatile memory
  - Built-in error correction code (ECC)
  - Configurable write protection
- Optimized low-power modes (at 3 V)
  - Active mode: 142 µA/MHz
  - Standby: – LPM3 with 32768-Hz crystal: 1.43 µA (with SVS enabled)
- High-performance analog
  - One 12-channel 12-bit analog-to-digital converter (ADC)
  - Two enhanced comparators (eCOMP)
  - Four smart analog combo (SAC-L3)
    - Supports General-Purpose Operational Amplifier (OA)
    - Configurable PGA mode supports
    - Built-in 12-bit reference DAC for offset and bias settings

Features: MSP430FR235x MCUs are supported by an extensive hardware and software ecosystem with reference designs and code examples to get your design started quickly. TI provides the MSP430FR2355 LaunchPad™ development kit and also free MSP430Ware™ example software, which is available within TI Resource Explorer.

3.2 Schematic

Figure 3-1 shows the schematics for the prototype board that were built as a proof of concept and to provide the example performance data found in this document.

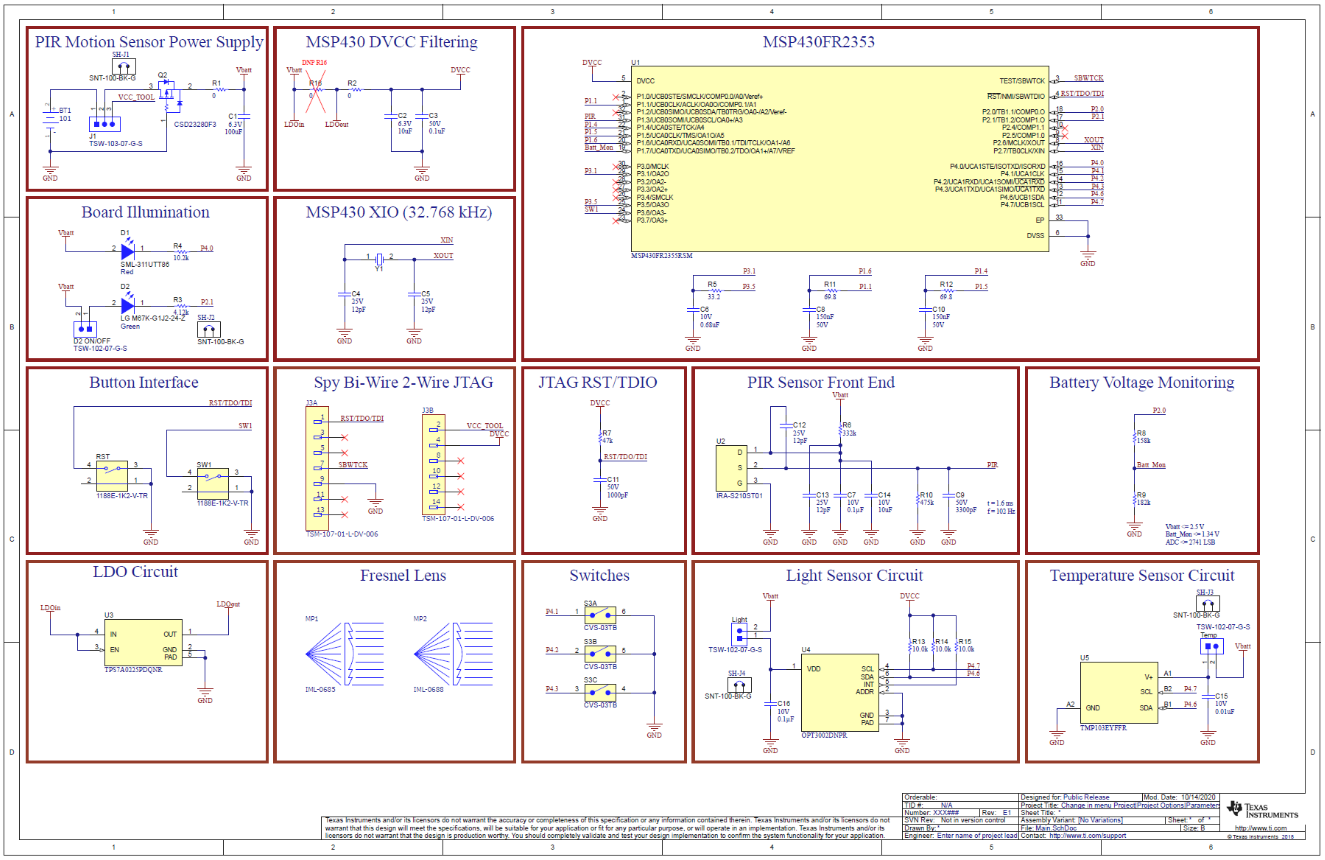

Figure 3-1. Schematic

4 Results

To test the range of the MSP430 PIR motion detector, the prototype board was set on a tripod inside a building and pointed down a hallway at measured distances. An adult and a child would walk back and forth across the hallway and the MSP430 data-logged the PIR signal after it's processing. The PIR motion detector was able to correctly detect motion out to 36 ft (11 m) and indicate the motion with a LED. Below are the waveforms that were data-logged:

4.1 Distance: 15 ft (4.5 m)

Motion events are extremely clear and direction back and forth can be determined for both adult and child based on the order of the high and low spikes.

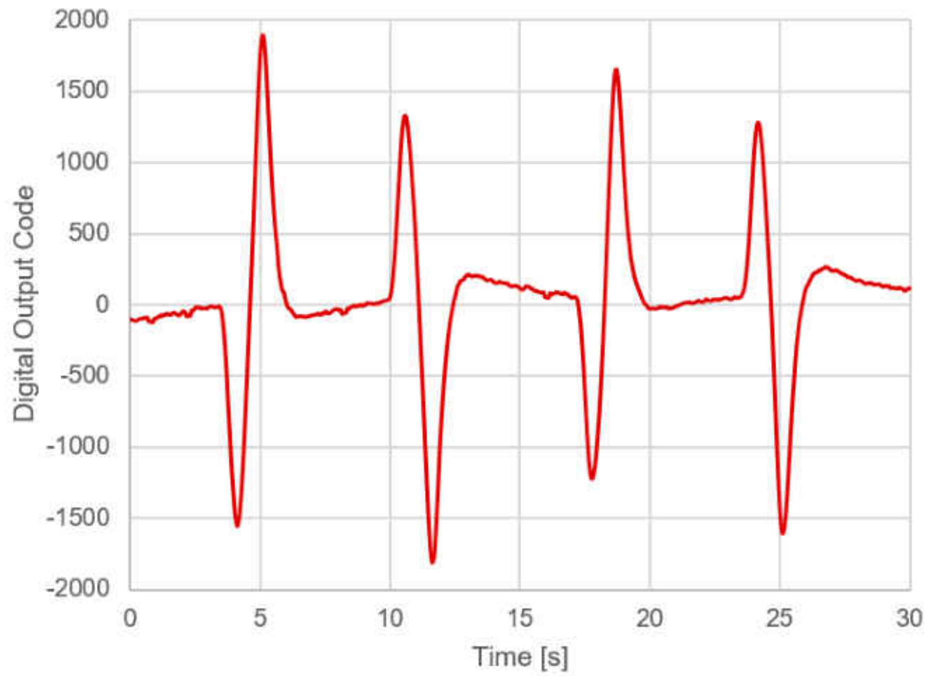

Figure 4-1. Adult at 15 ft (4.5 m), speed 1 m/s

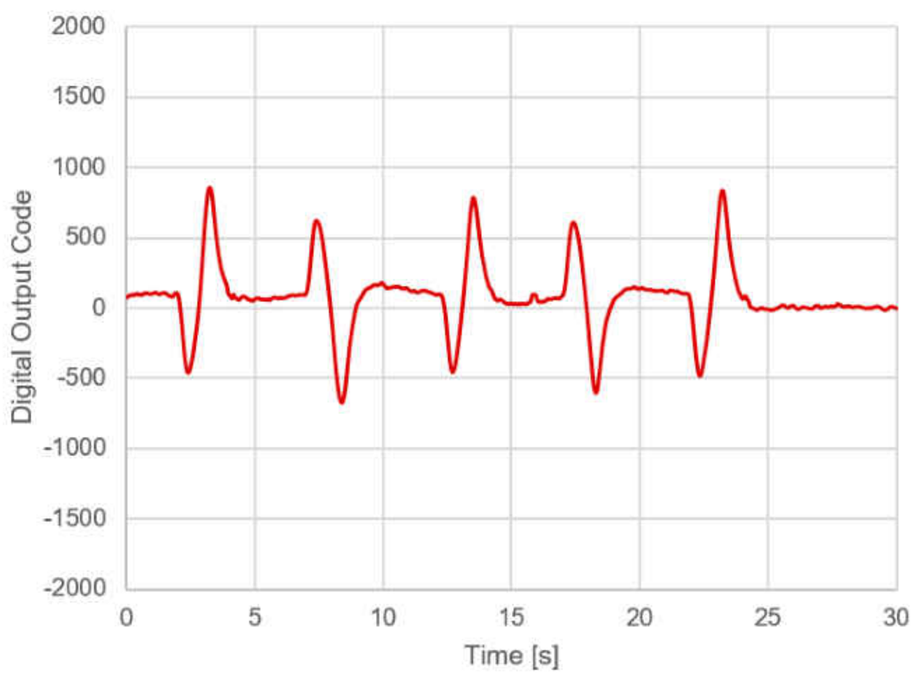

Figure 4-2. Child at 15 ft (4.5 m), speed 1 m/s

4.2 Distance: 22.5 ft (6.9 m)

Motion event amplitude have gone down, but motion events and direction back and forth can still be determined for both adult and child.

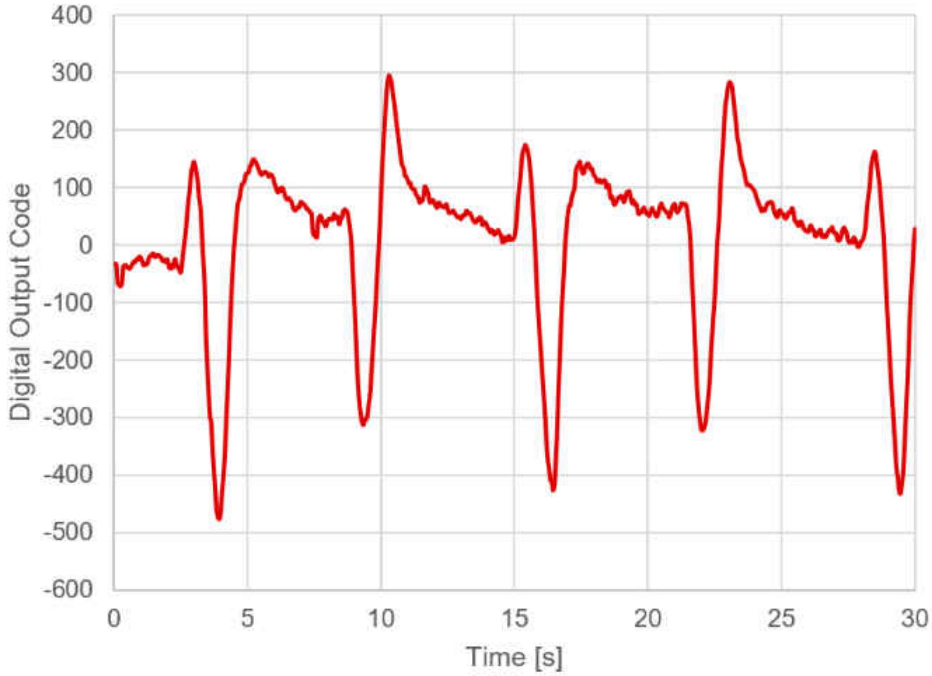

Figure 4-3. Adult at 22.5 ft (6.9 m), speed 1 m/s

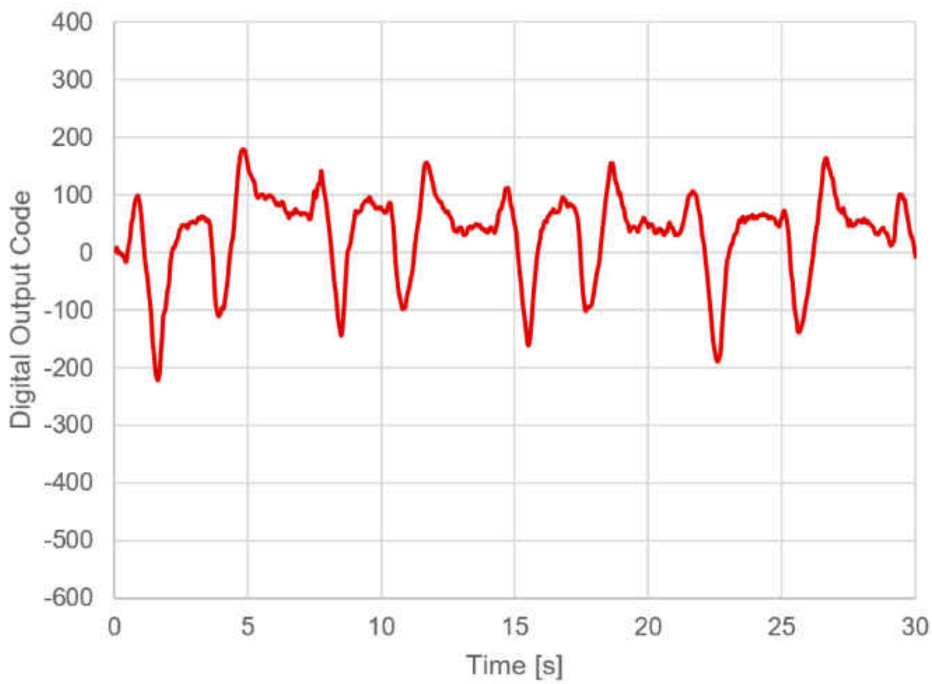

Figure 4-4. Child at 22.5 ft (6.9 m), speed 1 m/s

4.3 Distance: 36.5 ft (11.1 m)

At this distance, the amplitude from the motion events have shrunk substantially, but the motion is still clear in the wave form and clearly stands out vs the small RMS noise. These motion events were still correctly detected by the MSP430.

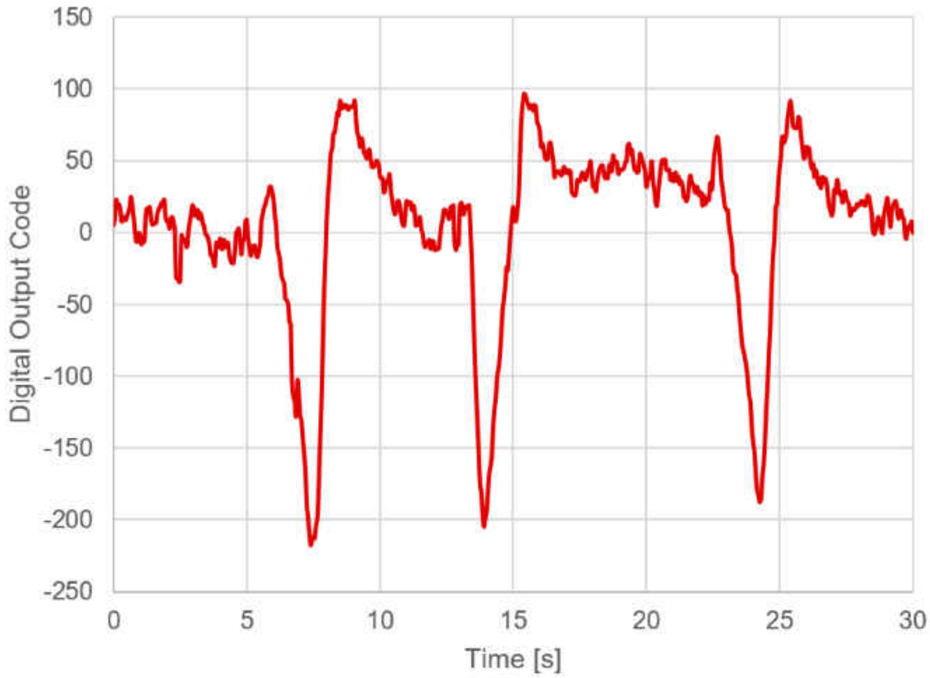

Figure 4-5. Adult at 36.5 ft (11.1 m), speed 1 m/s

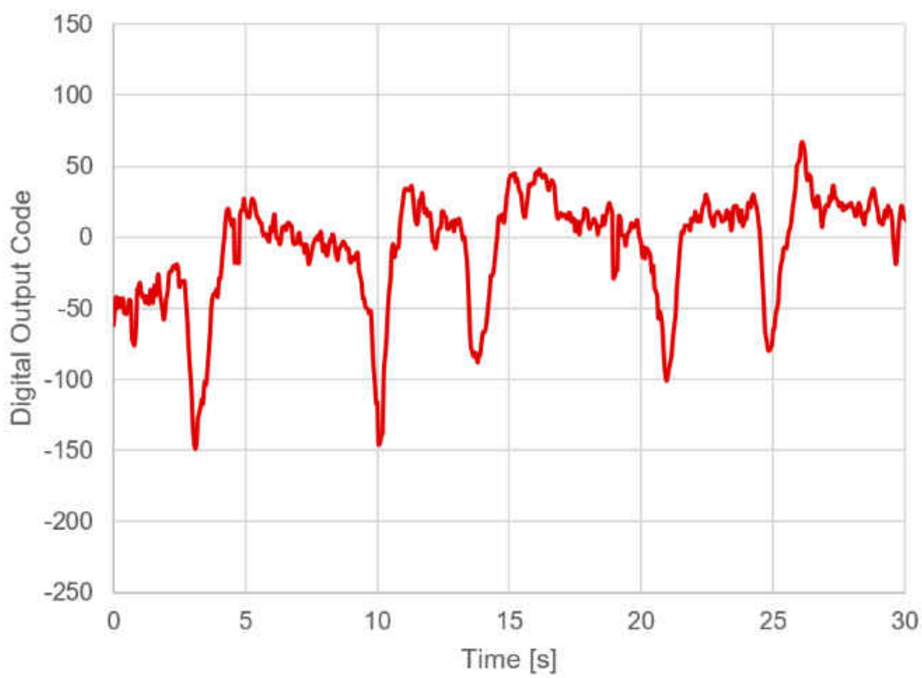

Figure 4-6. Child at 36.5 ft (11.1 m), speed 1 m/s

5 Summary

PIR Motion detectors have remained mostly unchanged for the last decade but finally new, updated solutions are possible by leveraging devices like the MSP430FR2355 with advanced analog integration. The MSP430FR2355 PIR Motion Detector offers a completely fresh and competitive solution to motion detection applications. The integrated capacitorless signal chain offers great performance and flexibility, with the ability to detect motion out to 26ft. The solution provides significant BOM savings and board simplification with integrated SACs and an analog PIR sensor. Finally, the software controlled AFE also allows for a very low power solution, with approximately 6 µA average current.

6 References

- Texas Instruments: *MSP430FR235x, MSP430FR215x Mixed-Signal Microcontrollers Data Sheet*
- Texas Instruments: *MSP430FR4xx and MSP430FR2xx Family User's Guide*
- Texas Instruments: *Ultra-Low-Power Wireless PIR Motion Detector for Cost- Optimized Systems Reference Design*
- MSP430FR2355 LaunchPad™ development kit