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A Robust Precision Data Acquisition and Control Platform for Extreme High Temperature Environments

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Introduction

The needs of multiple industries has led to the increased placement of high precision electronics closer to high temperature areas. There are several drivers for this trend, such as in energy exploration, where accessing hard-to-reach resources often requires equipment designed to operate at 175°C and higher. Due to size and power limitations, active cooling is not practical and convection of heat is very limited. In other systems, it is desirable to locate sensors and signal conditioning nodes close to areas of elevated temperature, such as engines, braking systems, or high power energy conversion electronics, in order to improve the overall system reliability or reduce costs. Aerospace, automotive, heavy industrial, and other end applications are all working to overcome this design challenge.[1]

Historically, it has been very challenging for engineers to design reliable, high performance electronics for these applications due to the lack of availability of components specified by their manufacturers for these operating conditions. Fortunately, in recent years there has been an increasing number of components, both ICs and passives, specified by their manufacturers for high temperature operation at 175°C and higher. In addition, recent reference designs have also focused on the performance of some of these components combined together in signal chain subsystems for precision data acquisition in order to enable system designers to more rapidly adopt the technology, such as CN-0365, and help them reduce design risk and time to market. However, until now there has been a gap for a fully featured, well characterized, and widely available platform for high temperature precision data acquisition.

In this article we introduce a new high temperature, precision data acquisition and processing platform that has been designed to operate at 200°C. This platform includes a high temperature circuit assembly with a data acquisition front end and microcontroller, optimized firmware, data capture and analysis software, source code, design files, a bill of materials, and test reports. This platform is suitable for reference design, rapid prototyping, and lab testing of high temperature instrumentation systems. The dimensions and construction of the circuit assembly have been designed to be compatible with oil and gas instrumentation form factors, although it can also be used as the basis for other high temperature applications.

Hardware Architecture Overview

Instrumentation used in oil and gas exploration, also known as downhole tools, is similar to many precision data acquisition and control platforms, but has some specialized performance and reliability requirements and is interesting to examine as a case study for this reference platform. In this application, signals from various sensors are sampled in order to collect information about the surrounding geologic formations. These sensors could take the form of electrodes, coils, piezoelectric, or other transducers. Accelerometers, magnetometers, and gyroscopes provide information about the inclination and rotation rate of the drill string. Some of these sensors are very low bandwidth, while others are capable of providing information in the audio frequency range and higher. Multiple acquisition channels are required and must maintain high precision at high temperatures—typically 175°C and higher. In addition, many of these instruments run on battery power or have limited power generation available and must therefore have low power consumption and multiple modes of operation for power optimization.

In addition to electronic systems requirements, downhole applications also have mechanical constraints that can dictate the electronic assembly form factor and also affect component packaging and selection. The latter will be discussed in more detail in later sections, but it is significant to note that circuit assemblies in this segment tend to have restrictions on the board width. Electronic assemblies must be placed within tube-shaped pressure vessels used in drilling operations, which leads to long and narrow aspect ratios. This form factor limits the size and density of components that can be populated and it also can restrict the partitioning of the component layout and signal routing, which can have a significant effect on performance with high precision electronics and thus require attention to layout and other packaging design details. Figure 2 shows a typical form factor, a circuit assembly mounted in a tubular pressure vessel (transparent, top), and a cross section of a tubular pressure vessel with board mounted (bottom).

The robust reference design platform presented in this article builds on the CN-0365 analog front-end reference design with the goal of providing a foundation for a high temperature, low power microcontroller-based precision data acquisition and control solution that meets the requirements for many downhole instrumentation and other high temperature electronics. Based upon the AD7981 analog-to-digital SAR converter, this reference design demonstrates a fully featured system with 2 high speed simultaneously sampled channels along with 8 additional multiplexed channels suitable for covering the acquisition requirements of a broad range of downhole tools (10 channels total). This analog front end is connected via SPI ports to the VA10800 ARM® Cortex®-M0 microcontroller from Alliances partners Vorago Technologies and Petromar Technologies. The design is the latest addition to the growing ecosystem of products and solutions for high temperature applications from ADI.

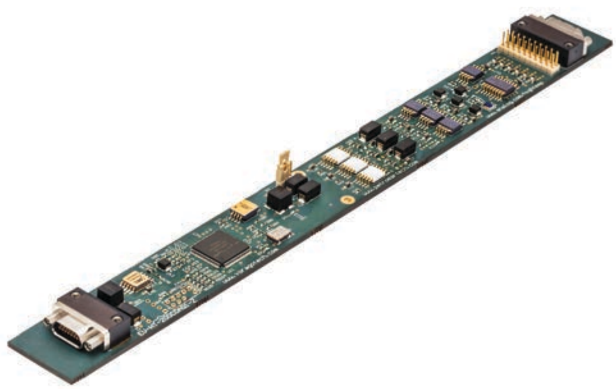

Figure 1. High temperature reference platform.

Once acquired, the data can be processed locally or transmitted via a UART or optional RS-485 communications interface. Other supporting components on the board, including memory, clock, power, and passives, are all rated for high temperature operation by their respective suppliers and verified to operate reliably at 200°C or higher. Figure 1 and 2 show the actual board and high level block diagram for this high temperature reference platform. The board rendering in Figure 2 is indicative of the downhole electronics board layout and form factor, approximately 11.4" long and 1.1" wide.

Figure 2. Downhole electronic assembly form factor.

The design of the precision data acquisition channel for this platform is covered extensively by the CN-0365 application note.[3] That design serves as the basis for the three ADC inputs on this platform, although some changes and optimizations were made, mostly in passive component selection, in order to address the form factor requirements of the board and extended reliable operation up to 200°C. The reference acquisition channel circuit is shown in Figure 4. There are 2 digital multiplexed channels that each contain a complete data acquisition channel, similar to CN-0365, that are capable of running at high sample rates. There is also an analog multiplexed channel that adds an ADG798 multiplexer in front of the inputs, which is optimized for lower throughput inputs. R1 and R3 provide a 1.25 V bias for the noninverting input of U1 and prevent it from floating to the rail of the analog input if left open, or if the multiplexer is deselected. R8 and R9 can be changed to increase the gain of U1. R4, R7, and C1 are the antialiasing filter, but they can be reconfigured as an attenuator or alternate filter configuration. R5, R6, and C4 form the RC filter between the ADC driver and ADC input that limits the amount of out-of-band noise arriving at the ADC input and attenuates the kickback voltage from the switched capacitors in the ADC's input.[4]

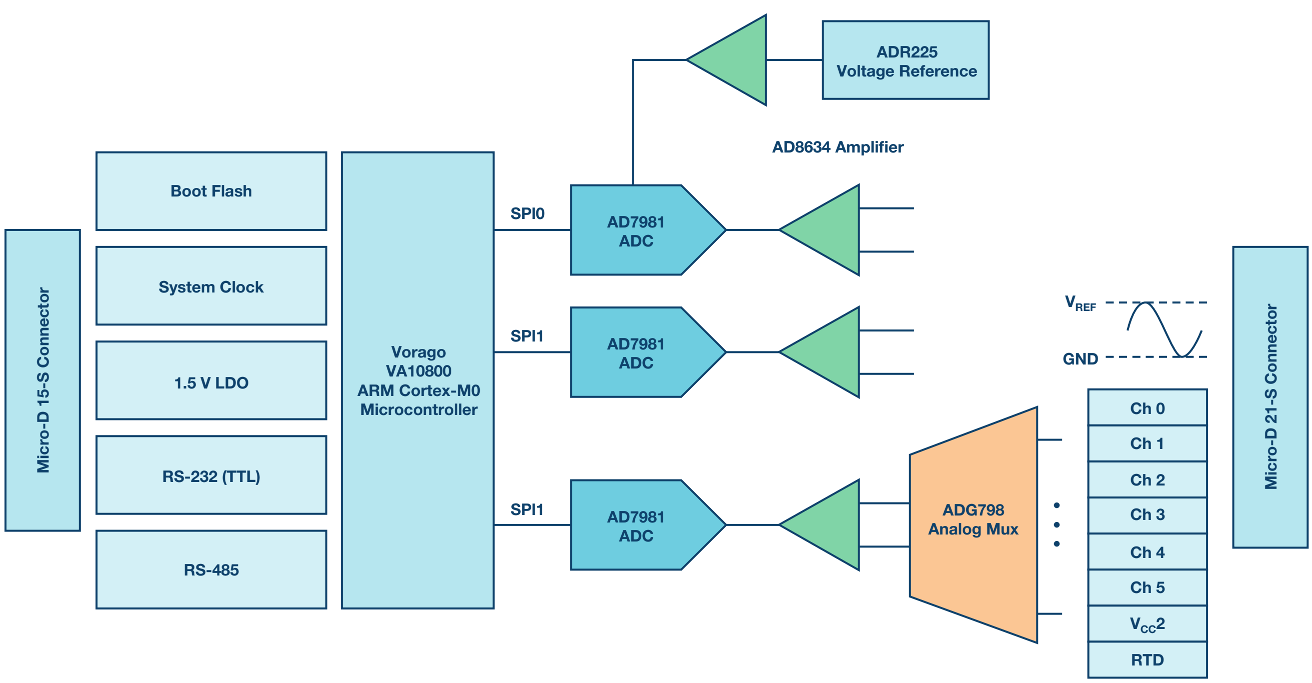

Figure 3. High temperature reference platform block diagram.

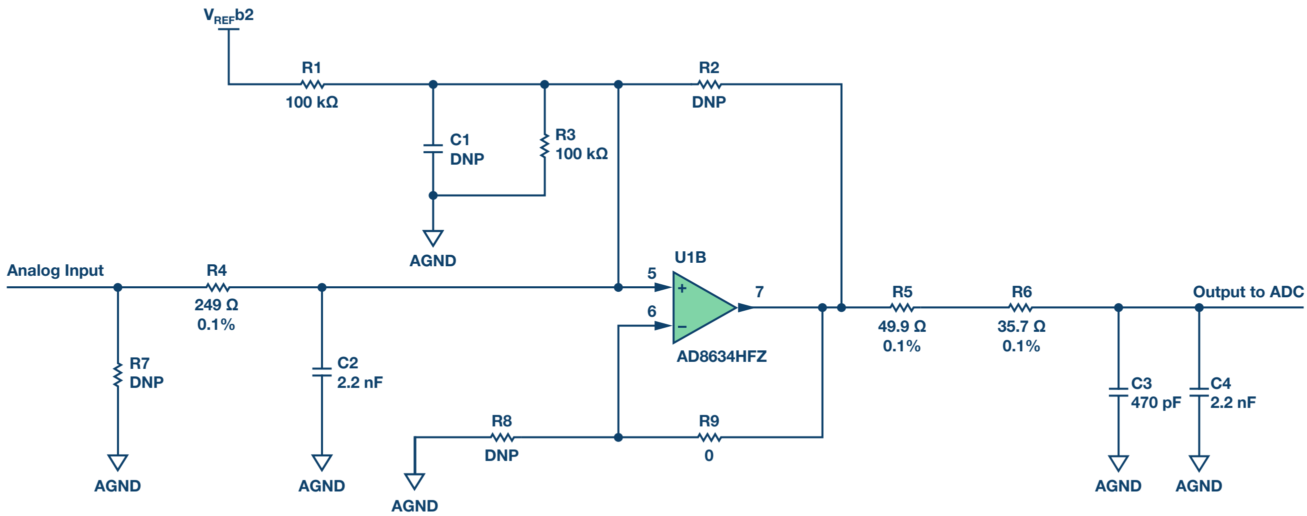

Figure 4. ADC driver configuration.

This platform was designed to take advantage of several key features of the AD7981 ADC. This 16-bit, 600 kSPS converter is capable of greater than 85 dB typical SINAD and ±0.6 LSB typical INL with a 2.5 V reference and no missing codes. Greater than 90 dB SINAD can be achieved with a 5 V reference, although that was not selected for this platform in order to maintain compatibility with lower voltage systems. Because the ADC core automatically powers down between conversion cycles, ADC power consumption automatically scales linearly with throughput. This allows power savings to be realized when using the converter at lower sampling rates.

Software Overview

Firmware

Firmware for the platform is built upon the FreeRTOS operating system and facilitates simple incorporation of tasks, such as data processing and other forms of communication. Code has been optimized to efficiently complete fast ADC conversions for nonmultiplexed channels 0 and 1, and down to 10 µs for the multiplexed channels 2 through 9. Conversion results can be processed locally, or streamed out of a UART channel at 2 Mbps. The conversion result buffer is 16 kB (8k samples), which can be shared among several channels or dedicated to a single channel. This firmware is provided in open source format to allow customization by the end user and can serve as the basis for end applications.

Data Capture and Analysis Software

Figure 5 shows the data capture and analysis software, which has been designed in .NET to interface with the circuit assembly through a USB-UART-TTL level translator. A well-defined protocol allows communication with the hardware including control and data streaming. Data can be captured in burst modes and also continuously. In addition, data analysis features are included to analyze and verify SNR, THD, and SINAD in the time and frequency domains (for example, FFT). Data can also be logged to files (for example, exported in Excel) for storage or processing in other applications. As with the firmware, the data capture software source code is freely available for customization by the end user.

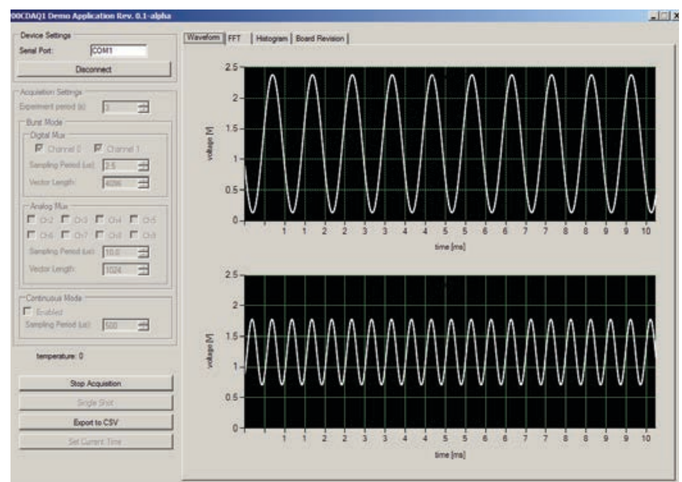

Figure 5. Data capture and analysis software.

High Temperature Construction

This reference platform was constructed using components and other materials that are suitable for 200°C operation. All components used on the assembly are rated for high temperature operation (unless otherwise noted) by the respective manufacturer and are readily available off the shelf from global distributors. The full BOM, PCB artwork, and assembly drawings are freely available as part of the reference design package.

Capacitors

C0G or NP0 dielectric capacitors are used for low value filtering and decoupling. These dielectrics have a very flat coefficient over temperature and are generally more tolerant to board flexing stresses.[5] Additionally, C0G or NP0 type capacitors are recommended for an RC filter that has high Q, low temperature coefficient, and stable electrical characteristics under varying voltages. Small footprint 0805 or less ceramics are used to minimize CTE mismatch between component and PCB. High temperature tantalum capacitors are chosen for bulk energy storage with trade-off considerations between footprint size and ESR.

Resistors

Thin film SMT resistors, automotive grade PATT series, are used for the majority of this design and are readily available in the marketplace. Some thick film SMT resistors are used for specific values and sizes as necessary in the design as well.

Connectors

The board is connectorized with a 200°C rated Micro-D, which is common in high reliability industries. To reduce signal crosstalk, provisions were made for the shell of the connector to be grounded to the PCB in the assembly. For applications where the highest signal integrity and lowest crosstalk are required, high temperature specialty connectors (or no connector) and coaxial or shielded balanced inputs should be utilized to minimize crosstalk.

PCB Design and Layout

The long and narrow PCB form factor was chosen for suitability in downhole applications where circuit boards have to conform to the constraints of a borehole and pressure housing. The circuit board material chosen is a high temperature halogen free polyimide. A 0.093" board thickness was specified for added rigidity and planarity over standard 0.062" thickness boards.

A nickel-gold surface finish is used, where nickel provides a barrier that resists intermetallic growth, and gold provides a good surface for solder joint bonding.

For the chosen 0.093" board thickness, a typical four layer stack-up will involve a ~13 mil copper layer separation with a large 60 mil internal core. At six layers, layer separation is typically 9.5 mil and 28 mil. For this reason, a six layer design was utilized and allows a ground plane next to each signal layer for better noise performance.

Power and digital communication signals feed into one connector and analog signals come in on the opposing connector. This provides good isolation and signal flow between digital and analog domains. The plane split is midboard, with power filtering provided near the split. The digital control lines that do cross the split plane are minimized, and series terminations are provided to minimize coupling of digital noise. The digital and analog ground planes are bonded at a single point with a copper net tie to provide a low impedance return path to the driving sources.

The multiplexer control signals run the length of the analog section but are routed to keep away from critical analog signal paths. In practice these multiplex control lines change synchronously with the acquisition measurement and crosstalk effects are thus minimized.

Solder

Sn95/Sb05 was chosen to provide a high enough melting point (>230°C) over the 200°C operational temperature and provide good workability and general assembly house availability.

Board Mounting

The post mounts provided on this board are for convenience only and are only useful for mounting in bench testing or lab situations. They are not suitable mounts for high shock and vibration environments. For use in high shock and vibration environments, the board can be prepared by first staking components to the board with epoxy. Susceptible items like the IDC headers can be encapsulated or removed from the assembly. Typical mounting for downhole or other harsh environment applications would involve a rail mount system that secures the perimeter of the board with flexible shock mount gaskets. Alternatively, the assembly can be fully encapsulated and potted inside mounting hardware that is then affixed to the chassis or enclosure.

More information on the appropriate parts can be found in the article "A Low Power Data Acquisition Solution for High Temperature Electronics Applications."[2]

Performance Test Results

Extensive testing was performed on several boards to assess typical performance over temperature, along with a 200 hour temperature soak at 200°C ambient to qualify the assembly process and board reliability.

The ac and dc signal chain performance is a key precision measurement metric of a SAR ADC-based precision data acquisition system. A ratiometric and robust platform achieves above –100 dB crosstalk and ±60 mV max offset drift at 200°C when running the ADC at 600 kSPS. For the ac test, a low distortion 1 kHz tone is used as the input signal and the board is powered with $+5\ V_{DC}/–2.5\ V_{DC}$ analog supplies. An FFT of this tone acquired at 400 kSPS with spectrum analysis calculations are shown in Figure 6. Better than 84 dB SNR and –96 dB THD is obtained at 200°C. Figure 7 shows the SNR and SINAD and Figure 8 shows THD over temperature for the nonmultiplexed channels with the same input tone.

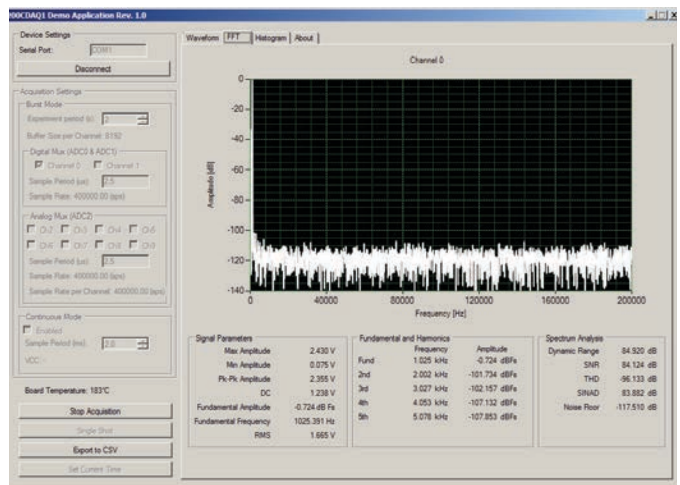

Figure 6. FFT and spectrum analysis at 200°C.

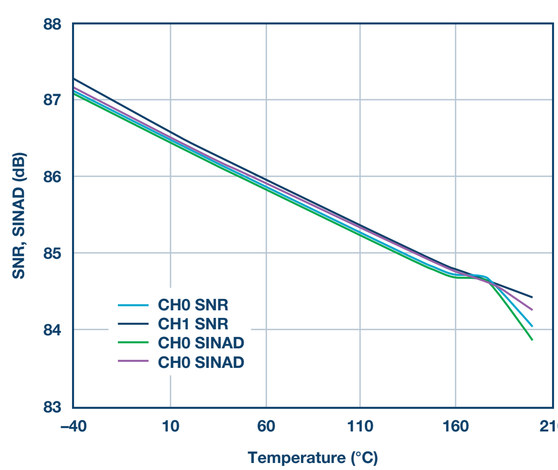

Figure 7. SNR and SINAD over temperature.

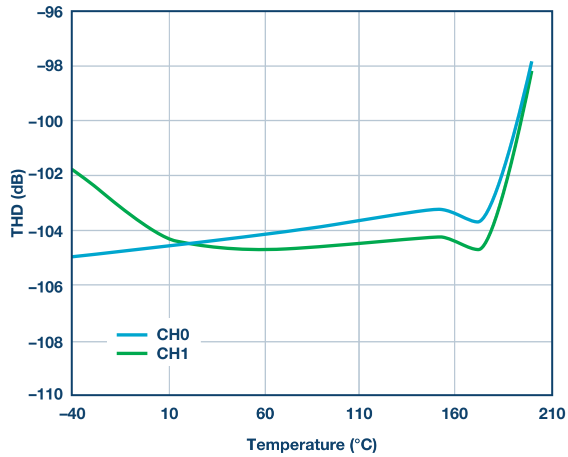

Figure 8. THD over temperature.

Current consumption on the analog and digital rails was measured over temperature as shown in Figure 9. Total power consumption at room temperature is 155 mW, increasing to 225 mW at 200°C. Power consumption on the 3.3 V rail is dominated from the microcontroller, which is running at full clock rate, and a precision oscillator. The converters were set to acquire a burst of 8192 samples every second.

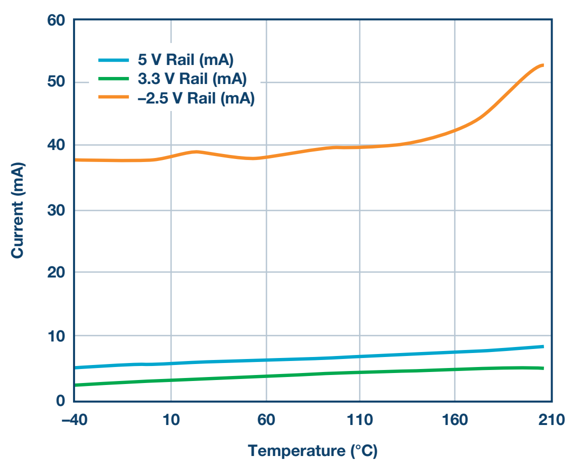

Figure 9. Current consumption for 2.5 V, 3 V, and 5 V rails

Test results of additional parameters can be found on the reference platform, which is qualified and characterized for 200°C operation.

Example Applications

In many applications in oil and gas exploration, aerospace, and heavy industrial, accelerometers are used both for orientation and vibration sensing. Accelerometers with analog outputs can give the highest degree of accuracy with flexibility to condition the sensor output as appropriate for the application.

The ADXL206 is a precision, low power, complete dual-axis iMEMS® accelerometer for use in high temperature environments. It provides ±5 *g* range and 0.5 Hz ≤ bandwidth ≤ 2.5 kHz. The output of the ADXL206 is centered about ½ V_{CC} and is ratiometric to V_{CC}. If the ADXL206 and the EV-HT-200CDAQ1 share V_{CC} (available on the connector), the V_{CC} reference available on channel S7 of the multiplexer can be used to zero dc offsets and power supply drift. An example circuit is shown in Figure 10. The 0 V to 5 V signal range of the ADXL206 must be scaled by ½ to fit within the 0 V to 2.5 V range of the precision data acquisition system. This is accomplished by first buffering the outputs and then using the attenuators inside the data acquisition system. C2 and C3 set the bandwidth of the ADXL206; the example in Figure 9 shows a bandwidth of 33 Hz. Low bandwidth applications can make use of the multiplexer inputs; for the highest bandwidth and accuracy, the two nonmultiplexed input channels can be used.

Summary

This article introduced a new, highly integrated robust, precision data acquisition reference platform, EV-HT-200CDAQ1, that is qualified and characterized for 200°C operation. This platform allows designers of high temperature electronics systems to use the latest state-of-the-art components for rapid prototyping and evaluation, minimizing development time and time to market. More information on the platform including full design package and software can be found here.

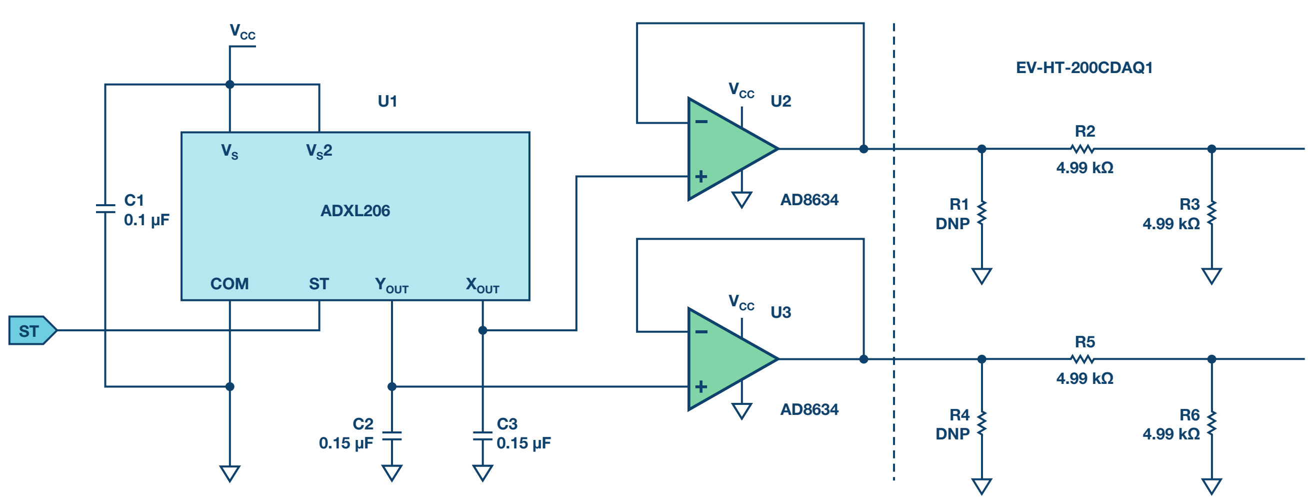

Figure 10. Interfacing high temperature accelerometer to EV-HT-200CDAQ1.

References

[1] Jeff Watson and Gustavo Castro. "High Temperature Electronics Pose Design and Reliability Challenges." *Analog Dialogue* Vol. 46, No. 4, April 2012.

[2] Jeff Watson and Maithil Pachchigar. "A Low Power Data Acquisition Solution for High Temperature Applications." *Analog Dialogue*, Vol. 49, No. 3, August 2015.

[3] CN-0365: *16-Bit, 600 kSPS, Low Power Data Acquisition System for High Temperature Environments*. Analog Devices, Inc., June 2015.

[4] Alan Walsh. "Front-End Amplifier and RC Filter Design for a Precision SAR Analog-to-Digital Converter." *Analog Dialogue*, Vol. 46, No. 4, December 2012.

[5] John L. Evans, James R. Thompson, Mark Christopher, Peter Jacobsen, and R. Wayne Johnson. "The Changing Automotive Environment: High Temperature Electronics." *IEEE Transactions on Electronics Packaging Manufacturing*, Vol. 27, No. 3, July 2004.

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