WHITE PAPER

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TEXAS INSTRUMENTS

Integrating mixed signal capabilities on MSP430™ MCUs in industrial automation applications

Introduction

This paper proposes a number of reference designs using Texas Instruments ultra-low-power MSP430™ microcontrollers (MCUs). The industrial automation market is well established and continues to develop every year. This market is especially focused on integrating smart control and automation solutions with a strong focus on low-power, low-cost solutions. The MSP430 MCU family has many derivatives that meet these requirements and provide ample mixed signal capabilities for this market. By utilizing these capabilities, industrial automation application designs can be greatly simplified and improved.

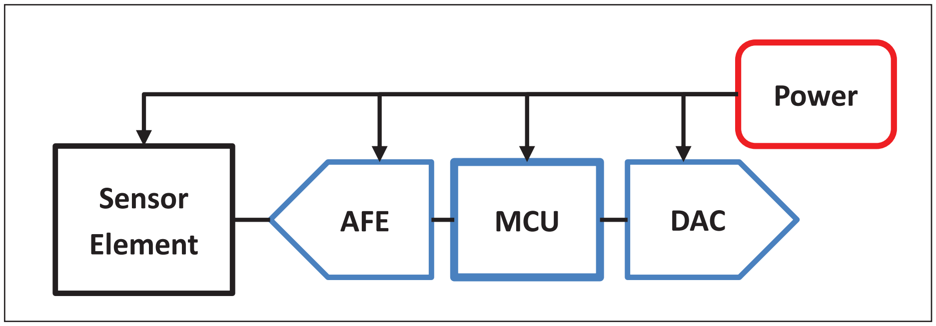
Two wire 4-20 mA loops are used extensively in factory automation applications to monitor the output response of sensor solutions [1]. Typical sensors used in these solutions monitor pressure, temperature, flow, speed, level, strain and much more. The linearity of the 4-20 mA communication loop represents the sensor output value where 4 mA defines the off state while 20 mA defines the maximum output value of the sensor. The transmitter thus translates the sensor output value to a control signal necessary to regulate the flow of current in the current loop. The correlation of the loop current with the process variable is set by the transmitter. A range of current values within the 4-20 mA span represents a given output value of the sensor. Given the communication loop is based on a current value, the accuracy of the signal is not impacted by the voltage drop in the interconnecting wire. Therefore, the distance between the transmitter and the receiver can be in the thousands of meter range. In this case, the transmitter does not source the current. Current is drawn by the voltage source connected to its output terminals. This translates to an additional advantage in that the loop provides power to the transmitter itself.

In this paper, onboard analog components are used on two MSP430 MCUs to design a flexible single-chip voltage control current source as part of a 2-wire 4-20 mA transmitter design. Output data from the physical design is compared to the SPICE simulations.

Integrated analog modules on MSP430 MCUs

Among the capabilities of MSP430 MCUs used in the designs outlined in this work, the most important are those which integrate analog functionalities. Namely, the modules that drive the functionality of these 2-wire 4-20 mA transmitters are the analog-to-digital converter (ADC) module, the digital-to-analog converter (DAC) module, the TimerA module and the integrated op-amps (OA).

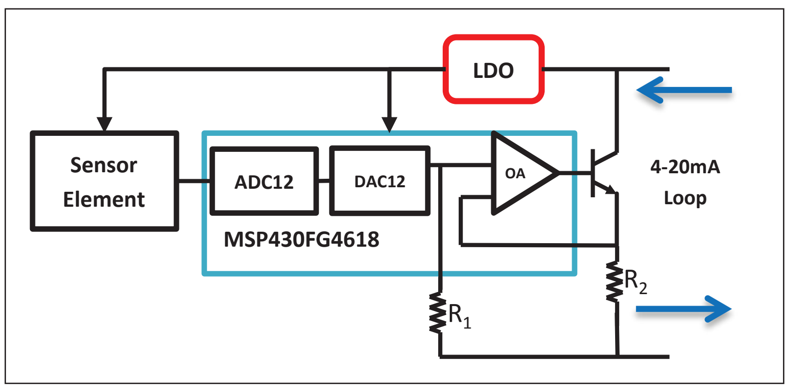
As seen in Figure 1, these capabilities are usually pushed to additional embedded products; the MCU is used as a communication buffer between the external analog front end (AFE) and DAC parts. However, the modules on MSP430 MCUs are able to emulate the performance of these external parts and provide a feasible 2-wire 4-20 mA transmitter solution on a single chip.



▲ ***Figure 1*** *– Block diagram of basic sensor system*

Proposed current loop transmitter designs

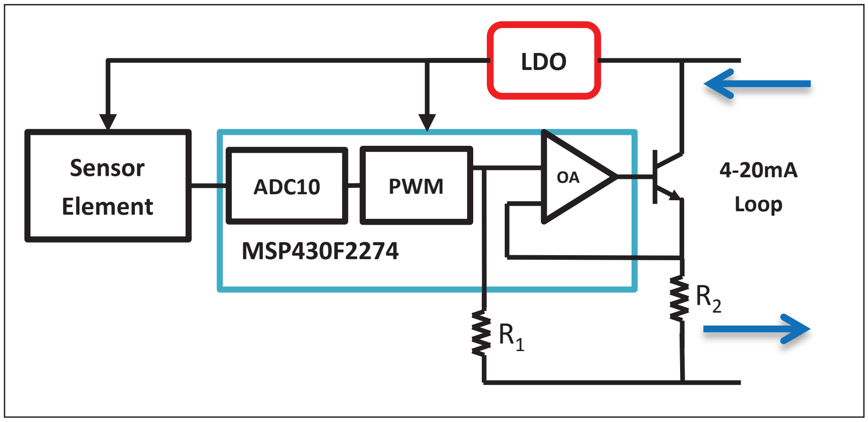
In this section, two proposed designs will be introduced and explained in some detail. The first design that will be discussed includes the MSP430FG4618 MCU. This particular MSP430 device includes a 12-bit successive approximation register (SAR) ADC, integrated op amps, and a 12-bit voltage-output DAC [2]. With the addition of limited external circuitry, and an LDO providing a constant 3.3 V source, the MSP430FG4618 MCU can replicate the duties of all three other pieces normally included in a basic sensor system. Figure 2 shows a basic block diagram for this proposed design.



▲ ***Figure 2*** *– Block diagram for MSP430FG4618 MCU-based transmitter design leveraging the DAC12 module*

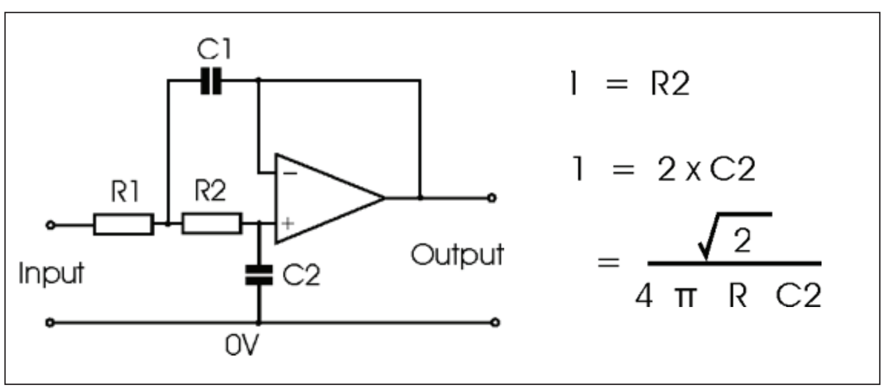
The integrated op-amp on the MSP430FG4618 MCU is utilized in a way to take the voltage output of the DAC12 and operate as a current source. In this design, the reference current is amplified by a factor that is a ratio of R_1 and R_2, giving that loop = $(I_{ref})\,R_1 / R_2$. These resistors were then chosen and create a gain ratio large enough to achieve the upper end of the 4-20 mA spectrum. Additionally, a resistor bridging between the DAC12 output and non-inverting input of the op-amp was chosen as a function of the full scale range (FSR) of the DAC's output. Precisely, the resistor value was to be equal to the FSR/12 µA.

The other proposed design includes the mixed signal capabilities of the MSP430F2274 MCU. This derivative does not contain a voltage DAC on board, so one must be emulated. Similar to the MSP430FG4618 device, however, the MSP430F2274 MCU includes a SAR ADC (only 10-bit accuracy) and integrated op-amps that are well suited for driving a current loop application. Figure 3 shows a basic block diagram of the system using the MSP430F2274 MCU [3].



▲ ***Figure 3*** *– Block diagram of the MSP430F2274 MCU-based current loop transmitter design*

As mentioned before, no voltage DAC is integrated onto the MSP430F2274 MCU, so one is emulated. To achieve this, a 16-bit timer module is used to make an adjustable pulse-width modulator (PWM) with a 12-bit accuracy. This output signal of varying duty cycles can then be routed through an integrated op-amp with minimal additional circuitry, which acts as a low pass filter designed to pass only a DC voltage source from its output. This filter can be designed in a way so that the cutoff frequency is lower than the PWM frequency, thus ensuring the monotonicity of the voltage output [4]. The effective two-pole low pass filter circuit is defined by the circuit diagram and equations shown in Figure 4.

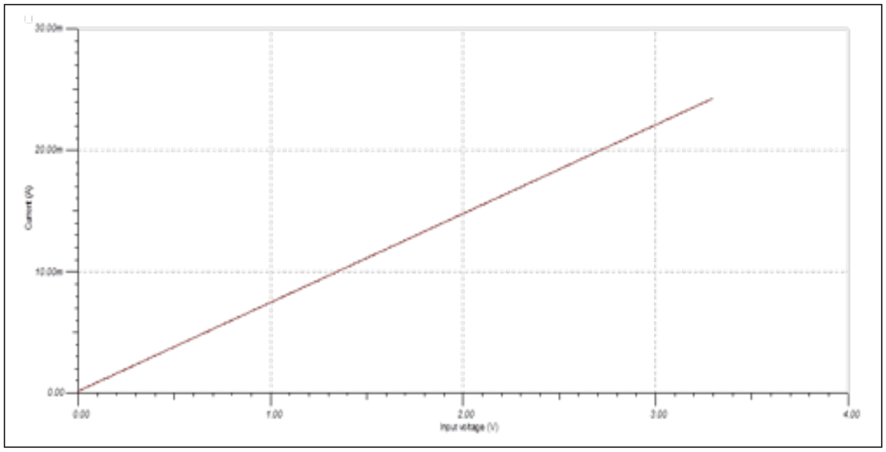


▲ ***Figure 4*** *– Two-pole low pass op amp filter theory [4]*

Similar to the design which included the MSP430FG4618 MCU, the MSP430F2274 MCU-based design utilizes the op-amp to take the now DC voltage source supplied by the PWM filtered through another op-amp and provides a current source for the loop. As such, the external resistors (including the bridging resistor) were tuned specifically for this design and the new FSR of this emulated PWM DAC to achieve the full 4-20 mA standard.

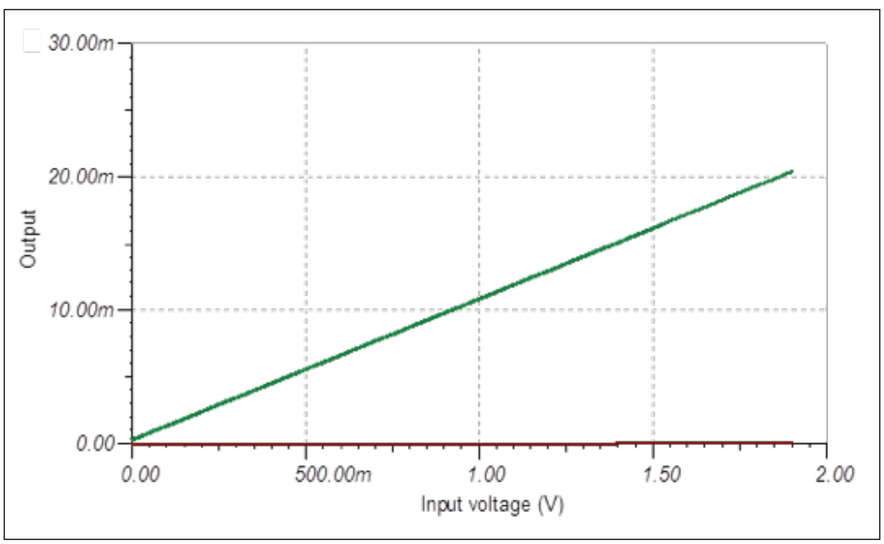
Current results and ongoing work

This section includes the simulation and experimental results that have been achieved to date. To begin, each of the designs were taken and built in SPICE simulations. Figure 5 shows the results that were achieved from simulating the design that included the MSP430FG4618 device over an estimated DAC12 output FSR of 3.3 V. Although the graph in Figure 5 is quite small, the important things to notice are the linearity of the current response across voltage, and the design would exceed 20 mA at the estimated FSR of the DAC12.



▲ ***Figure 5*** *– MSP430FG4618 MCU-based design SPICE simulation results*

In experimentation, however, the FSR of the DAC12 was equal to the internal voltage reference on the MSP430FG4618 MCU, which was set to 2.5 V. Thus, the tuning spoken of in the previous section was done to achieve similar results across the FSR of the DAC12. Similarly, the design which included the MSP430F2274 MCU was also built as a SPICE simulation. The results of which are shown in Figure 6 below. For this design, before simulating the full design, the voltage output of the PWM DAC was categorized so that an accurate FSR of 1.9 V could be applied as the simulation limits.



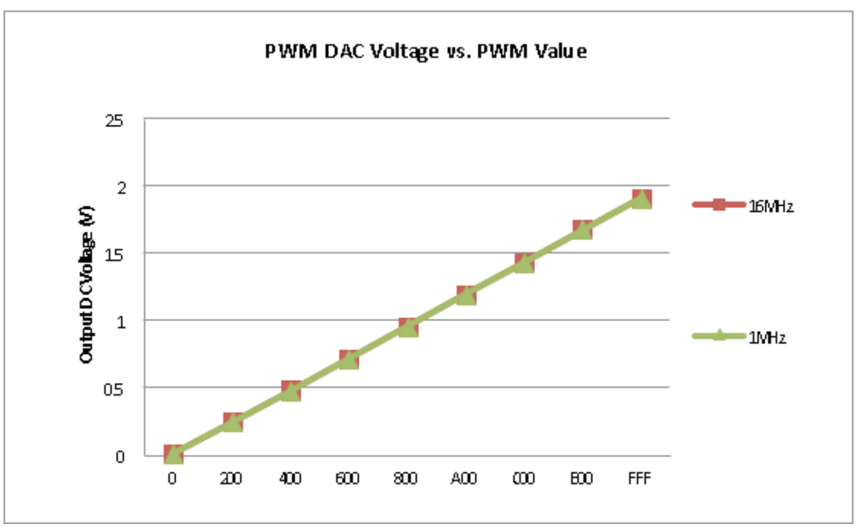
▲ ***Figure 6****– MSP430F2272 MCU-based design SPICE simulation results*

As seen in Figure 6, this design also was able to achieve a current output at the FSR equal to, if not a bit greater than 20 mA. Also, it should be noted that this design also shows a linear response as the PWM DAC voltage is increased (as the duty cycle of the PWM is increased).

Previously, it was mentioned that a timer module was utilized as a PWM and routed through op-amp circuitry to emulate a 12-bit DAC. This emulated DAC was then characterized across a number of different duty cycle values. The results of this testing are shown in Table 1. This table shows DC voltage output values following the two-pole low pass op-amp filter described in the previous section and Figure 4. The testing was done with the digitally controlled oscillator (DCO) which sourced the CPU and timer module at two different frequencies: 1 MHz and 16 MHz. The PWM values are shown as hexadecimal values and the duty cycle can be calculated as a percentage of the full 12-bit value 0xFFF. When plotted, these values give the highly linear plot shown in Figure 7.

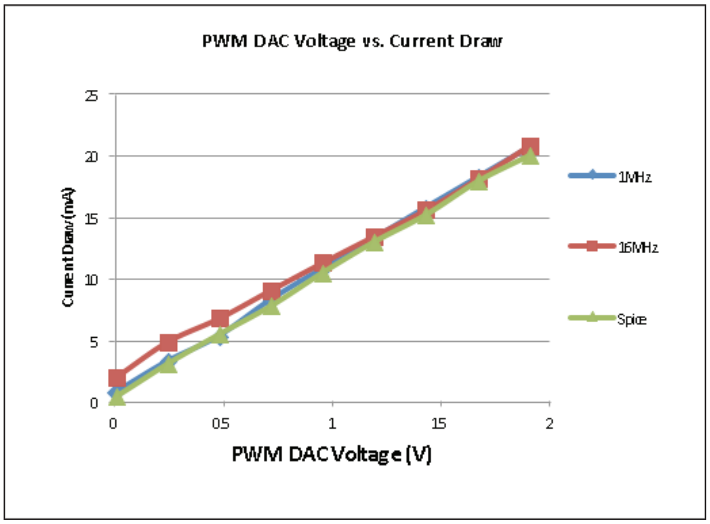
PWM Val	1 MHz (V)	16 MHz (V)
0x000	0.0015	0.0026
0x200	0.2417	0.2399
0x400	0.4777	0.4785
0x600	0.7162	0.7167
0x800	0.9543	0.9549
0xA00	1.19	1.1931
0xC00	1.4313	1.4315
0xE00	1.6733	1.6728
0xFFF	1.903	1.907

▲ ***Table 1*** *– PWM DAC voltage levels*



▲ ***Figure 7*** *– MSP430F2274-based PWM DAC output results*

This design was also fully tested on the bench with multiple data points for the current draw of the entire system. The voltage and current data was transposed to create the plot in Figure 8. As seen in the Figure, the current draw is largely linear as the 12-bit PWM duty cycle is increased; running the DCO at 1 MHz proved to be much more accurate to the SPICE simulation data than at 16 MHz. This is because the MSP430 MCU intrinsically consumes more power when operated at a higher frequency and the difference is much smaller (less noticeable) at higher voltages, and therefore higher overall current draws.



▲ ***Figure 8*** *– MSP430F2274 MCU experimental results plotted along SPICE simulation results*

As important as the range and linearity of the designs, the latent current measurement (current draw without DAC voltage output) is also of utmost importance for these designs. Because a sensor element has not been added onto these reference designs, and will add to the overall current consumption of the system, it is important to have as small of a latent current as possible. Table 2 marks not only these values, but also the experimentally found max current values in the current setup. It is apparent that not only do these systems easily stay below the threshold of 4 mA allowing for ample buffer for a sensor element to be added to the system.

Design	f DCO	I min	I max
MSP430FG4618	1 MHz	1.74 mA	25.3 mA
MSP430F2274	1 MHz	0.74 mA	20.63 mA
MSP430F2274	16 MHz	1.99 mA	20.78 mA

▲ ***Table 2*** *– Latent current Max/Min current values*

Conclusions and future work

In reviewing the findings of this paper, a number of basic conclusions can be made about the proposed reference designs. First, by looking simply at the linearity of not only the PWM-simulated DAC, but also the final current loop measurements, the simplified current loop designs achieve results that are comparable to current solutions. Second, the latent current measurements for each of these systems easily achieve the market-specific benchmark of ~2.5 mA for an industrial system without a sensor element present. Additionally, these results are achieved in a fashion that is simpler, and in the case of the MSP430F2274-based design, cheaper than most existing solutions, adding novelty to the design's results.

Beyond these successes, a number of continuing works and testing are required to bring these designs up to a standard that would be sufficient and truly competitive. Included in this would be testing the system across temperature and other conditions that may be present in an industrial environment. Specifically within this space, the linearity of the clock sources which control the output of the DACs (either explicit or emulated) is of utmost importance. The system needs to be able to comply with temperature variation and continue to operate correctly and efficiently at all test points. Further analysis of this will be done before these reference designs are fully released.

A final point of future work for these designs and future similar designs is to incorporate "smart" digital communication protocols into the design. Specifically, a future course for these designs is to include the HART protocol which involves overlaying a 500 µA, 1200 bps FSK signal on top of the traditional 4-20 mA current loop [HCF]. This protocol allows for multiple variables to be transmitted or a number of different control commands to be passed along digitally between the field sensor and the master device.

References

[1] Yuval Hernik-Bar, "How to select precision resistors for 4-20mA current loop", EDN, Internet: http://www.edn.com/design/sensors/4419750/How-to-select-precision-resistors-for-4-20mA-current-loop, [August, 2013]

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