MAX35103EVKIT2 VOLUMETRIC CONTROL FIRMWARE EXAMPLE

Introduction

This appnote and accompanying volumetric firmware use the MAX35103EVKIT2# to demonstrate how to add volumetric shut-off control to an existing residential irrigation system. The user should refer to the MAX35103EVKIT2# datasheet for information about the hardware platform.

Included with the volumetric firmware package is a low-level, portable API for the MAX3510x family of time-to-digital converters.

Requirements

At minimum, the firmware requires the MAX35103EVKIT2# and IAR Embedded Workbench for ARM. There are a few different hardware configurations are supported depending on the desired mode of evaluation. Please refer to the MAX35103EVKIT2 datasheet for an overview of the required system connections.

1. Lab bench static configuration
2. Lab bench water flow configuration
3. Lab bench system integrated configuration
4. Field system integrated configuration

The Lab bench static configuration (1) allows for quick, first-time evaluation of the MAX35103EVKIT2 and the volumetric firmware. This configuration places the ultrasonic transducer assembly in a small container filled with water. A bench power supply or a wall adapter powers the board. This is all that is needed to observe basic firmware functionality involving sampling using the MAX35103. However, this configuration doesn't allow for water flow measurement.

The lab bench water flow configuration (2) adds a small aquarium hobby pump and plumbing to the ultrasonic transducer to provide a simple test system that includes water flow. This requires a reservoir for water. A 5 gallon plastic bucket or 5-10 gallon aquarium is required. Plumbing can consist of PVC pipe and connections or flexible hose with appropriate adapters. Optionally, this configuration could include an irrigation water valve for control evaluation.

The lab bench system integrated configuration (3) adds an off-the-shelf irrigation controller to #2 for full lab-based evaluation. The irrigation controller is connected as described in the MAX35103EVKIT2 datasheet. This configuration can also include an irrigation water valve for control evaluation.

The most complete test bed is the field system integrated configuration (4). This configuration requires that the MAX35103EVKIT2 be inserted in a real irrigation system between the irrigation controller and a water valve. Additionally, the ultrasonic transducer assembly is plumbed in to the irrigation segment controlled by the water valve.

It is up to the user to decide which method is most appropriate for their application and the particulars of how components should be plumbed together. The only requirement of the firmware is that the MAX35103EVKIT2 be connected to a water-filled Audiowell ultrasonic transducer assembly.

Firmware Architecture

The volumetric firmware architecture is depicted in ***Figure 1***. The application code exists at the top and is implemented in main.c. The application code depends upon support from the board, CPU, and MAX35103 support libraries.

The MAX35103 chip support library provides an API for the MAX35103 and depends upon a portability layer. The portability layer abstracts the SPI which allows for easy porting of the MAX35103 support library to other platforms.

The physical parameters of the ultrasonic transducer assembly are abstracted in ultrasonic transducer module. This includes MAX35103 specific configuration and mathematical models of the transducer.

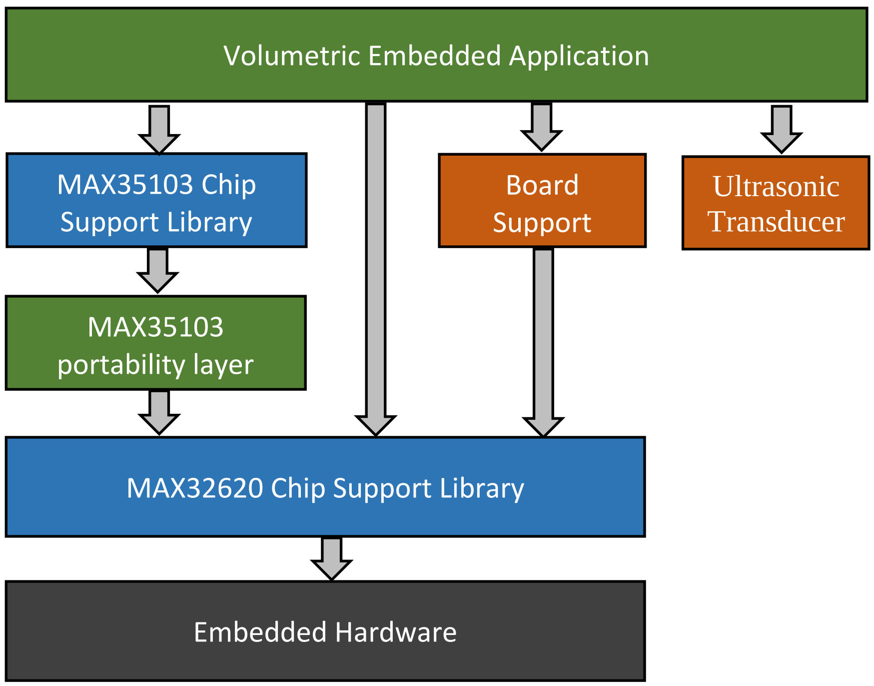


FIGURE 1 - FIRMWARE ARCHITECTURE

Firmware Package Contents

The volumetric firmware is provided as a zip archive. Extract the archive to a convenient directory on your computer. ***Figure 2*** below show the directory structure.

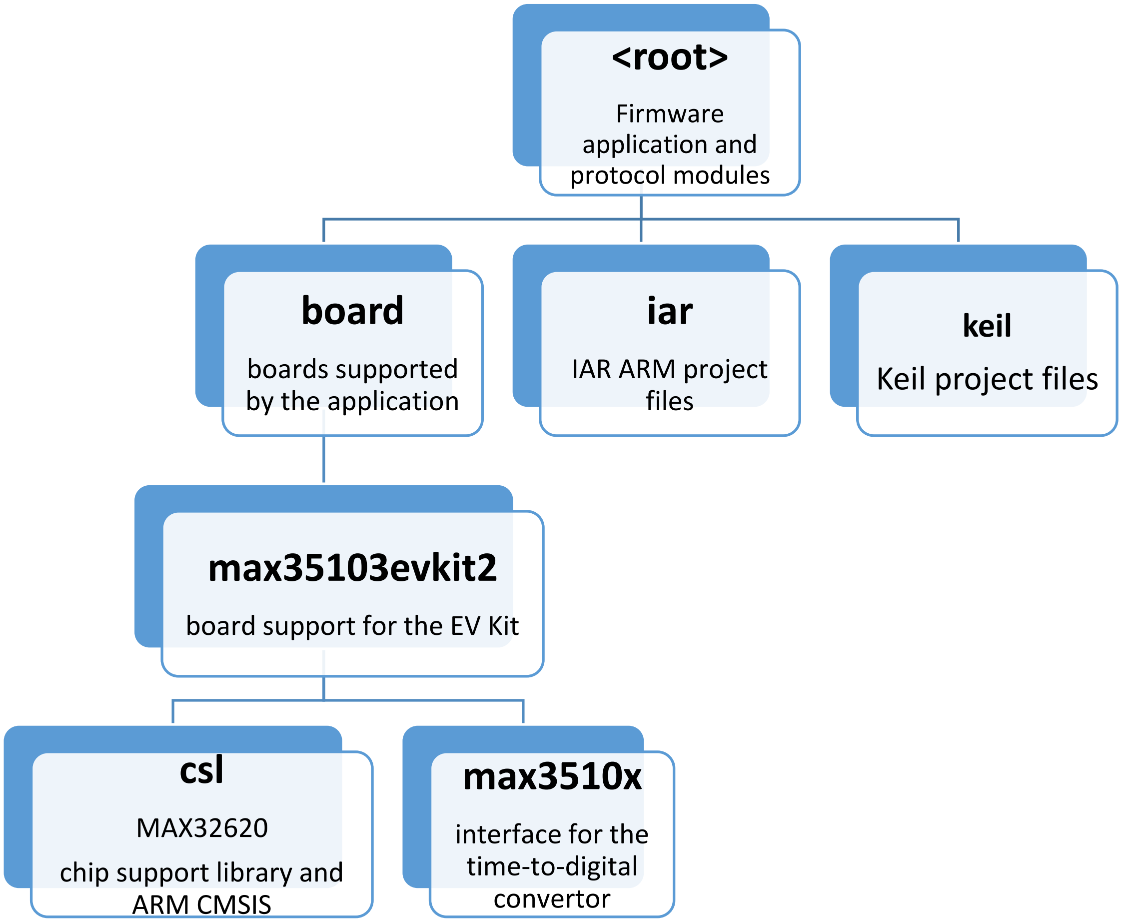


FIGURE 2 - FIRMWARE DIRECTORY STRUCTURE

Firmware Functionality

The volumetric application will power the attached irrigation water valve via the solid state relay circuit as soon as power is applied. It will then continually record the amount of water flowing through the ultrasonic transducer assembly via the MAX35103. When the volume of water exceeds the amount set by the two 10-position switches, the application will turn off the water valve. Functionally it repeated once power is cycled.

The switches indicate the amount of water in gallons as follows:

$$Water\ Volume\ (gallons) = S1 * 1000 + S2 * 100$$

The MAX35103EVKIT2 and volumetric firmware example is intended to be run while inserted into a residential irrigation system with power coming from an irrigation controller. The irrigation controllers are typically programmed to provide power to the irrigation valve for a set amount of time. This time period should be set long enough to allow enough water to flow.

main.c contains the high-level volumetric application.

board.c contains initialization and functions specific to the MAX35103EVKIT2 board.

transducer.c contains MAX35103 register initialization data and mathematical model specific to the ultrasonic transducer assembly included in the kit.

The CSL directory contains the chip specific support library for the MAX32620 MCU.

The max3510x directory contains a portable library for the MAX35103 time-to-digital converter.

Transducer Mathematics

The purpose of this section is to show how you can obtain water flow speed and speed-of-sound data using only the time measurements provided by the MAX35103.

Water flow through the ultrasonic transducer assembly is based on measuring the time it takes a sound wave to travel between the two transducers. The MAX35103 can measure this time with a resolution of 3.82ps.

Flow is detected when the time measured between the transducers is different in one direction verses the other. The difference is caused by the contribution of the water speed to the sound wave speed. It is increases overall speed in the direction of water flow, and decreases it by the same amount in the direction opposite of water flow.

The MAX35103 only provides acoustic propagation time information. This data must be converted to water volume over time. In order to do this, a mathematical model of the transducer is necessary. Most of the data for this model will come from the mechanical specifications of the transducer assembly. A cross-sectional view of the ultrasonic transducer assembly included in the MAX35103EVKIT2 can be seen in ***Figure 3.***

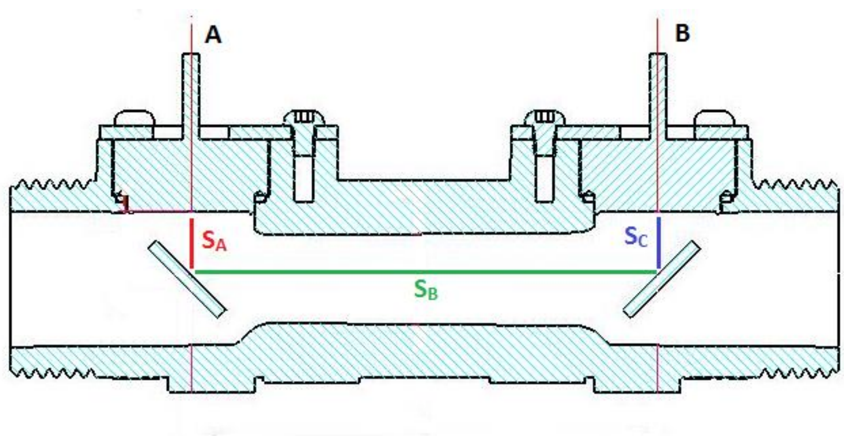


FIGURE 3 - ULTRASONIC TRANSDUCER ASSEMBLY

The assembly consists of two ultrasonic transducers, **A** and **B**. Sound waves are emitted by transducer **A** and detected by transducer **B** on the first measurement cycle and then emitted by transducer **B** and detected by transducer **A** on the second measurement cycle. These two measurements are the only two inputs to the mathematical model needed.

In reality, sound waves travel in all directions from the emitting transducer, but modeling this would be difficult and ultimately unnecessary. For most applications, all that is needed is a straight-line approximation of sound wave propagation. $\mathbf{S_A}$, $\mathbf{S_B}$, and $\mathbf{S_C}$ are the three line segments that represent the predominate path of sound energy. $\mathbf{S_A}$ defines the sound path between transducer **A** and reflector **A**. $\mathbf{S_B}$ defines the sound path between reflector **A** and reflector **B**. $\mathbf{S_C}$ defines the sound path between reflector **B** and transducer **B**.

The acoustic path of segments $\mathbf{S_A}$ and $\mathbf{S_B}$ is perpendicular to the water flow through the assembly. This means that the contribution of these segments to total acoustic propagation time isn't influenced by water flow through the assembly. Segment $\mathbf{S_B}$ is collinear with water flow and is the only segment that imparts water flow information into total acoustic propagation time.

Herein lies another simplification of reality in the mathematical model: Water flow is assumed to be laminar and collinear along segment $\mathbf{S_B}$. In reality, turbulence exists and will impact the speed of the acoustic wave in varying degrees at different points along the acoustic path. Turbulence may also change in relation to flow rate, temperature, and pressure.

This simplification will introduce some error into the final result. In the case of the irrigation application described here, this error is assumed to be acceptable. However other applications may require a more sophisticated model and/or error compensation based on calibration data.

We'll define $\mathbf{L_C}$ (collinear length) to be the length of segment $\mathbf{S_B}$. $\mathbf{L_P}$ (perpendicular length) is defined as the length of segment $\mathbf{S_A}$ and also segment $\mathbf{S_B}$. Two equations can be written to describe propagation time in each direction (from **A** to **B**, and from **B** to **A**).

eq.1: $$t_{ab} = \frac{L_c}{s_s + s_w} + \frac{2 \cdot L_p}{s_s} + \mathrm{Z_d}$$

eq.2: $$t_{ba} = \frac{L_c}{s_s - s_w} + \frac{2 \cdot L_p}{s_s} + \mathrm{Z_d}$$

$\mathbf{S_s}$ is the speed of sound through the assembly

$\mathbf{S_w}$ is the speed of the water from left to right (**A** to **B**)

$\mathbf{t_{ab}}$ and $\mathbf{t_{ba}}$ is the propagation time from **A** to **B** and from **B** to **A** respectively. These are the values given by the MAX35103 time-to-digital converter.

$\mathbf{Z_d}$ is the total electrical signal delay imposed by the MAX35103, the transducers, and any circuitry in between.

Equation 1 describes the time it takes for the ultrasonic wave to travel from **A** to **B**. Equation 2 describes the time it takes for the ultrasonic wave to travel from **B** to **A**. The only differences between the two equations is the sign of $\mathbf{S_w}$,that is, the speed of water flow from **A** to **B**. If water flow is zero, you can see that both equations become identical along with $\mathbf{t_{ab}}$ and $\mathbf{t_{ba}}$.

We'll make one final simplification to the model. We'll assume that $\mathbf{Z_d}$ is negligible compared to the other two terms in the equation. In a typical system, Z_d is in the 20-50ns range. For the transducer assembly provided in the MAX35103EVKIT2, the typical acoustic propagation time is around 62uS. In this case, $\mathbf{Z_d}$ is more than thee orders of magnitude smaller than the sum of the other terms, so it's safe to ignore.

The next step is to set $\mathbf{Z_d}$ to zero and solve both equations for $\mathbf{S_s}$. We want to do this in order to isolate and cancel $\mathbf{S_s}$ from the equation which will leave us with only $\mathbf{t_{ab}}$ and $\mathbf{t_{ba}}$ as function inputs.

eq.3:

$$s_s = \frac{L_c + 2 \cdot L_p - s_w \cdot t_{ab} - \sqrt{8 \cdot L_p \cdot s_w \cdot t_{ab} + \left(s_w \cdot t_{ab} - L_c - 2 \cdot L_p\right)^2}}{2 \cdot t_{ab}}$$

$$s_s = \frac{L_c + 2 \cdot L_p - s_w \cdot t_{ba} - \sqrt{-8 \cdot L_p \cdot s_w \cdot t_{ba} + \left(s_w \cdot t_{ba} - L_c - 2 \cdot L_p\right)^2}}{2 \cdot t_{ba}}$$

Next, we set both equations equal and solve for $\mathbf{S_w}$:

eq.4: $s_w =$

$$\frac{\left(4 \cdot L_p + L_c\right) \cdot (t_{ab}^2 + t_{ba}^2) - \left(6 \cdot L_c + 8 \cdot L_p\right) \cdot t_{ab} \cdot t_{ba} + (t_{ab} + t_{ba}) \cdot \sqrt{\left(2 \cdot L_c^2 - 16 \cdot L_c \cdot L_p - 32 \cdot L_p^2\right) \cdot t_{ab} \cdot t_{ba} + \left(L_c^2 + 8 \cdot L_c \cdot L_p + 16 \cdot L_p^2\right) \cdot (t_{ab}^2 + t_{ba}^2)}}{4 \cdot t_{\mathrm{ab}} \cdot t_{\mathrm{ba}} \cdot (t_{\mathrm{ab}} - t_{\mathrm{ba}})}$$

Equation 4 looks complicated, but much of it simplifies into coefficients multiplied by terms involving $\mathbf{t_{ab}}$ and $\mathbf{t_{ba}}$. The coefficients are highlighted in red.

An implementation of this equation can be found in transducer.c.

It's important to note that the above equations assume that the speed of sound through the medium doesn't change significantly from the **A** to **B** measurement to the **B** to **A** measurement. Since the speed of sound through the medium is influenced by temperature and pressure, these quantities are assumed to be constant through the measurement period as well.

The MAX35103 can typically perform both measurements in less than 200uS. This allows for the above assumption for the vast majority of flow measurement and speed-of-sound measurement applications. Applications that are subject to extremely high medium accelerations or density/temperature changes relative to flow rate will need to expand upon the model presented here.

Equation 4 gives the speed of the water along segment $\mathbf{S_B}$. Most applications, including the volumetric example application, require volume. Equation 5 below converts linear speed to volume per sample period.

eq.5: $$V = s_w \cdot r^2 \cdot \pi \cdot t_s$$

r is the radius of the transducer assembly along segment $\mathbf{S_B}$.

t_s is the sampling period.

The mathematical method described in equations 1 through 4 can also be used to calculate the speed of sound , **S_s**. First, solve for **S_w**, then isolate **S_s**

eq.6: $$s_S = \frac{(4 \cdot L_p + L_c) \cdot (t_{ab} + t_{ba}) + \sqrt{(2 \cdot L_c^2 - 16 \cdot L_c \cdot L_p - 32 \cdot L_p^2) \cdot t_{\mathrm{ab}} \cdot t_{\mathrm{ba}} + (L_c^2 + 8 \cdot L_c \cdot L_p + 16 \cdot L_p^2) \cdot (t_{\mathrm{ab}}^2 + t_{\mathrm{ba}}^2)}}{4 \cdot t_{\mathrm{ab}} \cdot t_{\mathrm{ba}}}$$

Notice that the coefficients that appear in equation 6 are also present in equation 4 and the term under the radical is the same.

While this discussion hasn't mentioned units, the transducer functions use meters/second for water speed and cubic meters for volume. The volumetric example application itself converts this to gallons per sample period.

Building the Firmware with IAR

The volumetric example application can be built and debugged with IAR ARM. The IAR project file, volumetric.eww, can be found in the IAR subdirectory.

First, select ***volumetric*** project from the workspace drop-down list. Select 'Make' from the right-click context menu.

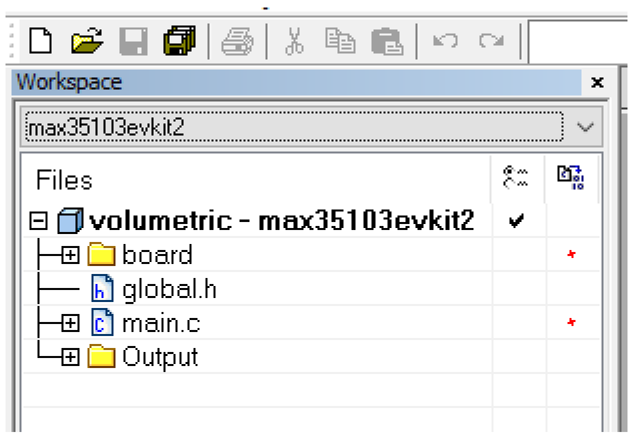


FIGURE 4 - SELECT VOLUMETRIC PROJECT

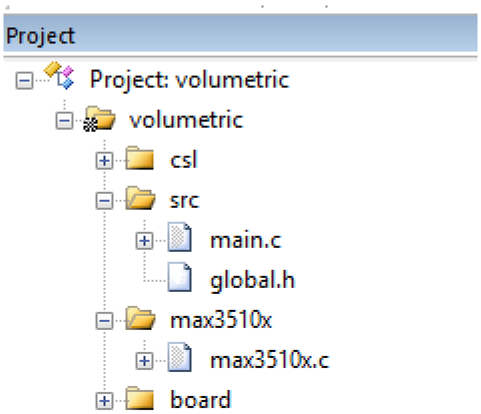
It will also be necessary to configure IAR according to the JTAG adapter that you have. The MAX35103EVKIT2 features a standard 10-pin JTAG ARM header for debugging and flashing. This can be done via the project options dialog box.

Building the Firmware with Keil uVision

The volumetric example application can be built and debugged with Keil uVision. The uVision project file, volumetric.uvprojx, can be found in the keil subdirectory.

First, select the ***volumetric*** folder under the project key from the workspace drop-down list. Select 'Build Target' from the right-click context menu.

It will also be necessary to configure Keil according to the JTAG adapter that you have. The MAX35103EVKIT2 features a standard 10-pin JTAG ARM header for debugging and flashing. This can be done via the project options dialog box.



Programming and Debugging

There are two methods for programing and debugging the MAX103EVKIT2. One uses the USB port and the other requires an external ARM JTAG adapter, like a Segger J-Link.

The USB connector exposes a CMSIS-DAP interface which consists of a debugger interface, and serial port, and a mass storage device. Binary images built for the MAX32620 MCU can be programmed by dropping the image onto the mass storage device as if it were a flash drive. CMSIS-DAP capable debuggers like Keil uVision can use the debugger interface to program and debug images.

J1 is a standard 10-pin ARM JTAG connector that allows debugging and programing through any SWD capable JTAG adapter that supports the MAX32620. The Segger J-Link can be used with both IAR and Keil via this header. An optional 20-pin to 10-pin adapter board, like the Olimex ARM-JTAG-20-10, may be necessary.

Hardware Configuration

The MAX35103EVKIT2# PCB must be connected to the ultrasonic flow body as described in the MAX35103EVKIT2# Datasheet. ***Figure 5*** shows the connections available on the MAX35103EVKIT2# PCB.

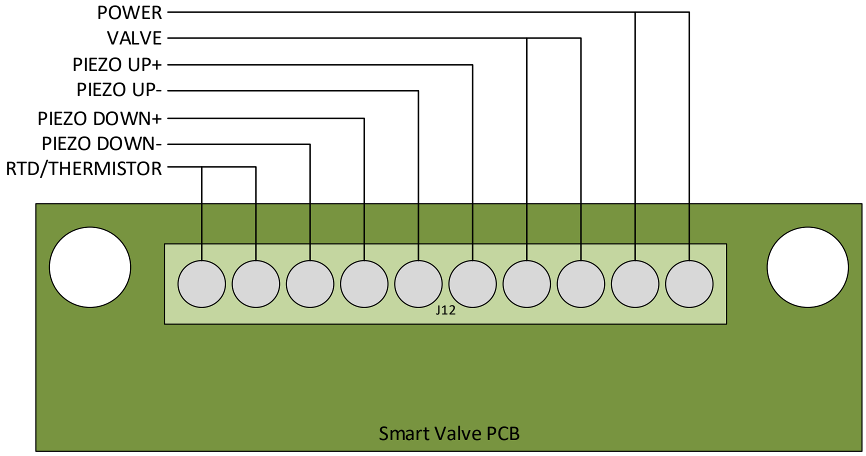


FIGURE 5 – SMART VALVE J2 PINOUT

- POWER should be connected to a 6-24VAC or DC source capable of supplying 200mA (most of this power is needed to activate the water valve solenoid).
- VALVE can be left unconnected.
- PIEZOP UP +/- should be connected to one of the flow body transducers
- PIEZO DOWN +/- should be connected to the other flow body transducer.
- RTD/THERMISTOR can be left unconnected.

Please see the MAX35103EVKIT2 datasheet for details about the hardware.