Converting Analog Controllers to Smart Controllers with the TMS320C2000 DSPs

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ABSTRACT

Modern applications demand faster, cheaper, and better motor control systems, and the performance demanded from embedded motor controllers is ever increasing. Programmable controllers offer the unique opportunity to improve performance, reduce cost, and enable designers to improve the efficiency of motor control systems. Such performance objectives typically need advanced algorithms that are computationally intensive and are best implemented on digital signal processors (DSPs).

For most engineers looking to implement control algorithms on DSPs, they are faced with a significant barrier – a definite lack of comprehensive information on the process of achieving the conversion.

Texas Instruments (TI)™ has constructed a comprehensive portfolio of control solutions with the TMS320C2000 DSP controllers, to assist with this conversion process. This application note provides an overview of the process used to convert an existing legacy analog or microcontroller-based solution into a DSP-enabled solution.

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1 Motivation

Modern high-performance motor controllers are expected to concurrently achieve several objectives. They must meet or exceed the dynamical specifications, and in addition, they must satisfy several other requirements. Examples are high efficiency, power factor, and electromagnetic compatibility (EMC).

To meet all these requirements, designers are turning to mathematical algorithms that are computationally demanding.

Digital signal processors provide an excellent means to implement controllers to meet this goal, but one of the major barriers that designers are faced with is the lack of a clear process and documentation on how to bring everything together. There are several excellent application examples, which describe specific applications. Several excellent textbooks discuss, in detail, the mathematics needed to model, design, and analyze discrete time-sampled data controllers.

However, all of these seem to either assume that the designer has either already implemented the conversion from the analog control system to a digital one, and just needs to know how to design the controllers, or has a specific application that is served exactly by a specific application example.

This application note aims to provide a bridge to help designers make the conversion; however, it does not intend to be adequate to describe in any detail the mathematics of discrete controllers, for example. For that background, the reader should refer one of the several textbooks on the subject, included in the references section of this application note.

Texas Instruments has put together a comprehensive portfolio of solutions to help, and this application note will point to several of those for typical examples.

2 Analog Controllers vs Digital Controllers

In order to convert analog controllers to digital controllers, the first step is to gain an understanding of the strengths and weaknesses of both forms of controllers.

2.1 Comparative Strengths of Digital Controllers

Digital controllers offer several advantages, which make a very convincing case for implementing new controllers with digital techniques – and converting existing analog controllers to new, digital implementations.

Some of these advantages are:

- **Programmability brings new opportunities to the table:** Programmable DSP controllers offer new capabilities, such as implementing advanced algorithms for motor control, which enable higher performance, and lower energy consumption, among other things.
- **Digital controllers are immune to drifts:** Digital controllers work with elements that operate in saturation, well outside the linear operation. As such, their functioning is substantially unaffected by either time or temperature drifts. Equations in software do not drift, so the definitions of the control laws remain consistent, unlike analog controllers.
- **Software can automate calibration:** Even with digital controllers, there is a significant amount of analog circuitry wrapped around the controller. However, software implemented on programmable controllers can calibrate out the inaccuracies, and software can automate this calibration process. This lowers the cost of manufacturing by eliminating a manual calibration step.

- **Ease of implementation:** Functions are easily implemented in software. It is far easier to code the equation ‘x=y+z;’ in software than it is to design an analog circuit to do the addition.
- **Faster time to market:** Programmable digital controllers make it possible to leverage existing off-the-shelf controllers, which allow the fastest realization of a design. In addition, the design of controllers is often an iterative process, with repeated design and test steps, until the specifications are met. Such an iterative process can be executed very rapidly by means of a software-configurable controller. Such a controller can be configured in minutes, versus a circuit change, which is not easy.

  Trimming gains can also be done on-line, which gives designers a friendly means of changing the control system while observing the system response.
- **Control law changes are software updates:** During system design, often it becomes necessary to change the control law, beyond just changing the gains. A new structure may be needed, or a boundary condition must be covered. Making changes to analog controllers is a very slow process. For programmable controllers, it is a matter of designing the controller, and then changing the coefficients in software. Flexibility during design is key to faster system design.
- **Far less sensitive to component tolerances:** Digital controllers are far less susceptible to component tolerances. Since they implement algorithms in software, gains and parameters are far more consistent and reproducible.

2.2 Digital Controller Issues Needing Management

Digital controllers require somewhat of a new approach, and there are considerations that must be taken into account when designing a system with a digital signal controller.

- **Quantization affects controller implementation:** Controllers implemented in both fixed and floating-point DSPs are affected by quantization. For fixed-point numbers, the number of bits used to represent the number quite directly determines the precision of the representation. Designers must understand and manage how this precision affects their control system.

  Fortunately, new 32-bit DSP controllers such as the TMS320F2812 offer designers a 32-bit computation capability for control – this makes quantization all but disappear. At 32 bits, resolution is 1 part in 4,294,967,296 which corresponds to a precision of 0.0000000232% – this is usually adequate for most controllers.

  Contrary to first appearances, floating-point processors do not necessarily offer better precision. Many 32-bit wide representations of floating-point numbers have 24 bits for the mantissa, and this is far less resolution than a fixed point controller for the same number of bits. Floating-point numbers excel in providing dynamic range, not resolution.
- **Digital controllers mean designers must work with discrete time math:** One of the most important challenges in working with discretized controllers is that designers must work in the z-plane, and get used to discrete time-design considerations. This is usually quite a rewarding experience; most system designers are able to readjust to using z-transforms and converting from s-plane to z-plane with ease.

3 Converting Analog Controllers to DSP based Digital Controllers

To convert an analog controller to a DSP-based digital control system involves understanding the existing system, and then creating an equivalent system with a DSP-based controller, that has the desired performance characteristics. Often this is a two-step process; first creating an equivalent, and then adding in additional features.

Converting a controller to an analog controller is best accomplished in a well-organized manner. Sections 3.1 through 3.8 outline the procedure to achieve this conversion. Also, Figure 1 provides a flowchart of this procedure.

3.1 System Identification

This step begins with an overview of an existing system. In this step, a rough specification must be assembled, with a succinct list of the specifications goals and objectives for the new design. It is useful to answer several questions at this point.

- Is this redesign simply a digitization of a controller, without substantial changes in the operation?
- On the other hand, is it part of a wider implementation upgrade?
- Are there new functions that are to be absorbed by this controller implementation?
- Does a dynamical specification exist?

If a formal dynamical specification does not exist, it would be useful to create one in this step.

Once a scope of the design effort is available, the next step is to understand the various control systems. So, for every sub-system, the following key parameters must be identified. Some of the key system parameters, quantities, and terms are defined below.

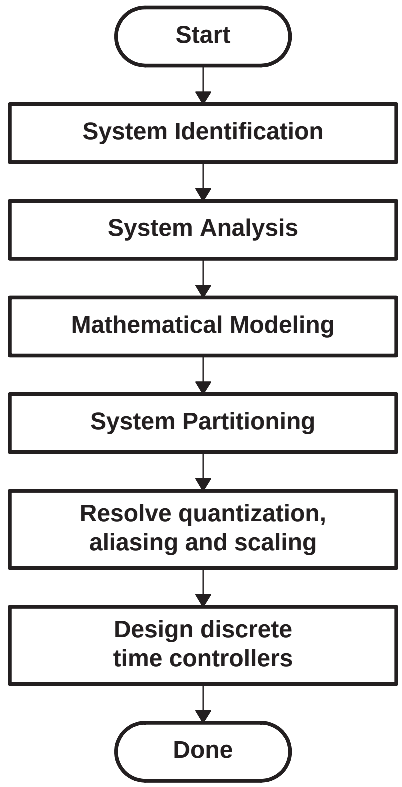


Figure 1. Flowchart for Converting an Analog Control System to a Digital Controller Implementation

- **Controlled quantities:** The controlled quantities are the variables that are controlled, either directly or indirectly. These are generally the output of the system, or intermediate quantities. For example, in a temperature control system, the temperature is the controlled quantity. On the other hand, if the temperature control is really just a means of controlling the reaction rate in a chemical reactor, then the temperature may still be the controlled quantity for a specific control loop, without being a formal output from the system. The output usually appears as one of the controlled quantities.
- **Set-point or reference value:** For every quantity that is controlled in a system, there is a corresponding desired value, or goal or target. The control loop is designed with the aim of matching the controlled quantities to the set points. The set-point represents, at any particular instant in time, the desired value of the controlled quantity. Sometimes, the set point may be generated within the system, especially for intermediate variables.
- **Feedback quantities:** Usually sensor outputs are fed back to the control loops. The control loop then responds to the variation between the “reference” or set-point, and the feedback value, and adjusts the system so that the two are in agreement.
- **Control outputs:** The output of the control loop drives the actuator in order to achieve the set point value, and drive the error to zero.

3.1.1 System Identification for the Example System in Figure 2

In Figure 2, the quantity that is controlled is the current in the inductor, and that is not the output of the system. This is a sub-system, part of a larger motor control system for example, which implements closed current loop control to establish a certain magnetic field in a motor. The sense resistor senses the current, and turns it into a voltage, which is fed back into the controller. The set point is provided by means of a voltage reference, which is proportional to the desired current.

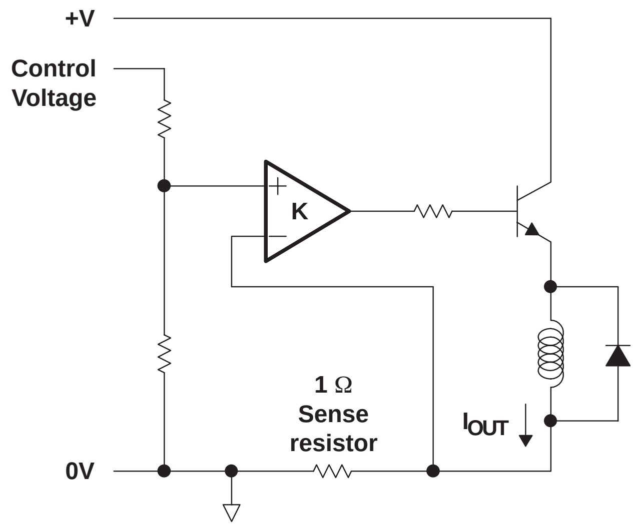


Figure 2. A Sample Control System

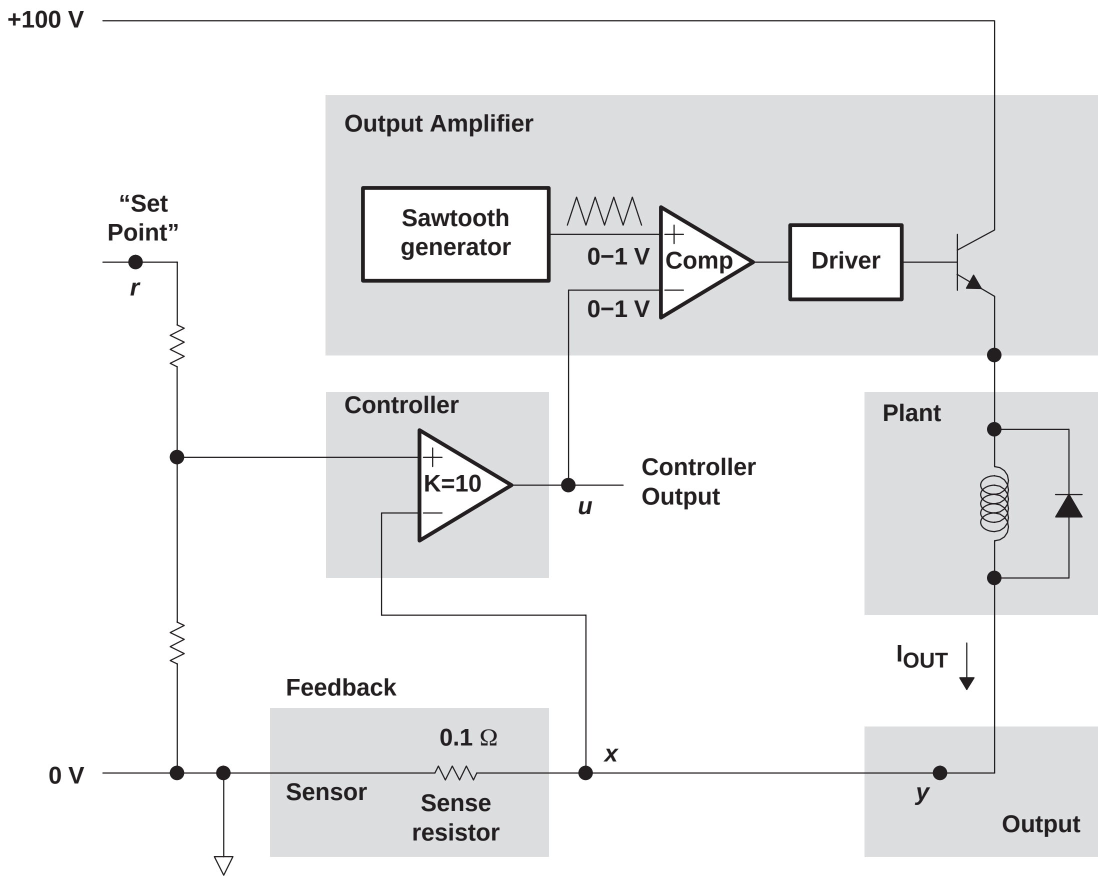


Figure 3. System Identification for Example System in Figure 2

3.1.2 Controller Selection

The controller shown in Figure 2 is shown as having a gain, and receiving the reference and feedback signals. The controller itself is shown separated out in Figure 4. The controller is the “intelligence” in the system, which is tasked with controlling the output to the desired value.

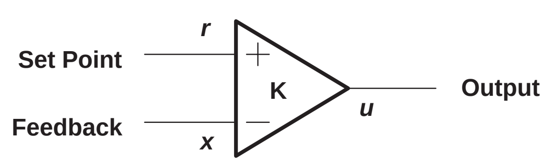
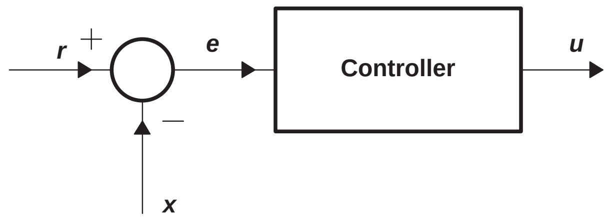


Figure 4. The Controller

If the output is greater than, or less than the desired value, the controller acts to correct the situation.

In most situations, the controller does not act upon either the reference or the feedback signal individually, but instead acts upon the difference between the two, which is defined as the control error. This configuration is shown in Figure 5.



$$e \equiv r - x$$

Figure 5. Error Based Control

Various control topologies are possible. For a review of various controller topologies, see 1-4 listed in the Reference section of this application report as a useful source of various possible configurations.

3.1.3 What Goes Inside that Box Marked "Controller"?

The controller creates the control output to accomplish the goal, which is to drive the controlled variable to the desired value. Various mathematical relationships are used to derive the output from the error value. Such a mathematical relationship is known as a control law. A control law describes the relationship between the set point, feedback value, and the output of the controller.

A variety of common control laws is used in industrial applications, and some of them are proportional, proportional-integral, and proportional-integral-derivative. These control actions are shown in Figure 6, Figure 7, and Figure 8. Other common configurations are lead, lag, or lead-lag controllers. The controller choice is governed by the system characteristics and the dynamical performance specifications.

Control Law

$$u = K_p \cdot e$$

Topology

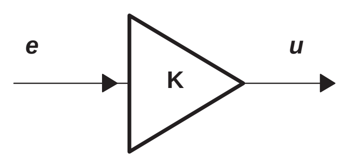


Figure 6. Proportional Controller

Control Law

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^T e(t)dt$$

Topology

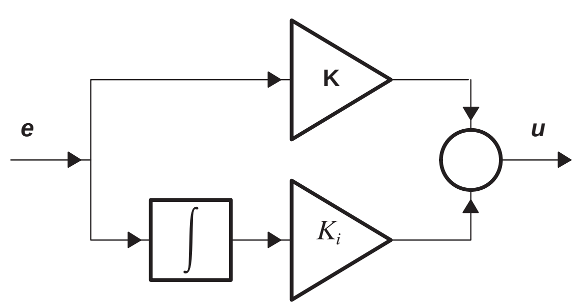


Figure 7. Proportional-Integral Controller

The addition of a derivative control action, in general, has the effect of improving system response to fast changes in the output, or in the reference. However, this also has the effect of increasing the sensitivity to noise, since a differentiator will differentiate any input or measurement noise in the system as well.

Control Law

$$u = K_p \cdot e + K_i \cdot \int e \cdot dt + K_d \cdot \frac{de}{dt}$$

Topology

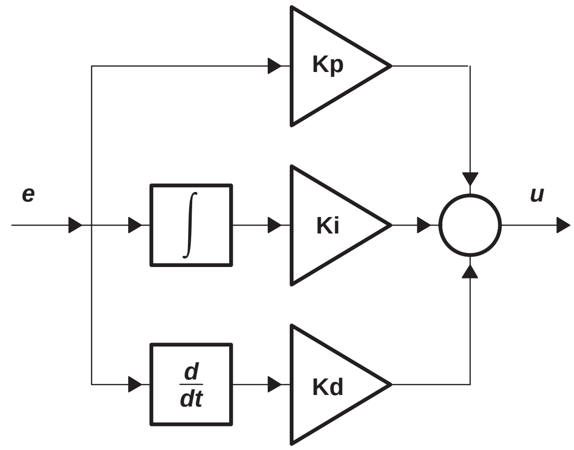


Figure 8. Proportional-Integral-Derivative Controller

3.2 System Analysis

The next step, after identifying key system parameters and quantities, is to seek out a mathematical description of the system, so that conversion to a digital implementation can be done. To describe the control loop, the techniques that must be used are either based on models of the system, or based on measurements made with a real system.

3.2.1 Create a Block Diagram

The first step, before creating a model, is to create a block diagram representation of the system. A block diagram simplifies the creation of a mathematical transfer function model for the entire system. An example of a block diagram representation for the sample system is shown in Figure 9.

The block diagram has several annotations on it. The ranges for various voltages are marked. Also, the gains for the amplifiers and other elements in the signal chain are identified. The idea is that the block diagram contains most of the information used to create a model of the system.

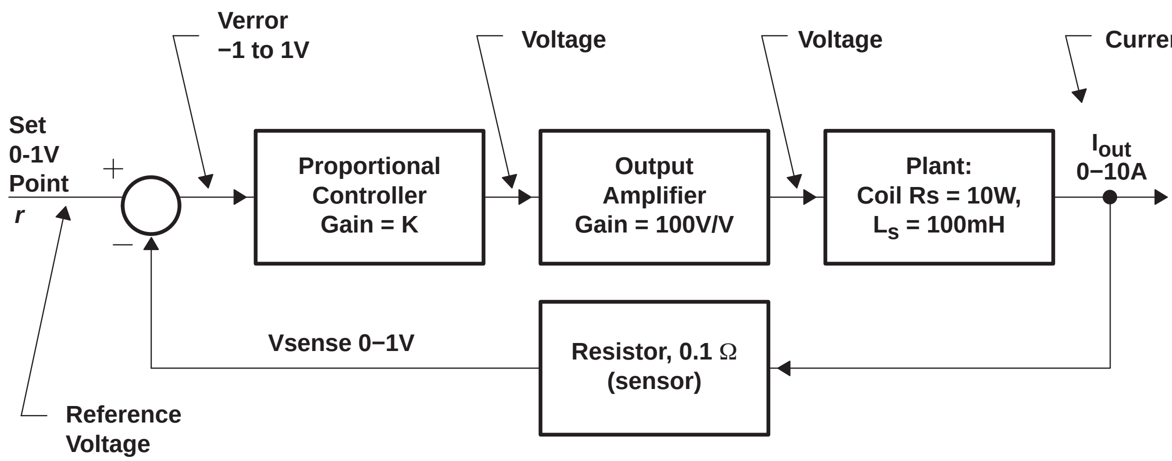


Figure 9. Block Diagram for Sample System in Figure 3

3.2.2 Identify Controllers Which are to be Converted into Digital Controllers

The next step is to identify the controllers that are the best candidates for conversion into digital software implementations. Most controllers are generally described by either linear or non-linear control laws. To obtain a discrete time domain representation, the simplest way is to write down an s-plane description, and then transform to a z-plane description. Once this is accomplished, a simple process can be followed to convert that to a difference equation.

The one consideration, which might prevent implementation of a digital controller, is if the control function has an extremely wide bandwidth. For instance, a control function to control a system that has significant dynamics at 20MHz may not be candidate for implementation on a 150MIPS DSP controller. For most motor control and mechanism control, the fastest dynamics are not the mechanical dynamics – these are an order of magnitude slower than the dynamics of the servo current loops. These electrical dynamics are usually of the order of several kHz at most. These are easily converted to digital software implementations, suitable for implementation on a programmable digital signal processor.

3.3 Create a Mathematical Definition for the System

Once a proper block diagram is assembled, then the next step is to describe the system mathematically. This involves creating transfer function models for the control systems. The topic of creating models for systems has been dealt with extensively in textbooks. See *Modern Control Engineering*, by K. Ogata in the References section for details.

For the system block diagram in Figure 9, the following are the components in the loop gain:

3.3.1 The Controller Gain

This is the gain of the controller chosen. For now, we assume that this controller has a simple proportional gain of K, and this gain will be chosen based upon the dynamical specifications desired.

3.3.2 The Output Amplifier

The output amplifier has a gain of 100V/V, since a PWM control voltage of 0−1V causes a duty cycle change from 0−100%, and the bus voltage is 100V. Therefore, a 0.5V change in the control output will cause a 50V change in the output to the plant. This is modeled as a pure proportional gain as well; any amplifier dynamics are neglected.

3.3.3 Plant Transfer Function

The plant is an R-L model for a simple coil, and the coil transfer function may be modeled as follows:

$$V_L^{(t)} = i(t) \cdot R + L \cdot \frac{di(t)}{dt} \tag{1}$$

This equation can be transformed via the Laplace transform, and that gives an algebraic equation, which can be written as:

$$V(s) = I(s) \cdot R + L \cdot sI(s) \tag{2}$$

Rearranging as a transfer function we have:

$$\frac{I(s)}{V(s)} = \frac{1/L}{s + R/l}$$
$$\frac{I(s)}{V(s)} = \frac{10}{s + 100} \tag{3}$$

Now, we substitute values for the constants R=10Ω and L=100mH, and have:

This is a so-called s-domain transfer function, and is very useful to model the plant. The plant has a simple pole at s= –100 and has a DC gain of 0.1. The output of the plant is current in amperes, and input is voltage in volts.

3.3.4 Sensor Gain

The output of the plant is converted into a voltage, so that it may be fed back to the control loop. In our case, the sensor is simply a resistor. Depending upon various application considerations, it could be a Hall Effect sensor, or a current transformer with a resistor in the secondary. To us, for now, it is more interesting to know that the mathematical description of this “current to voltage converter” – is governed by the following relationship (Ohm’s law):

$$V = I \cdot R \tag{4}$$

Thus the gain of the sensor is simply the resistance, and is 0.1 Volts per ampere.

3.3.5 Loop Gain

From a control system point of view, the description for the various system components is now compiled into the loop gain, and for our example system we may write the loop gain G(s) as:

$$G(s) = (K) \cdot (100) \cdot (0.1) \cdot \frac{10}{s + 100} \tag{5}$$

This may be then boiled down a little into the following form

$$G(s) = K \cdot \frac{100}{s + 100} \tag{6}$$

Equation (6) is a very important way of describing our system from a dynamical point of view. It represents all the gains and dynamics in the system, and allows the usage of several design techniques such as root locus, bode diagrams etc. for controller design. Once the controller has been designed, then the next step involves realizing the control system.

3.4 Partition the System into Hardware Components and Software Components

The next step, realizing a controller around a digital processor consists of deciding which portions of the systems will be digitized. The first step is to examine the system and then the controller that will be used to implement the system. Figure 10 shows a block diagram of the TI digital signal controller TMS320F2812. Therefore, when interfacing to our system, we make the following observations:

- PWM outputs can be used to control the switching transistor that is part of the output amplifier.

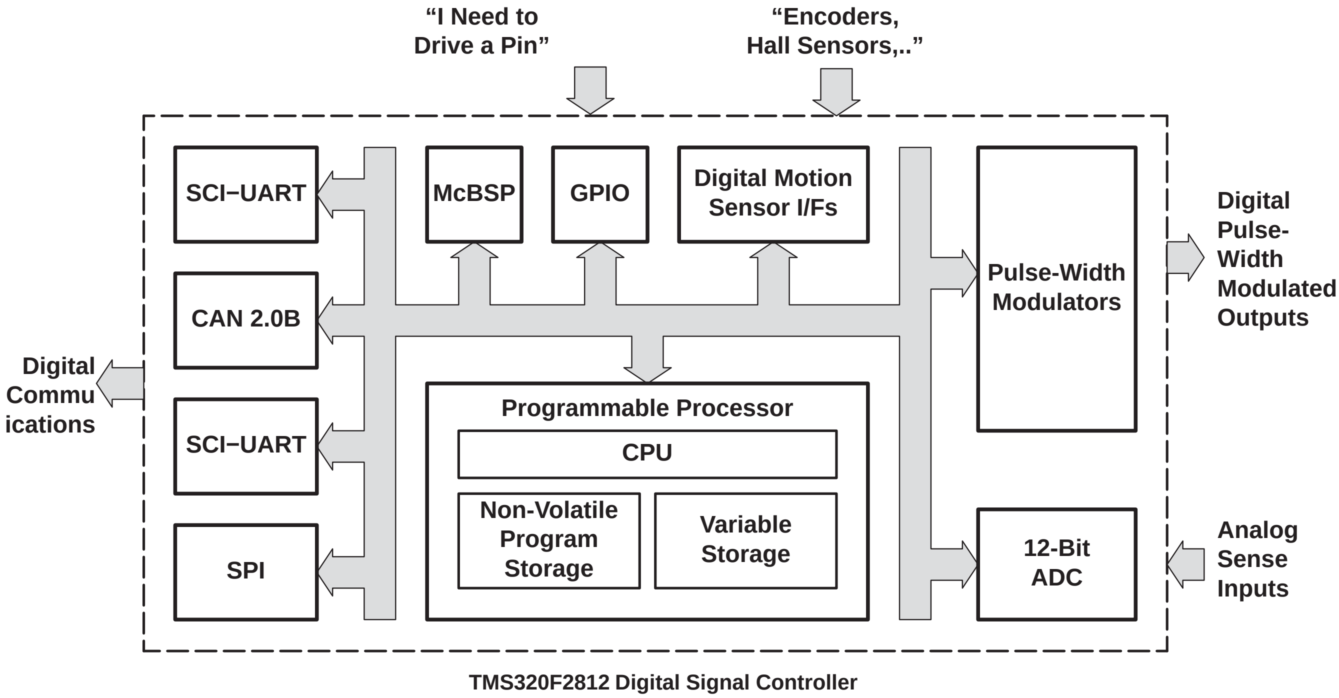


Figure 10. Block Diagram for a TMS320F2812 DSP controller

- Digital commands are transformed by the PWM logic, into duty-cycles. These duty cycles are quantized, but they are averaged out by the system time constants. The analog inputs on the analog-to-digital converter (ADC) will be the *window to the analog world,* looking out to the real world from within the digital software world. Anytime we want to find out the status or value of a variable such as current, or voltage, or temperature, in the external world, we will have to use this window. The value at these inputs is converted into a digital number, by the analog to digital converter.
- Since the ADC provides an analog input to the processor, and the PWMs constitute an analog output that is suitable to drive high power high current outputs, this constitutes a digital to analog interface. The processor then forms the part of the control loop on one side of this digital-to-analog interface. At this stage, the system can now be divided into a digital portion and an analog portion. This is shown in Figure 11.

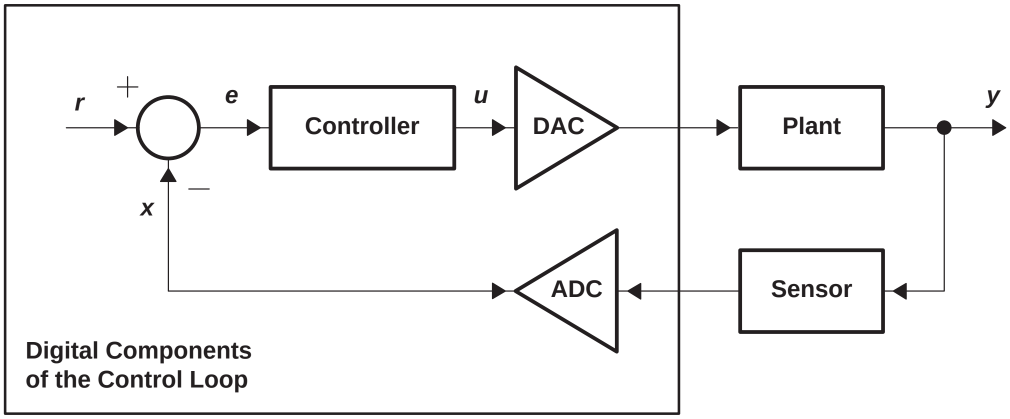


Figure 11. Digital and Analog Portions of a Control System

- To realize the most benefit out of making the conversion to a digital system, it is usually advantageous to convert as much of the control system into software as is possible, with the exception of the high power electronics, and the sensing circuitry. Any processing that was previously implemented as analog circuitry is best moved back into the controller software. For example, if there is a notch filter implemented to filter out a particular frequency, that filtering circuit could be eliminated by a software implementation of a notch filter, reducing component count. Figure 12 shows how the system in Figure 2 can be implemented using a digital signal processor. The controller's analog inputs are used to sense the feedback voltage and the reference input voltage. These voltages are then processed by the control algorithm. The software-based controller produces the output used to control the on-chip PWM logic. This PWM logic, outputs a PWM output at the pins of the controller, and this is then used to drive the switching element, via a driver. The driver is needed, since the switching element needs a large gate voltage or current. Secondly, in the configuration used, it will need a swing above the bus voltage.

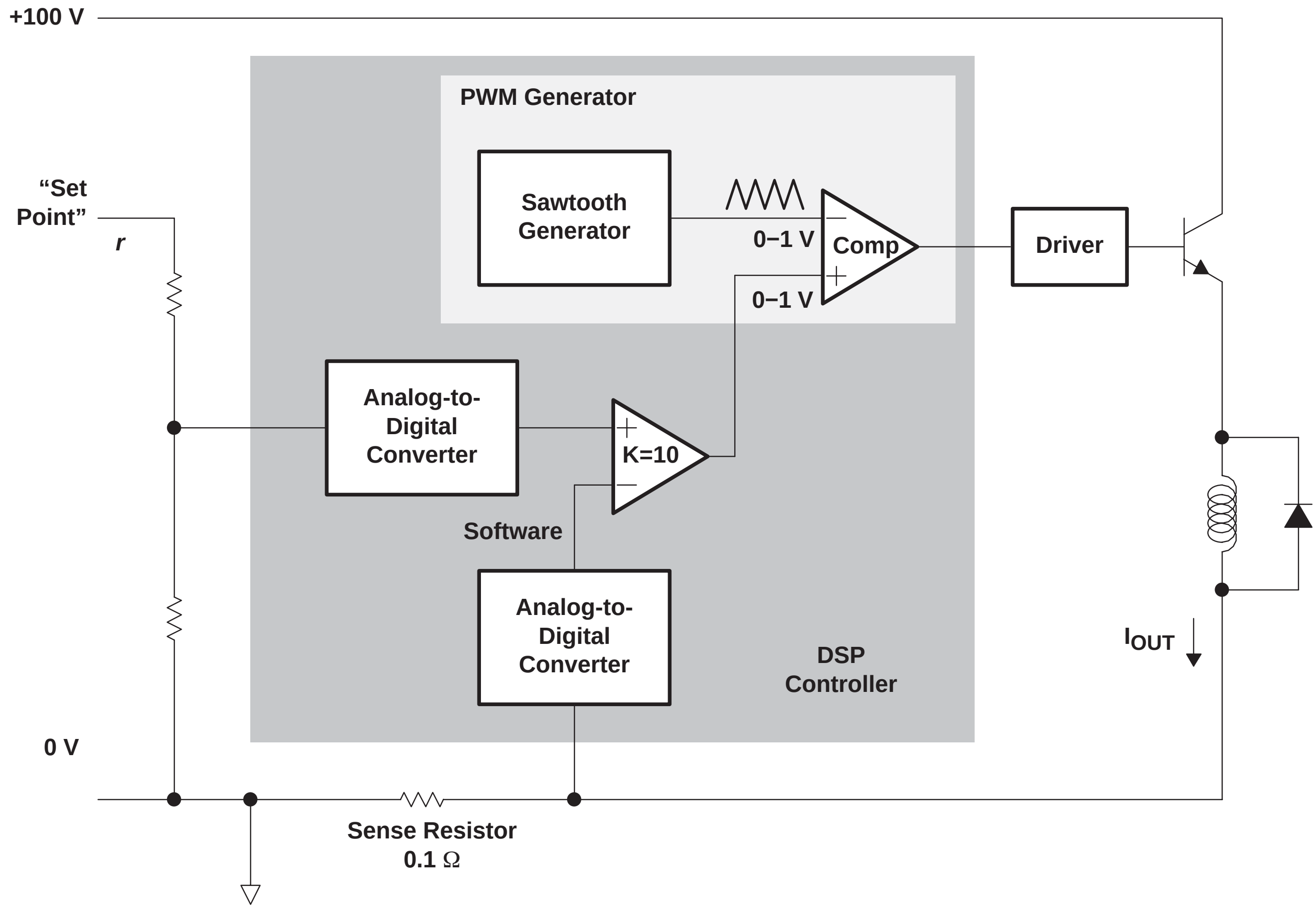


Figure 12. A Digital Implementation for the Sample System in Figure 2

In addition, it would also be useful to re-think the user interface at this point: Is the reference being generated by a potentiometer? On the other hand, is it a remote computer supplying it via a 4−20mA current loop? If so, there might be a possible optimization, by turning to a digital network connection to carry the command to this controller. The system partitioning for a real world software system is shown in Figure 13. The software block diagram is shown in Figure 14. All the control loop processing is done in software. The functions in hardware are all interfacing, physical voltage re-mapping, i.e., analog scaling, sensing and drivers for high voltage switching.

From a control loop perspective, vector control of a permanent magnet synchronous motor involves current loops, and speed loops with PI regulators generating the control action. There are also other monitoring and control actions.

The analog to digital converter is used to measure the currents in the motor windings and then that current measurement is translated by the on-chip ADC into a digital representation. This measured current value is then translated into a two phase synchronous reference frame that rotates synchronous to the rotor flux. That converts the sinusoidal currents to a pseudo DC values, and these are then regulated. The outputs of the regulators are then translated to the stationary reference frame, and then used to generate commands for driving the motor windings with voltages. These *voltages commands* are only software – the actual conversion to PWM happens on chip in the digital domain. Once that is done, the PWM is used to switch the bus voltage.

All these functions are implemented in software within the processor. The only analog functions that are signal processing of some sort are the anti-aliasing filters which are part of the analog signal chain, which are unavoidable.

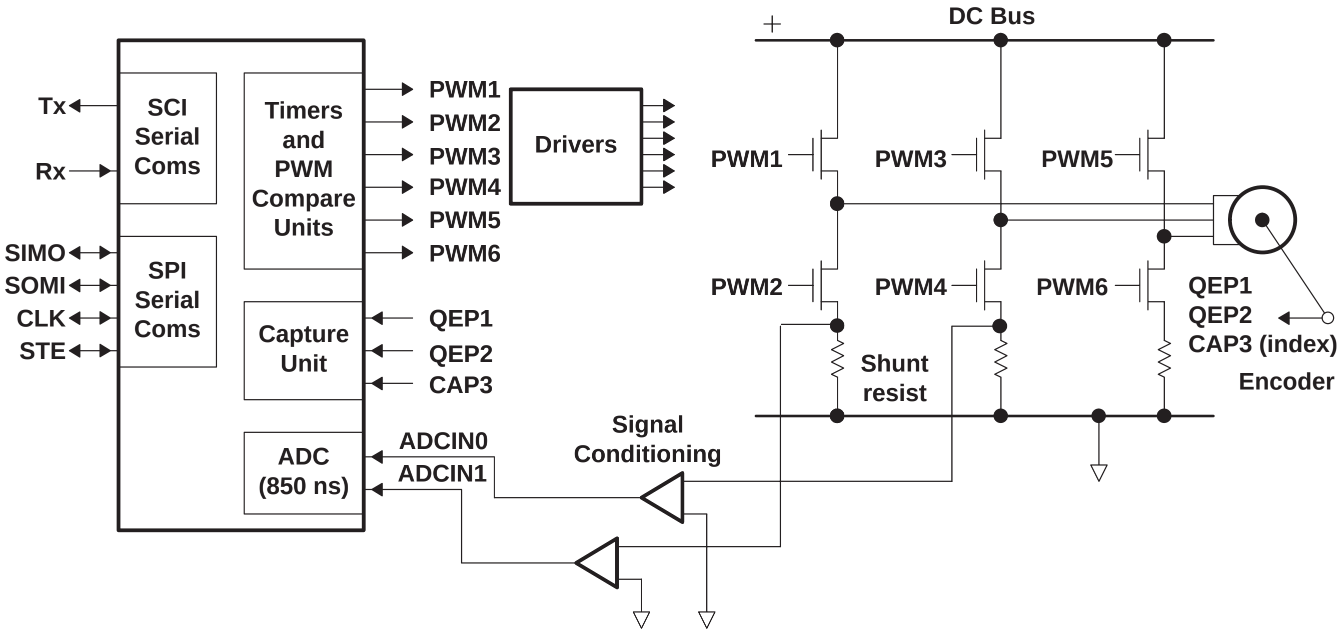


Figure 13. System Partitioning for Field-Oriented Control of a Permanent Magnet Synchronous Motor

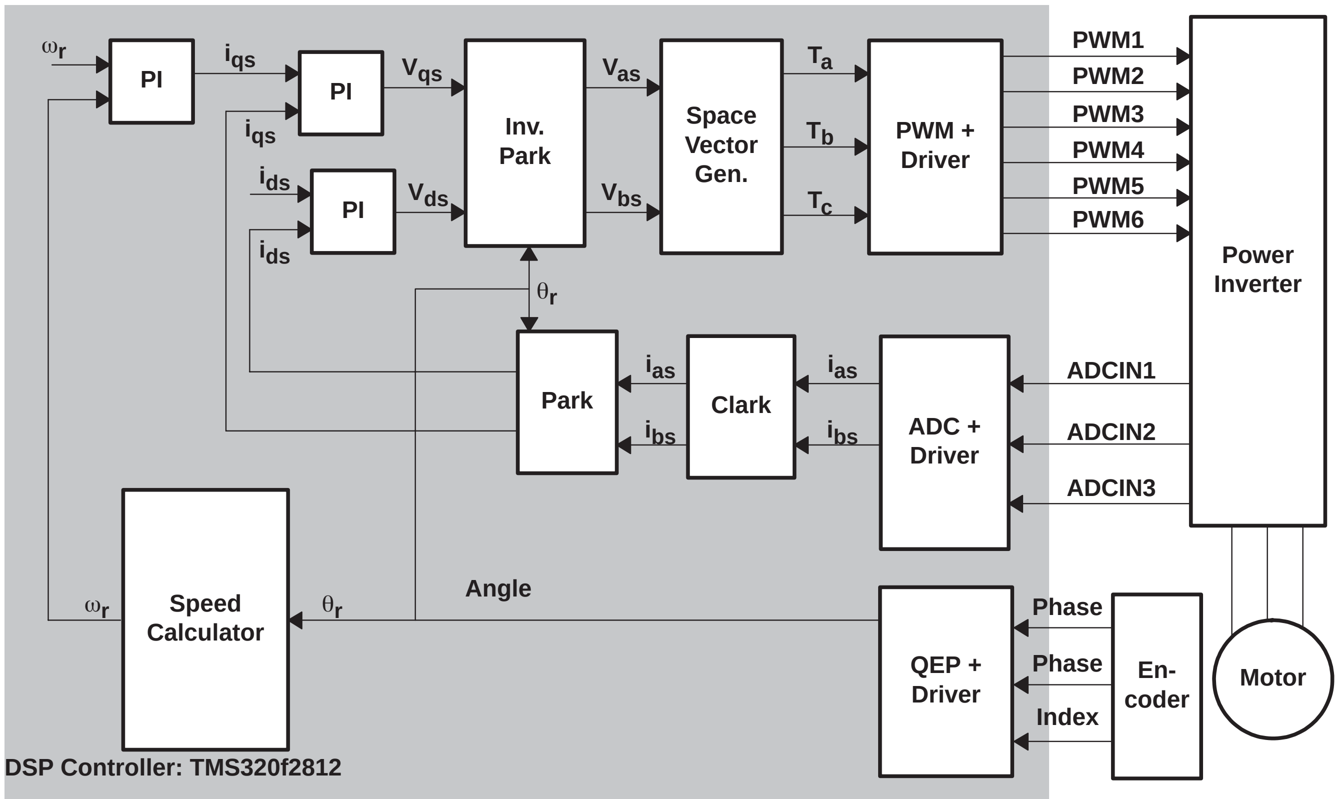


Figure 14. Software Block Diagram for the PMSM Field-Oriented Control

3.5 Quantization of Signals, Analog Range and Scaling

At this stage, the system is now close to the final form, in terms of the circuit diagrams. The interfacing must be examined and all the issues ironed out.

An important consideration is signal to noise ratio, and resolution. For control applications the signal being sampled is fed into an ADC, and then converted into a digital representation, i.e., a numeric value. At this point, a quantization is a fundamental part of the conversion process. When the ADC converts the signal to a digital form, it represents the value at the analog input pin, as a number between 0 and (2^N−1), where N is the number of bits of resolution that the analog-to-digital converter offers. This means that if you have a 4 bit converter, with an input range from 0V−3.3V, it will map all the analog values between 0V and 3.3 volts, into a number between 0 and 15. Thus, for all input voltages between 0V and 0.20625V the ADC outputs the code 0x0000. For all input voltages between 0.20625V and 0.41250V it outputs the code 0x0001. This creates the familiar staircase, shown in Figure 15. Information on the signals between 0V and 0.20625V is lost – the digital world is oblivious to anything in between. Similar things happen between each of the other threshold levels.

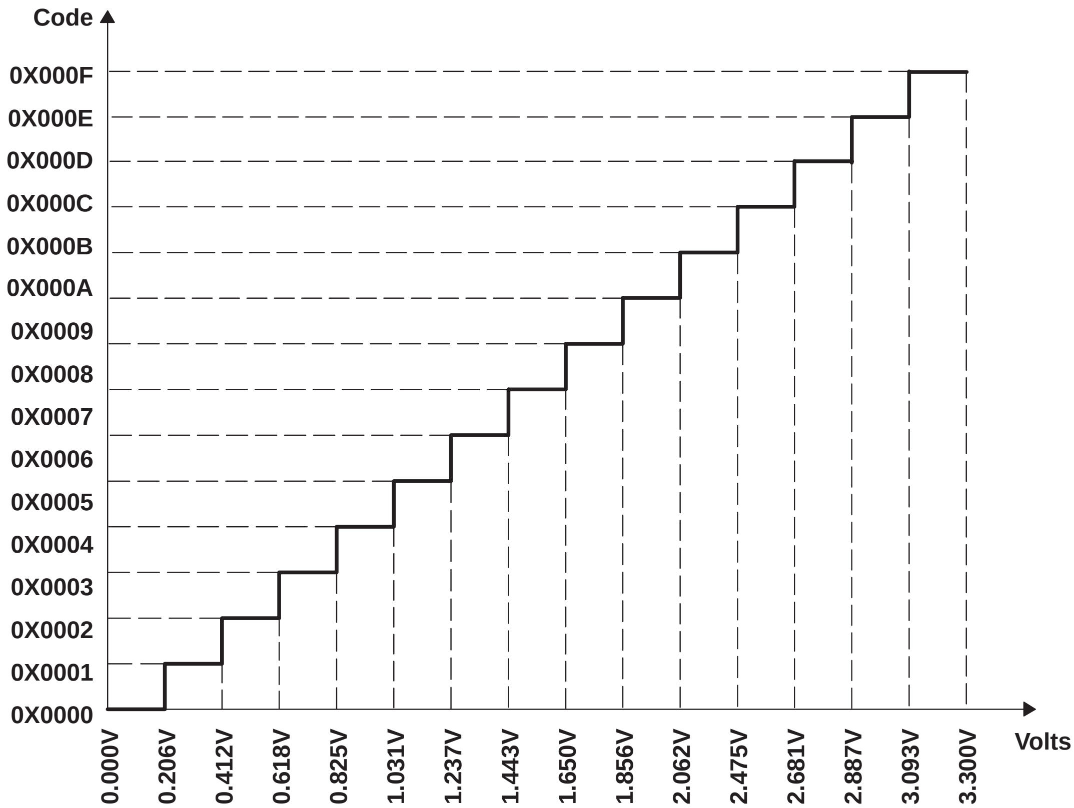


Figure 15. Quantization of Analog Signals During A-to-D Conversion With a Hypothetical 4-Bit Converter

This quantization effect means that a control signal that is sensed, with a possible range between 0.000V to 1.000V, will be converted into 5 steps. This is obviously non-optimal; it would be advantageous to scale the voltage to a range of 0V to 3.3V for the best representation, for the converter in Figure 15.

This is conditioned upon the fact that the control voltage only ever varies between 0V to 1V, including during transients, overloads, and all marginal conditions.

For a real converter, which has a 12-bit ADC, such as the ADC on the TMS320F2812, this is much less of an issue, but it still does get the best resolution by having a proper mapping.

Let us, for instance, suppose that in a motor control system, where the current in the winding of a motor is expected to range from −1A to +1A during normal operation, but during starts is expected to go from −2A to +2A. Allowing some margin, a choice for scaling would be to map the range of −2.5A to +2.5A to generate voltages of 0V to 3.0V (Since the converter on the F2812 DSP controller has an input range of 0−3.0V). Then if the sense resistor is 0.1Ω, then, the sense voltage generated is −0.25V to +0.25V. Therefore, an offset of 0.25V must be added, and then a gain of 6.0 would be needed. This must be done in analog circuitry, since this is physical re-mapping of voltages.

3.6 Anti-Aliasing Considerations

A phenomenon that is introduced into a control system, as a direct consequence of the sampling process, is aliasing. Aliasing can cause a number of undesirable effects, and is undesired most of the time.

The frequency spectrum is re-mapped by the sampling process, as indicated in Figure 16. Of special interest is the fact, that signal components with frequencies greater than one-half of the sampling frequency (f_s) are *folded back*. This means that any frequency that is greater than $f_s/2$ will cause a shadow or an alias in the range (0, $f_s/2$). This means that if such frequencies are present in, for instance, the feedback, then the controller will respond to these frequencies and the system response will be affected, most often, in a detrimental manner. Thus, with aliasing, the system will misrepresent signals with frequencies greater than $f_s/2$ as low frequency signals. That problem must be avoided by filtering out frequency components over $f_s/2$. In fact, for control systems it is almost mandatory to have a sampling rate that is well over four times the highest significant component present. For an example of how aliasing can generate a fictitious signal from under-sampling a high frequency signal, see Figure 17. A high frequency signal x(t) is under-sampled, and the sample stream contains data points at what essentially boils down to a beat frequency between the signal, and a multiple of the sampling frequency.

This drives the controller, and the controller will respond with control actions, thinking that the controlled plant is behaving erratically. This will cause havoc with the plant, which will then respond to the controller output.

The implications range from undesired oscillations in output, unexpected ‘bumps’ in the controlled quantity, to severe instability and system failure.

Aliasing must therefore be controlled to avoid such consequences. Anti-aliasing filters, accompanied by higher sampling frequencies, are used to avoid these ill effects.

This is easily achieved by adding simple RC filters, and well-chosen sampling frequencies.

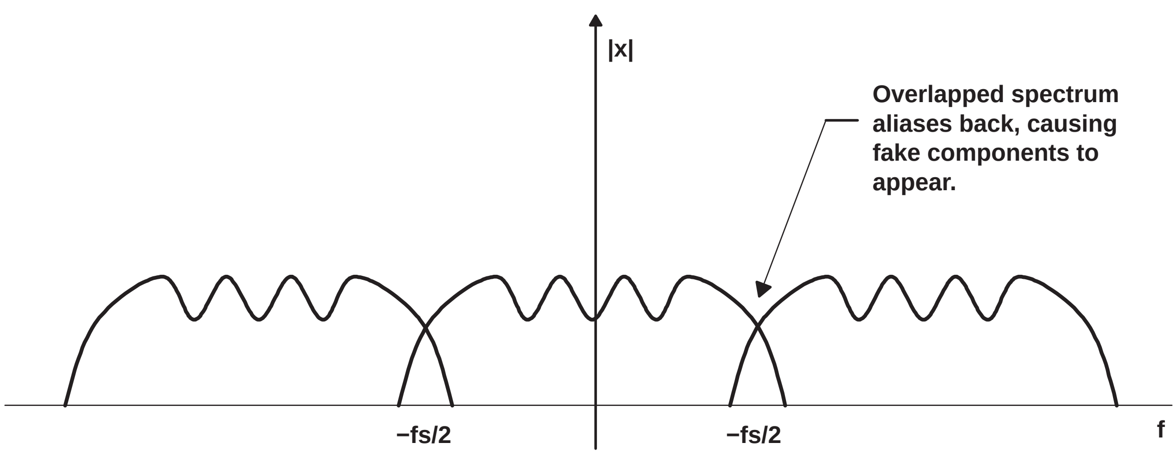


Figure 16. Frequency Remapping With Conversion to a Sampled Discrete Time System

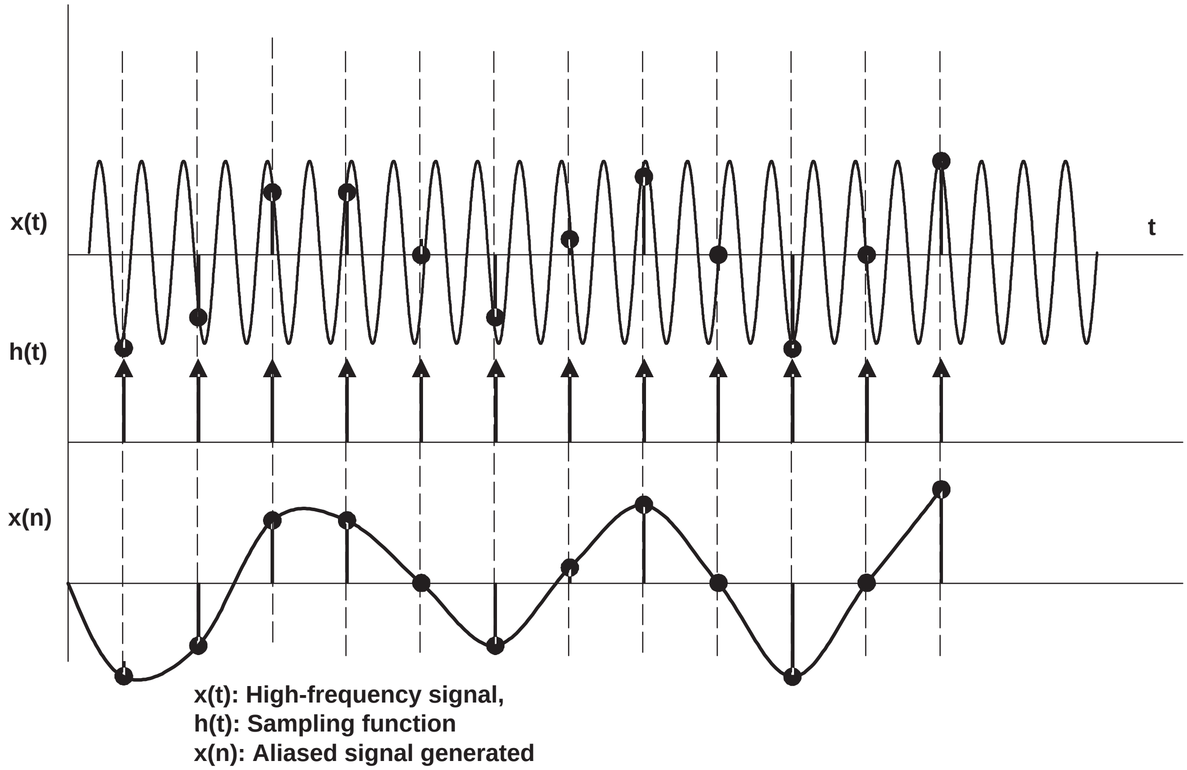


Figure 17. How Aliasing Generates a Fictitious Low-Frequency Signal

3.7 Design Discrete Time Controllers to Implement the Control Function

Several approaches are used in designing software controllers in the discrete time domain.

The first approach consists of designing continuous time controllers – the s-plane design – and then translating this to the z-plane, i.e., to the discrete time domain.

A number of mathematical techniques are used to perform this translation. Some of the most popular are mentioned in the following subsections. For detailed descriptions, examples, and theory, refer the references section.

Also known as Tustin's approximation, the bilinear transform involves substituting for 's' in a Laplace transform domain transfer function, and then simplifying to come up with a difference equation. This difference equation is then implemented.

$$s = \frac{2}{T} \cdot \frac{z-1}{z+1}$$

s = The Laplace transform variable

z= Z transform variable

T = sampling interval.

Other substitutions such as the zero-order hold are used; see the references 1−4 listed in the References section of this application report .

The matched pole zero technique consists of making the translation between the continuous time and discrete time domains, by attempting to find equivalent pole and zero locations in either plane.

Usually, the design of controls in the s-plane and translation to z-domain is a way to avoid redesigning a controller for translating an existing controller for implementation. However, the approaches that deal with designing controllers in discrete time domain give the most flexibility.

There are also design techniques, such as dead-beat controllers, which are only available in the discrete time domain.

Another approach, involving modeling the system as a state-space model, and converting the model to discrete time state-model, allows the designer to exploit techniques such as state observers to reduce or eliminate sensors.

As mentioned at the outset, this application report does not attempt to supply descriptions of the actual mathematics of the conversion, since this topic is covered in many excellent text books on the subject. Some of these are mentioned in the references section.

3.8 Choosing Sampling Rates in a Quantized Discrete Time Domain System

To discretize the controller, the designer must choose a sampling frequency that allows the designer to convert to a discrete form.

Obviously, the criterion for avoiding aliasing are important. However, in control systems, it is almost always necessary to go far beyond the sampling rates suggested by the Nyquist criterion.

In choosing a sampling frequency, determine the highest frequency component that is present in the system (ω_H). Then the sampling frequency chosen must be greater two times this. For example,

$$\omega_s > 2\omega_H$$

However, this does not usually allow the proper functioning of a control system. It is common practice to choose a frequency that is at least $4\omega_{H,}$ for first order systems. For higher order systems, e.g., second order systems, a common choice is a sampling rate that is 10 times faster than the highest frequency component present. This is driven by the requirements to keep the inter sample deviations to an acceptable minimum.

To illustrate this effect, Table 1 shows what happens to the controller coefficients as the sampling rate is changed.

For this example, a simple one pole transfer function is discretized.

The transfer function is

$$G(s) = \frac{100}{s + 100}$$

This was discretized in Matlab with the following command:

```
MATLAB>>SYSD= c2d(tf([100],[1 100]),Ts,'zoh')
```

Table 1. Discrete Time Controller Coefficients

Sampling Time Interval	Numerator	Denominator
0.01s	[0.632120]	[1.00000 −0.367879]
1.0 ms	[0.0951625]	[1.00000 −0.904837]
0.1 ms	[0.00995016]	[1.00000 −0.990049]
0.01 ms	0.00099950016	[1.00000 −0.999000]

At a properly selected sampling interval, the coefficients do not have significant issues, as we shall see. With over-sampling however, there arise significant resolution problems.

An examination of the coefficient magnitudes reveals the quantization effects. The first is a coefficient resolution issue. As the sampling rate is increased, the numerator coefficient starts getting smaller and smaller. At a sampling rate of 10µs, the coefficient has gone down to 0.00099950016. This in a Q15 representation (the best possible single precision resolution on a 16-bit processor) is represented as 0x0020. This means there is a 5-bit resolution for the coefficient.

This is a serious issue for 16-bit processors. On a 16-bit processor, efficiency dictates that we must have a 16-bit coefficient; multiple precision arithmetic is very cycle intensive. This leaves us with a choice of coefficient scaling that gives us only about 4-5 bits of resolution in the numerator.

These effects are the result of significant over-sampling. However, in certain cases, higher sampling rates may be justified. In such cases, employing 32-bit arithmetic will lead to far better numerical representation.

A 32-bit processor such as the TMS320F2812, that has native 32-bit representation for fractional numbers, does not have such issues dealing with the above situation.

4 Implementing Fixed-Point Arithmetic: F2812 and IQ Math Make it Easy

Many control algorithms are developed initially in floating-point versions, and then ported to fixed-point machines. Such scaling has traditionally been one of the roadblocks to implementers. Oftentimes, it presents an impediment to system implementers, that they avoid by not implementing advanced control strategies.

Fortunately, modern controllers are addressing this challenge. A tool such as the IQMath simplifies this task by giving programmers access to a new technology for easily implementing mathematical functions on fixed point DSPs. shows how easy it is to convert to IQ Math.

IQ Math is a TI technology that makes porting from floating point C language algorithms to a fixed point C language algorithms simpler by an order of magnitude. It simplifies development of algorithms to a point where the programmers are able to convert floating-point algorithms to fixed-point algorithms in a matter of minutes, contrasted with hours and days in the absence of such tools.

The key concept behind IQ Math is to scale everything back to a global fixed-point format, so that the conversion process to a fixed-point form becomes a mechanical process, which can be organized as a series of well-defined steps.

The C language compiler for the TI TMS320F2812 also compiles IQ math code very efficiently. It enables programmers to convert code by following a simple three-step procedure, and the compiler the produces efficient fixed-point code. The code in Figure 18 took about one minute to convert, and generates efficient fixed-point object code.

Floating point	`float  Y, M, X, B;` `y = M * X + B;`
“IQmath” in C	`_iq  Y, M, X, B;` `Y = _IQmpy(M, X) + B;`
“IQmath” in C++	`iq  Y, M, X, B;` `Y = M * X + B;`

Figure 18. Converting Code from Floating Point to IQMath

5 Leveraging Existing Collateral: Reduce Time to Market

Whether converting an existing analog control circuit into a digital DSP-enabled controller, or whether creating a new control system around a DSP, one of the common denominators is the creation of a large number of ‘infrastructure’ or reuse libraries.

Table 2. TI Foundation Software

Module Category	Modules
Peripheral and communication drivers	Virtual SPI drivers, virtual I2C drivers, serial EEPROM drivers, GPIO driver.
General control modules	PID controllers, extended precision PID controllers.
Motor control specific modules	Forward and inverse Clarke/Park transforms, BLDC specific PWM drivers, leg current measurement drivers, BLDC commutation triggers, ACI speed and rotor position estimators.
Fixed-point trigonometric and log routines	Fixed-point sine, cosine, tangent routines, square root, logarithm functions. Reciprocal calculation.
Fixed-point pseudo floating-point 32-bit math library	Multiply, divide, multiply with rounding, multiply with rounding and saturation, square root, sine and cosine, routines.
Signal processing functions	FIR (generic order), FIR (10th order), FIR (20th order), FIR using circular buffers. 128-, 256-, and 512-point complex and real FFTs.
Signal generator functions	Sinewave generators, ramp generators, trapezoidal profile generators.
Power conversion related functions	RMS computation, real power and apparent power computation, THD computation, PFC controllers.

Texas Instruments has done some of the work for designers, and has created a Motor Control Foundation Software Library that supplies several often re-used and commonly used components. These components make the creation of the control system software easier, and reduce the development cycle.

6 Conclusion

The choice of the control strategy is driven by the overall application complexity. For all but the simplest applications, designers are using advanced algorithms to address ever-increasing application requirements. TI's C2000 DSP controllers are making their lives easier. Analog-to-digital conversion is driving increasing features, and enabling new technology. Making the conversion from analog to digital control brings numerous advantages.

Careful management of the conversion process ensures that the application is partitioned correctly and makes the best possible use of the opportunities that the conversion brings. The conversion process itself is helped by ready-to-use software collateral, which reduces the implementation time significantly. Also, powerful compilers for the TMS320C2800 DSPs make implementation of fixed point arithmetic simpler.

7 References

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