Robotics Motor Control Design Guide

Abstract

This application note outlines Qorvo's Power Application Controller® (PAC) intelligent motor controller and drive (MCD) solutions in robotics applications, such as industrial and electronic assembly, and autonomous and collaborative robots. It reviews motor control requirements generally, describes the PAC MCD product series, and provides a detailed design example. Further implementation details are contained in corresponding product-specific datasheets, application notes, user guides, and evaluation kits.

1. Introduction

Robotics systems place stringent demands on motor control and drive electronics. Whether in an autonomous mobile robot, a precise robotic arm, or a collaborative service robot, motor controllers must deliver high precision, fast dynamic response, and energy-efficient operation under varied loads and conditions. Design challenges include tight speed/position control, high peak current and regenerative braking energy, safety requirements, and compact, thermally constrained space. Qorvo's PAC5xxx family of Power Application Controller® (PAC) System-on-Chip (SoC) motor controllers directly address these challenges by integrating a high-performance MCU, power management, gate drivers, and analog front-end into a single device. This application note assesses robot motor control requirements, presents a short overview of Qorvo solutions, and provides a design example of a rotating arm in a stationary robot.

2. Robot System

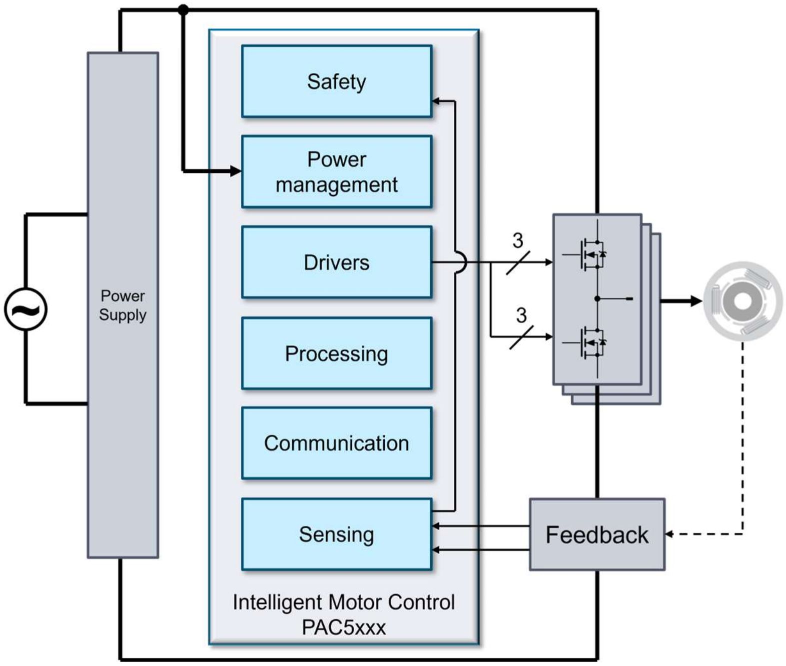

Fig. 2-1. Stationary robot system block diagram

In the stationary robot block diagram of Fig. 2-1, power runs from the AC grid and is commonly converted to 48 VDC, which complies with Safety Extra Low Voltage requirements. The highly integrated PAC intelligent motor controller combines several functions into a single, small package. All that remains is the 3-phase inverter, current sensing, and optional rotor position sensing.

Except for very high power applications, modern robots use either brushless DC (BLDC) motor or permanent magnet synchronous machine (PMSM) also called permanent magnet synchronous motor. Each type is a 3-phase motor that uses permanent magnets. A BLDC has concentrated windings and trapezoidal shaped back-electromotive force (BEMF) waveform, whereas PMSM has more sinusoidal BEMF. Sinusoidal commutation in a PMSM is preferred in precision robots due to smooth torque and high motor efficiency and utilization.

For both motor types, the goal is to optimize torque by aligning the rotating electromagnetic field 90 degrees from the permanent magnetic field. Both types require knowledge of the motor's magnetic flux angle. Sensorless flux angle estimation for six-step communication in BLDC motors uses voltage measurements of the alternately unenergized motor terminals, or Hall-effect (or other) sensors built onto the motor provide rotation information. Sensorless flux angle estimation in PMSM motors relies on synchronized phase current measurements and feedforward control. A position sensing approach uses a resolver, or an encoder. The math involved in aligning magnetic flux angles with sinusoidal commutation is called field-oriented control (FOC).

Moving a robot under load immediately after power up requires position sensing, regardless of motor/commutation type. Otherwise, a sensorless pulse-detect-go algorithm quickly finds the flux angle, allowing normal motor control to proceed.

A robotic intelligent motor controller must execute timing-critical measurements and intense calculations with enough bandwidth remaining for periodic safety checks and robust communication with the main robot processor. Integral protection from overcurrent, overtemperature, and under/overvoltage combine with requirements of standards such as IEC 60730 (Class B) for safe operation of electronic controls. Temperature and voltage touch-safe limits typically apply, so motors and inverters must operate efficiently to minimize heat generation. High peak motor current enables rapid acceleration and maximizes robot throughput.

3. Qorvo Solutions

Sensorless field-oriented control (FOC) is routinely accomplished in any of the PAC motor controllers. PAC52xxx motor controllers contain a 50 MHz Arm® Cortex®-M0 32-bit microcontroller core with 32 KB of embedded FLASH and 8 KB of SRAM. PAC55xxx motor controllers contain a 150 MHz Arm® Cortex®-M4F 32-bit microcontroller core with floating point unit (FPU), hardware multiply/divide, 128 KB of FLASH, and 32 KB of SRAM. They all contain peripherals, including pulse width modulation (PWM) and other timers, analog to digital converters (ADC) with associated state machine, various serial communications, and security.

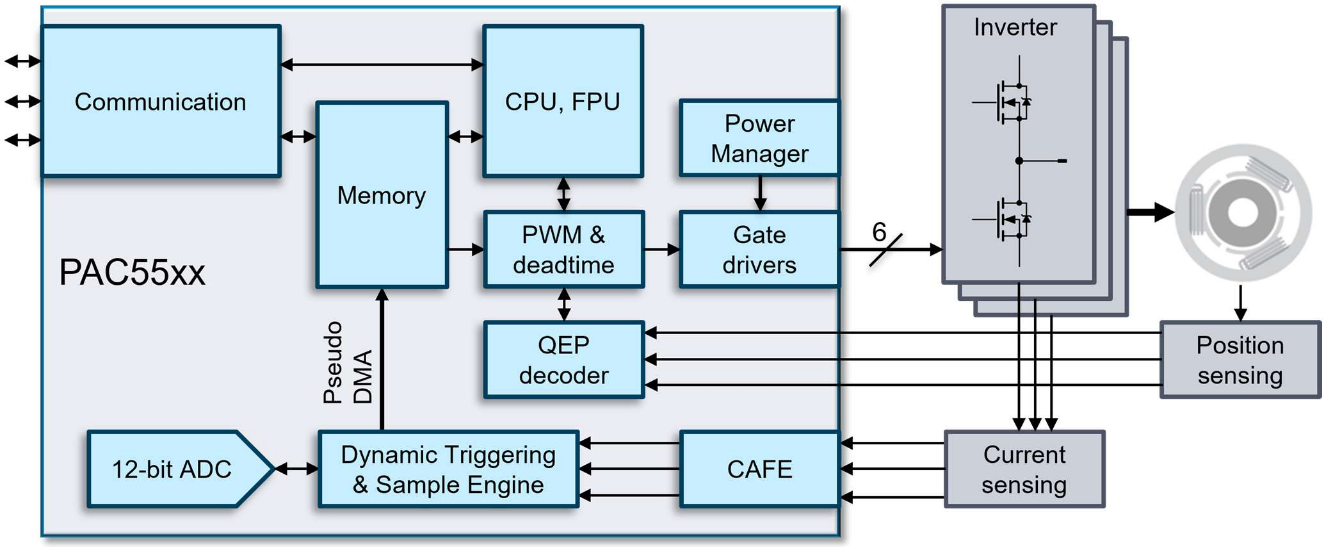

Fig. 3-1. PAC block diagram in robot application with precision positioning

Fig. 3-1 shows a block diagram of a PAC55xx intelligent motor controller. The 150 MHz, -M4 microcontroller core with floating point unit performs single-cycle 32 x 32-bit hardware multiply and 32-bit hardware divide, enabling high frequency, math-intensive robot control algorithms with plenty of bandwidth to spare for system-level functions such as external communication. An integrated quadrature decoder in PAC55xx controllers simplifies robot applications requiring position sensing by encoder. Six integrated gate drivers with low resistance totem-pole FETs enable switching external MOSFETs at high frequency. Integrated power management and configurable analog front end (CAFE™) further reduce board area and design time. Please see [1] for details.

4. Design Example

4.1. Overview

This design example is a robot arm that must accelerate/decelerate a 1.7 kg load at ±500 °/s^2 over a total arc of 180 °. Travel is evenly divided between accelerating and decelerating. After precisely positioning and releasing the load, the robot arm swings back, picks up another load, and repeats the process every 7.2 seconds. Fig. 4-1 shows angular velocity and acceleration for one complete pick-and-place cycle and the beginning of another.

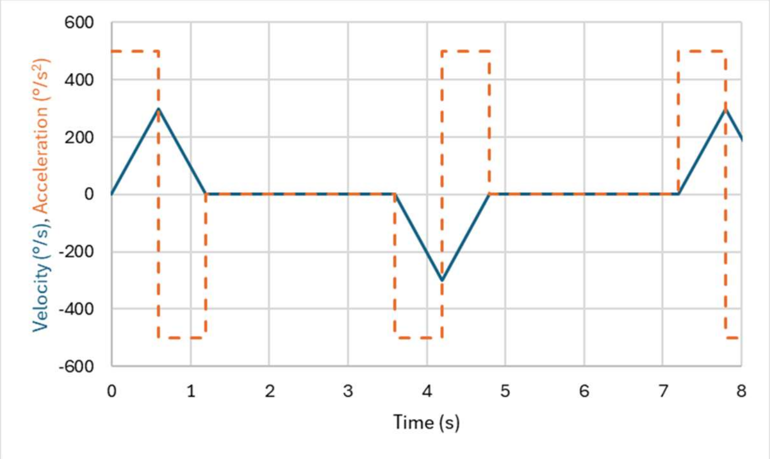

Fig. 4-1. Robot arm angular velocity (solid line) and acceleration (dashed line) versus time

The robot arm length is 0.5 m, and the load center of mass (CoM) is at the end of the arm, so 0.5 m from the arm pivot. The arm mass is 1.5 kg with CoM 0.25 m from the pivot. A direct drive, frameless motor mounted at the robot arm pivot joint eliminates gears and backlash. Note that the motor inertia is part of the arm's inertia. Power to the robot arm is from a 48 VDC supply with bidirectional power flow capability to accommodate regenerative braking while decelerating. The motor controller must communicate with a host computer by CAN bus.

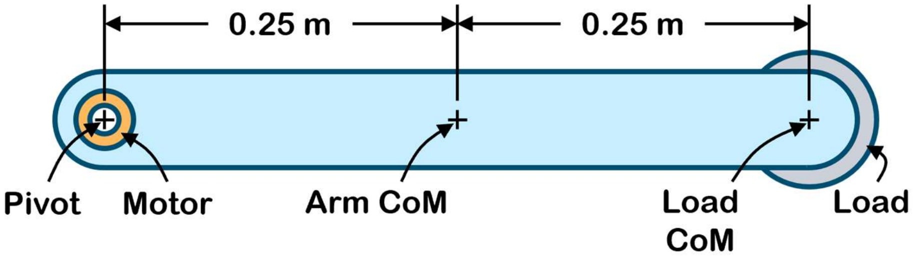

Fig. 4-2. Robot arm, motor, and load

Distances refer to the arm pivot as shown in Fig. 4-2. Summing the moments of inertia for each center of mass and multiplying by angular acceleration yields the required motor torque.

$$T_{motor,deliver} = \alpha \cdot \left(m_{arm} \cdot r^2_{arm\ CoM} + m_{load} \cdot r^2_{load\ CoM}\right) = 8.73\ rad/s^2 \cdot (1.5\ kg \cdot 0.25\ m^2 + 1.7\ kg \cdot 0.5\ m^2) = 4.53\ \text{Nm}$$

The same magnitude reverse torque applies during deceleration. Without the load, torque for acceleration/deceleration while returning to original position is:

$T_{motor,return} = \alpha \cdot m_{arm} \cdot r_{arm\ CoM}^{2} = 8.73\ rad/s^{2} \cdot 1.5\ kg \cdot 0.25\ m^{2} = 0.82$ Nm

4.2. Motor Selection

The motor speed is low because it is direct drive, and with precision positioning required, a PMSM with sinusoidal commutation is the best option. A mid-inductance winding option balances the tradeoff between quick velocity changes and back EMF voltage. A motor that could work is Magnetic Innovations part number 110-50-3-N1-T2. The air-cooled version is rated at 9.4 Nm continuous, which exceeds the maximum torque requirement of 4.53 Nm. Some motor parameters are listed here:

- Continuous torque: 9.4 Nm
- Peak torque: 32.3 Nm
- Continuous current: 9.5 A rms
- Torque constant K_{torque} (at 20 °C): 1.06 Nm/A rms
- Motor constant K_{motor} (at 20 °C): 1.3 Nm/√W
- Line-line back-EMF constant: 0.065 V/rpm
- Thermal resistance: 1.38 K/W

From the torque constant, we estimate the motor current during acceleration/deceleration as:

$i_{motor} = \frac{T_{motor}}{K_{torque}} = \frac{4.53\ Nm}{1.06\ Nm/A\ rms} = 4.3$ A RMS, which is well within limits.

Power loss in the motor during acceleration and deceleration while delivering the load is estimated as:

$P_{motor\ loss,acc} = \left(\frac{T_{motor}}{K_{motor}}\right)^{2} = \left(\frac{4.53\ Nm}{1.3\ Nm/\sqrt{W}}\right)^{2} = 11.8$ W

Acceleration/deceleration power loss while returning to the original position is approximately:

$P_{motor\ loss,acc} = \left(\frac{T_{motor}}{K_{motor}}\right)^{2} = \left(\frac{0.82\ Nm}{1.3\ Nm/\sqrt{W}}\right)^{2} = 0.39$ W

While delivering the load, constant acceleration α swings the arm half the rotation in $t_{accel} = \sqrt{\frac{2\cdot 180\,{}^{\circ}/_{2}}{500\,{}^{\circ}/_{s^{2}}}} = 0.60$ seconds with a peak velocity of $\omega_{peak} = 500\,{}^{\circ}/_{s^{2}} \cdot 0.6\ s = 300$ °/s.

There are two acceleration/deceleration periods of equal duration, and likewise two acceleration/deceleration periods while returning but with less power loss. Averaging over the entire cycle yields the average motor power loss.

$P_{motor\ loss,ave} = \frac{2\cdot 0.60\ s\cdot 11.8\ W + 2\cdot 0.60\ s\cdot 0.39\ W}{7.2\ s} = 2.0$ W

A metal robot arm can easily dissipate this much heat. We estimate motor temperature rise by multiplying its thermal resistance by average motor loss. 1.38 K/W · 2.0 W = 2.8 °C. This simplified thermal analysis is sufficient to assume that the motor is safe thermally, with plenty of margin. It would be verified by testing of course.

4.3. Power Supply Selection

Rotational power is torque multiplied by angular velocity ω. At the end or beginning of acceleration or deceleration respectively, the angular velocity is $\omega_{steady} = \frac{300\,^{\circ}}{s} \cdot \frac{1\ rotation}{360\,^{\circ}} \cdot \frac{60\ s}{min} = 50$ rpm. Line-to-line back-EMF at this speed is: $V_{BEMF} = \omega_{steady} \cdot K_{BEMF} = 50\ rpm \cdot 0.065\ V/rpm = 3.3$ V rms, and peak motor output power is 4.53 Nm ·50 rpm = 23.7 W. During deceleration, the braking torque transfers energy from the rotating mass through the inverter and power supply back into the AC grid. See Fig. 2-1. Return travel without the load requires much less peak power. Fig. 4-3 shows motor output power (solid line), and motor power loss (dashed line) during one complete pick-and-place cycle and the beginning of another.

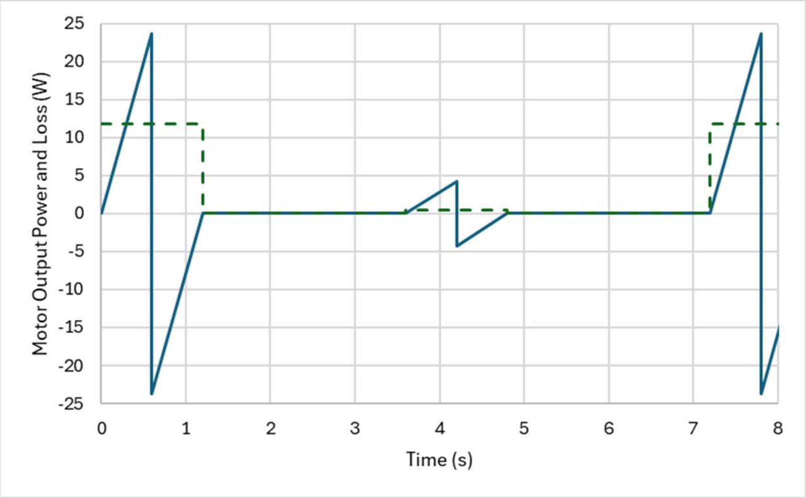

Fig. 4-3. Motor output power (solid line) and motor power loss (dashed line) versus time

Almost all mechanical energy is recuperated during deceleration (regenerative braking). On average, the power supply simply supplies power lost due to friction, wind resistance, conduction and switching loss in the inverter, and a tiny amount in the motor controller and surrounding components. Peak power, however, is much higher than average power, with motor peak power output plus loss totaling 35.5 W.

In this direct drive example, motor power loss is high compared to output power while accelerating/decelerating the load. Also, inverter modulation index is low, only about 0.11, which is less efficient for the inverter. There are two options to increase efficiency. The first is a larger motor. For example, the same diameter motor but 75 instead of 50 mm width reduces estimated peak and average motor loss to 7.1 and 1.2 W respectively. The second option is a gearbox, which would reduce motor torque and increase overall efficiency but would add cost, physical volume, backlash, weight, inertia, drag, and wear. This is the tradeoff of direct drive.

A key requirement of the 48 VDC power supply is bidirectional power flow. A power supply with a diode bridge rectifier at the input will not work. It must have full bridges with power transistors in both the AC-DC (input) and isolated DC-DC stages. For example, the AC-DC stage could be a (bridgeless) totem-pole power factor corrector, and the DC-DC could be CLLC full-bridge or dual active bridge.

4.4. Inverter MOSFET Selection

We need a rough estimate of power loss in the inverter MOSFETs in order to select them. Conduction loss is $P_{cond} = \frac{1}{2} \cdot R_{DS(on)} \cdot i_{ph,rms}^2$ because phase current always flows through one of two MOSFETs in each half-bridge, and each MOSFET is driven on during reverse (freewheeling) conduction as well as forward, and the difference in conduction loss during deadtime is negligible. $R_{DS(on)}$ is the MOSFET on resistance adjusted for temperature. A worst-case operating estimate of $R_{DS(on)}$ is twice the 25 °C value. Consider a 100 V rated MOSFET with 31 mΩ typical at 25 °C, part number PSMN039-100YS from Nexperia. Peak conduction loss per MOSFET is:

$$P_{cond,peak} = \frac{1}{2} \cdot 0.031 \cdot 2 \cdot 4.3^2 = 1.1 \text{ W.}$$

With a bus voltage of 48 V, switching loss is modest, about 2/3rd the conduction loss, bringing the total loss estimate per MOSFET to 1.8 W peak. As with motor power loss, MOSFET average power loss is much lower than peak, with sufficient cooling time between peaks. The small gate charge of 23 nC typical from 0 to 10 V is a light load for an MCD. This MOSFET, or one like it, should work well without paralleling and with plenty of safety margin.

4.5. Motor Controller Selection

Referring to application note MCD-AN-System Guide, any 72 V or higher rated MCD would work well in this design example. A well-regulated 48 V supply is 2/3rd of 72 V, so one of the newer released 72 V parts would be a good choice. Each PAC55xx includes CAN 2.0B and a QEP quadrature decoder, which is a nice option for precise position control. An FPU and ample memory simplify firmware development. PAC55710 is the choice here. This is not a safety-critical robot, so there is no need for a redundant MCU and corresponding brake and disable modes. PAC55710 supports simultaneous sample-and-hold of all three phase currents through three internal differential amplifiers, which facilitates field-oriented control (FOC) with sinusoidal commutation.

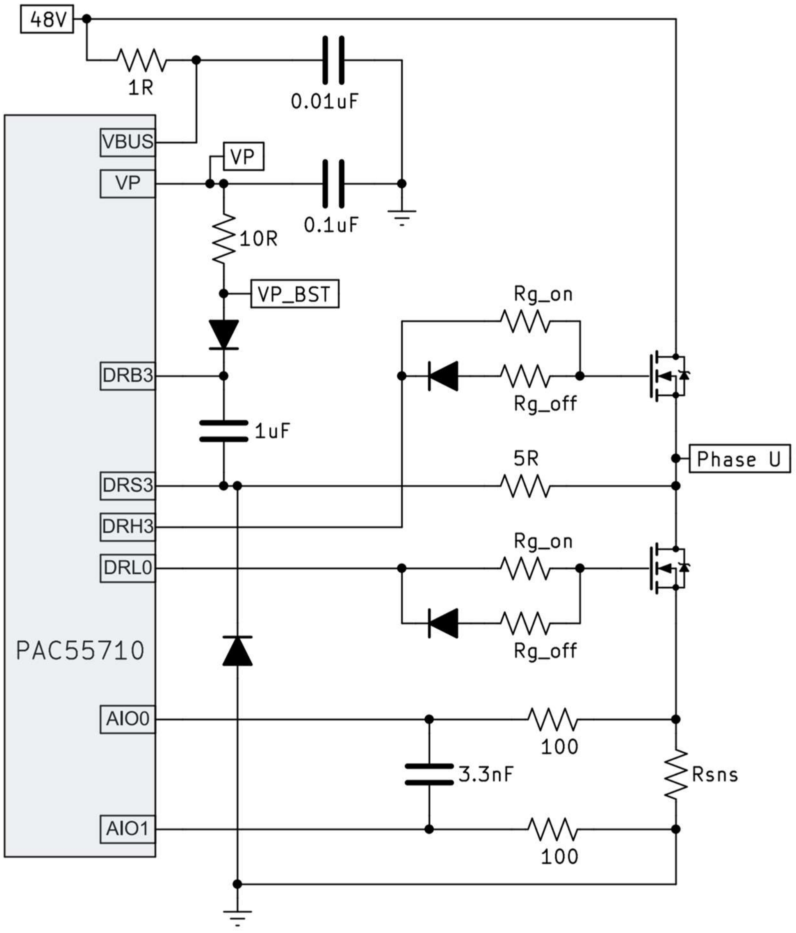

Fig. 4-4. Phase U of inverter drive with PAC55710

Fig. 4-4 shows the Application Specific Power Drivers and inverter phase U connections. Phase V and W are identical. High-side gate drive power is from a bootstrap for each phase, but node VP_BST is common for all phases. Low-side driver power is from VP.

Sense resistor Rsns is for phase current measurement. Its value is a tradeoff between resolution and power dissipation in Rsns. Voltage across Rsns routes to one of three precision differential amplifiers (diff-amp) with programmable gain of 1, 2, 4, 8, 16, 32, or 48. (Phases V and W use the other two diff-amps.) The diff-amp input voltage range of ±1.25 V limits Rsns to 0.11 Ω maximum with peak power dissipation of 14 W at peak current of 11.3 A. The lower practical limit for Rsns is about 2 mΩ with gain set at 48. A good compromise for Rsns is 10 mΩ, 5 W with amplifier gain set at 8. Full scale sense voltage is ±113 mV. Peak and average power loss in Rsns is about 1.3 W and 0.43 W respectively. A 20 mΩ sense resistor with amplifier gain set at 4 would also work well. A calibration step should be performed after final assembly to achieve the best accuracy.

The bulk of the remaining design work is configuring the PAC55710. Information for that is found in the datasheet, user guide, and evaluation kit.

5. Summary

Highly integrated PAC MCDs simplify a robot system to a power supply, a PAC MCD, an inverter, feedback, and finally the motor. A high performance MCU, DC-DC converters, gate drivers, analog circuits, and protection functions are all included in the MCD. The result is substantial savings in circuit board area as well as design time. A design example includes torque calculations and power requirements with a Magnetics Innovations direct-drive, frameless motor optimized for robotic applications. Inverter and feedback design conclude the example.

References

[1] J. Dodge, "Qorvo Motor Control & Drive System Guide," Qorvo. [Online]. Available: https://www.qorvo.com/products/d/da009837

Revision History

Revision	Author	Date	Description
A	Jonathan Dodge, P.E.	19 Feb. 2026	Initial draft

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