ENGINEERING
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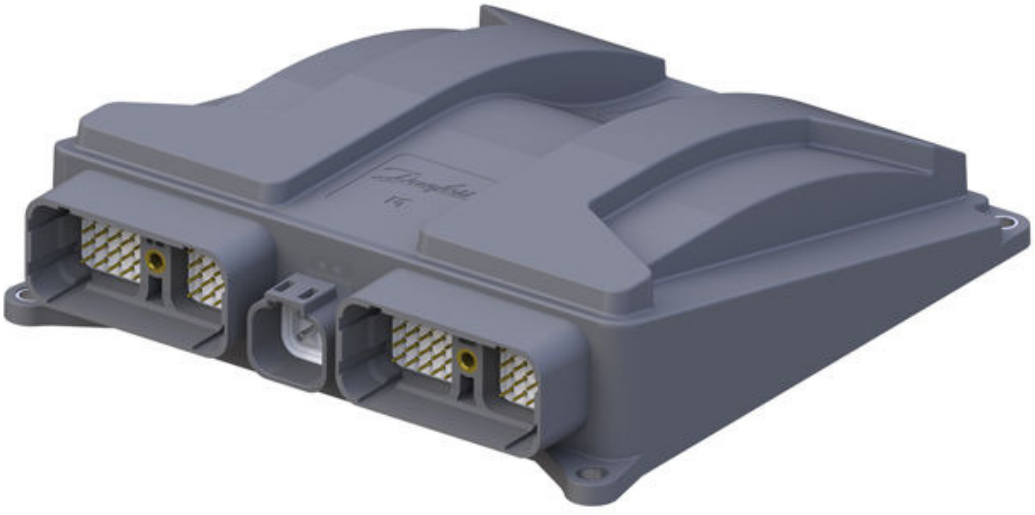
Safety Manual

PLUS+1 Controller
XL104-xxxx Functional Safety Implementation



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Revision history

Table of revisions

Date	Changed	Rev
March 2022	Corrected minor issues	0102
December 2020	First edition	0101

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Introduction

This safety implementation document provides information necessary to design, implement, verify and maintain a safety critical function utilizing the PLUS+1® XL104-XXXX Controller Family. This document provides necessary requirements for meeting the IEC 61508: 2010 Parts 1-7 and IEC 62061:2005+ A1:2012+ A2:2015 functional safety standards.

Abbreviations and definitions

Abbreviations

DC	Diagnostic Coverage
EUC	Equipment under control.
FMEDA	Failure modes, effects and diagnostic analysis.
HFT	Hardware fault tolerance.
PFH	Probability of failure per hour.
PFDAVG	Average probability of failure on demand.
SFF	Safe failure fraction, summarizes the fraction of failures which lead to a safe state and the fraction of failures which will be detected by diagnostic measures and lead to a defined safety action.
SIF	Safety instrumented function.
SIL	Safety integrity level.
SRS	Safety related system, implementation of one or more safety critical functions. An SRS is composed of any combination of sensor(s), control module(s), and actuator(s).
DIN	Digital input pins
DIN/AIN	Digital analog input pins
DIN/AIN/FreqIN	Digital analog and frequency input pins.
CrntIN (current)	Current input pins.
ResIN	Resistance input pins.
DOUT	Digital output pins.
CrntOUT (current)	Current output pins.
OS	Operating system.

Definitions

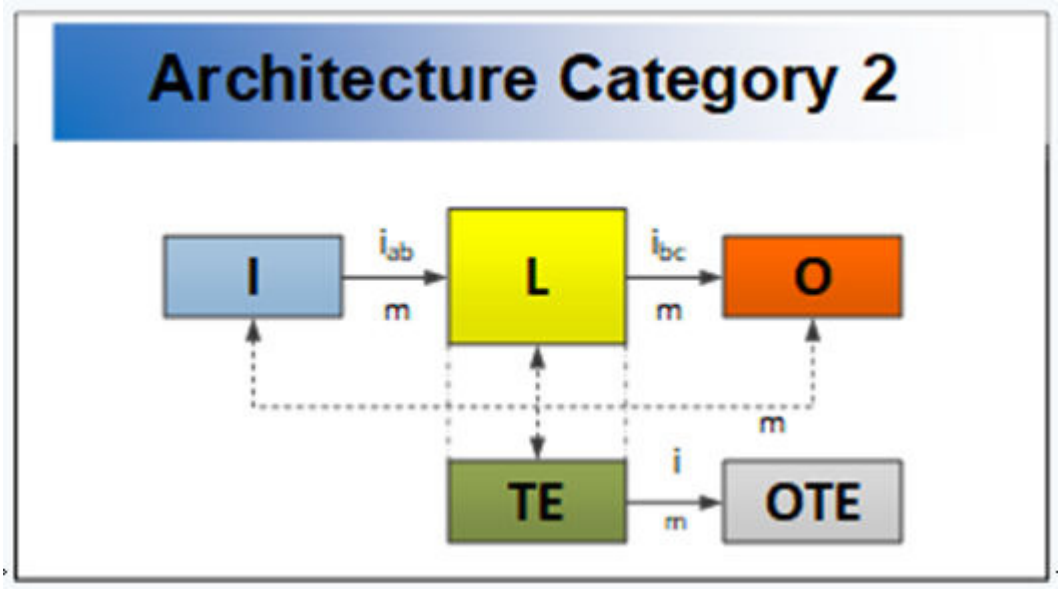
Continuous Demand Mode	Mode where the safety function retains the equipment under control in a safe state as part of its normal operation.
High Demand Mode	Mode where the safety function is only performed on demand, in order to transfer the EUC into a specified safe state, and where the frequency of demands is not greater than one per year.
Low Demand Mode	Mode where the safety function is only performed on demand, in order to transfer the EUC into a specified safe state, and where the frequency of demands is not greater than one per year. NOTE: The E/E/PE safety-related system that performs the safety function normally has no influence on the EUC or EUC control system until a demand arises. However, if the E/E/PE safety-related system fails in such a way that it is unable to carry out the safety function, then it may cause the EUC to move to a safe state (see 7.4.6 of IEC 61508).
Safety	Freedom from unacceptable risk of harm.
Functional Safety	The ability of a system to carry out the actions necessary to achieve or to maintain a defined safe state for the equipment, machinery, plant, and apparatus under control of the system.
Basic Safety	The equipment must be designed and manufactured such that it protects against risk of damage to persons by electrical shock and other hazards and against resulting fire and explosion. The protection must be effective under all conditions of the nominal operation and under single fault conditions.

Introduction

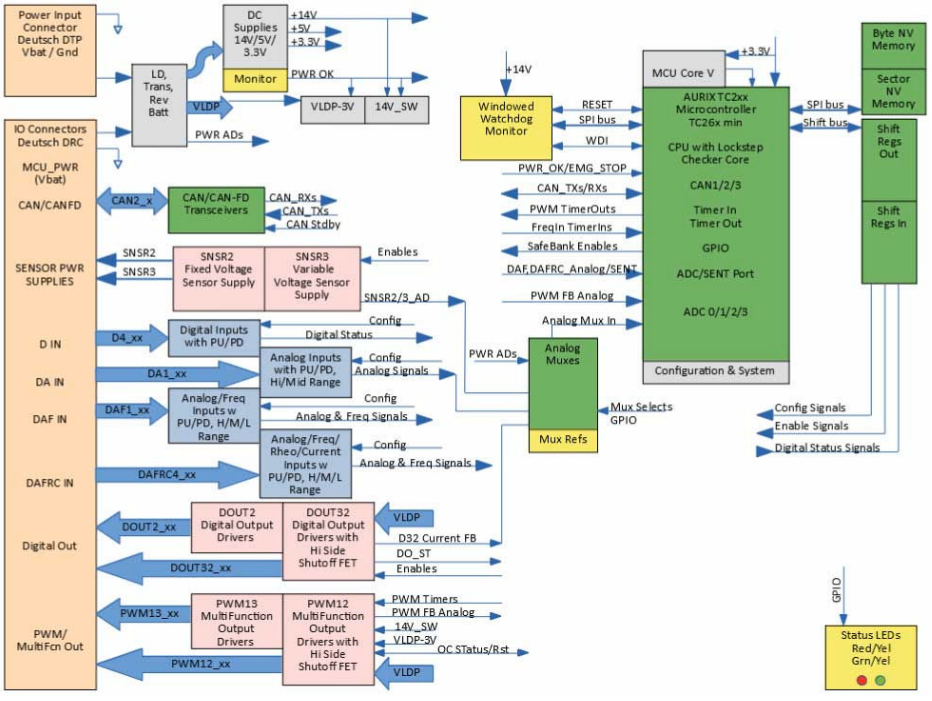
Safety Assessment	The investigation to arrive at a judgment, *based on evidence* of the safety achieved by safety-related systems.
Safety Critical Function	A set of equipment intended to reduce the risk due to a specific hazard.
Process Safety Time	The period of time between a failure occurring in the control system (with the potential to give rise to a hazardous event) and the occurrence of the hazardous event if the safety function is not performed.
Type A Component	*Non-Complex* element (using discrete elements); for details see 7.4.4.1.2 of IEC 61508
Type B Component	Complex element (using micro controllers or programmable logic); for details see 7.4.4.1.3 of IEC 61508.
Common Logic	Electrical components and circuitry typically involved with all applications regardless of the input-output channel configuration.

Overview

The Plus+1® XL104 Controller uses a Category 2 safety architecture as defined in ISO13849:



Much of the Test Equipment function for the Category 2 safety architecture is contained within the MCU itself. The MCU Test Equipment components include memory ECC hardware, a checker core, diagnostic hardware on ADCs and GPIOs, and software independent Emergency Stop hardware. An external windowed watchdog and monitor device is used as part of the Test Equipment.



The MCU will execute the Modular Safety Kernel (MSK). The inputs will be read and provided to the application. The application processes this information and will set the outputs to the desired values. The setting of the outputs is done from the MSK.

Component description and failure rates

Detailed analysis, review and documentation for compliance to ISO 13849 or ISO 25119 must be done by the designer or integrator of the safety related system.

Failure categories description

In order to judge the failure behavior of the PLUS+1® XL104 Controller, the following definitions for the failure of the component apply.

Definitions for failure of the component

Failure category[1]	Definition
Fail-Safe State	State where the safety output is de-energized.
Fail Safe	State where the safety output is de-energized.
Fail Detected	Failure that is detected by the Controller and causes the output signal to go to the predefined fail safe state.
Fail Dangerous	Failure that deviates the measured input state or the actual output by more than the safety accuracy (2% of span) and that leaves the output within the active range.
Fail Dangerous Undetected	Failure that is dangerous and that is not being diagnosed by automatic diagnostics or expected user logic.
Fail Dangerous Detected	Failure that is dangerous but is detected by automatic diagnostics or is expected to be detected by user logic.
Fail High[2,3]	Failure that causes a safety input signal to go to a value that is clearly above the normal range and can therefore be reliably detected by the user application software.
Fail Low[2,3]	Failure that causes a safety input signal to go to a value that is clearly below the normal range and can therefore be reliably detected by the user application software.
No Effect	Failure of a component that is part of the safety function but that has no effect on the safety function.
Annunciation Detected	Failure that does not directly impact safety but does impact the ability to detect a future fault (such as a fault in a diagnostic circuit) and that is detected by internal diagnostics.
Annunciation Undetected	Failure that does not directly impact safety but does impact the ability to detect a future fault (such as a fault in a diagnostic circuit) that is not detected by internal diagnostics.
λ_{SD}	Failure rate of all safe detected failures
λ_{SU}	Failure rate of all safe undetected failures
λ_{S}	Failure rate of all safe failures (detected and undetected), λSD + λSU
λ_{DD}	Failure rate of all dangerous detected failures
λ_{DU}	Failure rate of all dangerous undetected failures
λ_{D}	Failure rate of all dangerous failures, detected and undetected, λDD + λDU
FIT	Failures In Time (failures per 10^9 hours)

[1] The failure categories listed above expand upon the categories listed in IEC 61508, which are only safe and dangerous, both detected and undetected. In IEC 61508, the No Effect failures cannot contribute to the failure rate of the safety function. Therefore, they are not used for the Safe Failure Fraction calculation.

[2] Depending on the application, a Fail High or a Fail Low failure can either be safe or dangerous and may be detected or undetected depending on the user software application program.

[3] Consequently, during a Safety Integrity Level (SIL) verification assessment, the Fail High and Fail Low failure categories need to be classified as safe or dangerous, and as detected or undetected.

Failure rates

The results of the FMEDA analysis for the PLUS+1® XL104 Controller are presented in the following table. Common Logic consists of circuits in the controller that directly affect the performance of any Safety Function. The Test Equipment Logic consists of diagnostic circuits in the controller and is not directly included in a Safety Function reliability calculation. The failure rates below assume the implementation of all Recommended Diagnostics. If no diagnostics are implemented by the application, all Dangerous Detected Failures should be assumed to become Dangerous Undetected Failures.

Component description and failure rates

Refer to *Using the FMEDA results* on page 18 for an example of how to calculate the reliability of a Safety Function using these data.

Subsystem Failure rates (FIT)

Controller Subsystem	λ_S	λ_{DD}	λ_{DU}	DC
Common Logic	95.5	1420	176	88.9%
Test Equipment Logic	27.9	123	8.5	93.6%
CAN Port	0	38.9	2.9	93.1%
DIN	0	3	6.2	32.5%
DIN with key-switch	2.9	3	7.9	27.6%
DIN/AIN (Digital)	0	7	7.6	48.0%
DIN/AIN (Analog)	0	11.3	3.5	76.4%
DIN/AIN/FreqIN (Digital)	0	6.9	10.5	39.6%
DIN/AIN/FreqIN (Analog)	0	13.9	4.4	75.8%
DIN/AIN/FreqIN (Frequency)	0.05	11.6	3.3	77.8%
DIN/AIN/FreqIN/CrntIN/ResIN (Digital)	0	8.7	10.8	44.5%
DIN/AIN/FreqIN/CrntIN/ResIN (Analog)	0	11.7	8.3	58.6%
DIN/AIN/FreqIN/CrntIN/ResIN (Frequency)	0.12	11.9	5.2	69.5%
DIN/AIN/FreqIN/CrntIN/ResIN (ResIN)	0	13.6	7.1	65.7%
DIN/AIN/FreqIN/CrntIN/ResIN (Current)	1.22	11.3	13.4	45.6%
DOUT	1.6	48.8	2.5	65.9%
DOUT with Safebank	30.6	7.7	1.4	84.8%
CrntOUT (Current)	19.8	48.6	9.6	83.5%
CrntOUT (Current) with Safety FET	33	57	11.6	83.1%
Fixed Sensor Supply	22.2	18.4	5.17	78%
Variable Sensor Supply	25	27.3	3.71	88%

Recommended diagnostics

The PLUS+1® XL104 Controller should be implemented with diagnostics in the application to detect many dangerous failures and other failures that would result in the controller operating in a degraded mode. The machine integrator is responsible for the function safety and compliance to relevant standards.

The following table lists recommended diagnostics. These diagnostics should be implemented in the user application software that is loaded into the PLUS+1® XL104 Controller.

Diagnostics

Function	Failure mode	Condition	Action	Continuous or Start-up
Sensor power	Short to battery	Analog reading at or near maximum	Stop reading inputs powered by sensor power.	Continuous
Sensor power	Short to ground	Analog reading at or near zero	Stop reading inputs powered by sensor power.	Continuous
Sensor power	Out of range	Analog reading different than expected	Can compensate inputs for new voltage if possible	Continuous
Analog input	At Max	Analog reading at or near max	Stop using this input	Continuous
Analog input	At zero volts	Analog reading at or near zero	Stop using this input	Continuous
Frequency input	Open	Analog reading is at or near middle voltage	Ignore frequency input	Continuous

Component description and failure rates

Diagnostics (continued)

Function	Failure mode	Condition	Action	Continuous or Start-up
Frequency input	No signal	Analog value doesn't change for longer than the maximum period	Ignore frequency input	Continuous
Digital output	Load shorted	Status signal indicates short circuit or open load	Application dependent	Continuous
Digital output	Open load	Status signal indicates short circuit or open load	Application dependent	Continuous
Current driver	Load shorted	Duty cycle at least 50% less than expected for known load	Information only or turn off output	Continuous
Current driver	Load shorted	Status signal indicates short circuit	Turn off output immediately	Continuous
Current driver	Open load	Duty cycle at least 50% less than expected for known load	Information only or turn off output	Start-up
Current driver	Load shorted	The output current decays too slowly after the output is disabled	Turn off output immediately	Continuous
Current driver	Incorrect load	Coil resistance is greatly different than expected	Do not use that output	Continuous
Battery Power	Dangerously High	Battery voltage reading above 36V	Turn off all outputs and ignore inputs	Continuous
Battery Power	Dangerously Low	Battery voltage reading below 7V	Turn off all Current outputs	Continuous
CAN	Bus off	CAN bus status signal indicates bus off	Turn off outputs that rely on CAN information	Continuous
CAN	Time out	An expected message hasn't been received in the expected time	Turn off outputs that rely on that message	Continuous
CAN	Failed transition	Application requests message transmission while pending flag is active	Application dependent	Continuous
Configuration	Invalid configuration	Status signal indicates input or output is configured in an invalid way.	Make change to application software	Start-up

Design Considerations

Safety critical conitions

The PLUS+1® XL104 Controller can perform a wide variety of control functions. If these control functions are safety critical, then additional safety reliability can be achieved by configuring the controller to monitor the sensor inputs, perform diagnostics, and act to bring the machine to a safe state if safe operating parameters are violated.

The following sections describe features of thePLUS+1® XL104 Controller related to the implementation of Safety critical functions.

Functional Safety Implementation

Microcontroller

The microcontroller is the application processor containing normal application code required for machine operation machine level safety functions. The application will be developed in PLUS+1®GUIDE. The application contains modules for normal machine control and specific machine level safety functions. The processor sees all inputs and can set all outputs. The processor controls the safety functions, under kernel and application software control with a hardware-only channel from the Windowed Watchdog and Power Supply Monitor to disable the safety group functions.

Executed IN: Kernel

Application interaction: Application must have general safety handling and logical check for when it is safe to enable outputs. This may include start-up protection (FNR in neutral prior accepting driving inputs etc.)

The Application uses the API Enable signals to enable or to disable an output.

Sensor Power Outputs

The PLUS+1® XL104 Controller will generally have one or more Sensor Power Supply Outputs. The voltage level of these supplies are designed to be static. The output voltages may be constant or variable within the range of 3.0V to 12.0V, depending on the sensor supply hardware. The generated voltage level is monitored and is reported to the application. This reported value can be used by the application to use ratio metric scaling of analog inputs and to validate if the generated voltage of the sensor supply output is sufficient for connected sensors. This allows the application to bring the system into a safe state by shutting down safety relevant outputs in case the value is not in the expected state.

The sensor power outputs are current limited to prevent a high load on the supply output from affecting the internal operation of the controller. The application can use the output voltage monitor to determine if an error condition exists, and if so move the application into a safe state.

Executed IN: Kernel is providing the measurement of the sensor voltage channel and provides this to the API.

Application interaction: Application must use the Sensor Output feedback voltage (.Voltage) for ratio metric scaling and for range checking. If redundant monitoring is required, the application should use another analog input. In case of an out of range value or mismatch of reported value, the application shall bring the system into a safe state by shutting down safety relevant outputs.

Protection and Power Supplies

The elements of this circuitry protect the PLUS+1® XL104 Controller against power line transients and provide the necessary voltages for supplying the MCU, input and output circuitries, and internal control logic. The PLUS+1® XL104 Controller does not protect against nominal input voltages outside of the range from 0-36V. The internally generated 3.3V and 5V power supplies will be monitored against the 14V power supply, which has an independent internal reference. If any voltage is out of the specified tolerance, a digital indication of a power supply failure will be reported to the MCU. All outputs are then

Design Considerations

disabled by hardware without any software involvement. The power supply failure event processing is done in hardware because correct operation of the MCU cannot be assumed when a voltage rail is out of range.

Executed IN: Hardware circuitry.

Application interaction: Application must use the API signals to check whether outputs are functioning correctly.

MCU Core Voltage Supervisor

The core supply voltage for the MCU is under supervision to ensure an under voltage condition does not cause any malfunction of the MCU. This supervision uses the on chip power on reset / power down reset system. The MCU goes into or remains in reset mode when the core voltage is below its undervoltage threshold. In the reset state all the MCU outputs are disabled, and biased to an off state. All controller outputs are de-energized.

Executed IN: Hardware circuitry.

Application interaction: None. Hardware will reset the application. Hardware is designed so that a reset of the MCU brings all controller outputs to a safe or de-energized state.

ADC Checks

The MCU will generate a cyclic changing AD signal to validate the function of its AD-converter. This is used to identify a stuck-at situation.

Executed IN: Kernel creates and tests the the ADCs. The result is provided to the API.

Application interaction: Application must use this status information. In case of a problem value the application must take appropriate actions in order to ensure functional safety.

Digital Outputs

The digital output enables are set by the MCU under application and kernel control. Each Digital Output on Safebanks provides an output status signal and a current input signal. The current input signal is used to identify an overcurrent condition on the output. The Digital Outputs on Safebanks are able to be used directly in a safety function since they have multiple ways to de-energize the function by disconnecting the high side to the load.

When using a DOUT on Safebank output, the Safebank must be enabled and verified to be turned on before using the DOUT. This status is shown in the Safebank.Active bit. The application safety layer should use both the DOUT.DigFeedBack status and the Safebank.Active status when monitoring these Digital Outputs.

Each of these outputs is part of a Safe Group. The safety function application controls the enables for each Safe Group. The Safe Group Enables are turned off by the MCU Emergency Stop hardware if a power supply or watchdog event occurs.

Standard Digital Outputs are controlled by the MCU but are not part of a Safe Group. These Digital Outputs should not be used for safety critical functions.

Executed IN: The kernel controls the output, performs feedback calculations, and reads the status. The signals are provided to the API.

Application interaction: Application must use the provided feedback and status signals. In case of an identified problem, the application shall bring the system into a safe state by shutting down safety relevant outputs.

Multifunctional (Current) Outputs

The Multifunctional Outputs with Safety FETs are controlled by the MCU. Each of these outputs has an individual Safe Group. Each output provides a status signal for overcurrent as well as a current input

Design Considerations

signal to be used to identify feedback of the output. The Multifunction Outputs with Safety FETs are able to be used directly in a safety function since they have multiple ways to de-energize the function by disconnecting the high side to the load.

The safety function application controls the enables for each Safe Group. The Safe Group Enables are turned off by the MCU Emergency Stop hardware if a power supply or watchdog event occurs.

Standard Multifunctional Outputs are controlled by the MCU but are not part of a Safe Group. These outputs may be used in a safety function when in an H-bridge configuration to be able to de-energize the function by disconnecting either the high side or low side of the load.

Executed IN: The kernel controls the output, performs feedback calculations, and reads the status. The signals are provided to the API.

Application interaction: Application must use the provided feedback and status to determine proper operation. In case of an identified problem, the application shall bring the system into a safe state by shutting down safety relevant outputs.

Inputs

All digital and analog inputs are run to the MCU. In case higher MTTFd or Diagnostic Coverage numbers are required for input devices they should be connected to the external function in a redundant manner from the controller's IO connectors. Frequency inputs will be monitored by additional checks such as counter active checks and register overflow situation when no frequency is measured to monitor possible problems with the CPU capture unit.

Executed IN: Kernel is monitoring the CPU capture unit, signals, and doing feedback calculations, etc. and is providing info to API.

Application interaction: Application must use the status information provided by the API. In case of a problem value the application shall bring the system into a safe state by shutting down safety relevant outputs.

Clocks

The MCU is supplied with a clock from an external source. The MCU runs internal diagnostic routines at startup to detect a failed clock. A failed clock situation will be reported to the MSK, and the controller application will be prevented from starting.

Executed IN: Kernel.

Application interaction: None.

Start-up SRAM check

The MCU internal SRAMs will be checked at start-up to identify potential memory problems. In case of a RAM failure the system will not be started and the outputs will be kept deactivated.

Executed IN: Kernel tests the SRAM at startup and holds the controller outputs in a de-energized state. The application will not be started if a RAM error is found. Other memory errors will use the Kernel and the MCU Emergency Stop hardware to shut down the application and disable all outputs.

Application interaction: None. Hardware will reset the application. Hardware circuitry is designed so that a reset of the MCU brings all controller outputs to a safe or de-energized state.

Runtime SRAM checks

The MCU uses ECC detection and correction hardware to detect a memory bit failure while in use.

Executed IN: Kernel uses the MCU Memory Unit.

Application interaction: None. MCU hardware will reset the application. MCU hardware circuitry is designed so that a reset of the MCU brings all controller outputs to a safe or de-energized state.

Design Considerations

Program FLASH checks

During application download CRC16 checksums for relevant sections are calculated and will be stored inside the CPU. The checksum of the program memory will be calculated at start-up and during run-time. The application will not start if a checksum failure occurs.

The MCU uses ECC protection on data reads from the Program Flash memory. If a memory error is detected, the Kernel will reset the application.

Executed IN: Kernel at startup and MCU during runtime.

Application interaction: None. Hardware will reset the application. Hardware is designed so that a reset of the MCU brings all controller outputs to a safe or de-energized state.

Memory protection

The Kernel's RTOS will utilize the MCU's memory protection unit to prevent memory access violations (e.g. stack overflow). When a memory access violation is detected, the system will perform a reset.

Executed IN: Kernel's RTOS is utilizing the MCU's MPU.

Application interaction: None. Hardware will reset the application. Hardware is designed so that a reset of the MCU brings all controller outputs to a safe or de-energized state.

Non-volatile memory (EEPROM) data

The data stored inside the Non-Volatile Memory as well as the data presented to the application (located in RAM) is protected with a checksum to make sure the data is correct.

Executed IN: Kernel is monitoring the data.

Application interaction: Application must check NVMem.Status and check the single BIT values. The application shall also take measures to ensure parameters matching the application and parameter structure. The application is responsible for not exceeding the write lifetime of the Non-Volatile Memory.

User Application Software Development Requirements

The application must monitor the system relevant IOs (examples: sensor power voltage, input voltage, memory checks, EEPROM status) and the sequences of application processing. Dependant on the system, the application must disable certain outputs to bring the system into the safe state. Applications must be developed according to the following recommendations:

- **CAN Bus**

  The lower layers of the CAN channels provided by the MSK must be treated as black channels. System-specific requirements for the reliability to the communication through the CAN / CAN-FD channels must be fulfilled by a sufficient CAN protocol, such as SAE J1939-76 or EN 50325-5 (CANopen Safety).

- **Plausibility Checks on Input Data**

  The user application software must include plausibility checks on frequency input data to detect possible failures in frequency input calculations. Moreover, the user application software must include plausibility checks on all safety relevant inputs.

- **Quad Count Verification**

  The user application software must use the frequency values and the count value of the Quad encoder inputs to validate functionality.

- **Signal Comparison**

  Signal comparison must be implemented by the user application software for safety-related signals. Either inputs with redundant ADC channels should be used and/or two XL104 Controller inputs. Redundant channels must be utilized to provide reliability where there is concern about channel reliability based on PFH.

Design Considerations

- **Input Voltage Monitoring**

  The Input Voltage to the output functions must be monitored.

- **Sensor Power Supply Monitoring**

  The sensor power supplies must be monitored and used for any ratiometric calculations for attached the analog sensor inputs.

- **Safety-Capable Digital Outputs**

  Only safety-capable digital outputs with feedback and Safe Group features should be used to control safety-related outputs.

- **Safety-capable Multifunction (PWM/DOUT/PVGOUT) Outputs**

  Only safety-capable Multifunction (PWM/DOUT/PVGOUT) outputs with feedback and a Safety-FET should be used to control safety-related outputs.

- **High-Side and Low-Side Outputs**

  A high-side and a low-side output should be used to control a safety-related load if current shall be sunk.

- **Continuous Sampling of PWM Feedback**

  PWM feedback shall continuously be sampled and compared with the setpoint.

- **Over-Current Signal**

  The application must verify that the output current overload status returns to zero after commanding a zero output current or turning off the output.

- **Shutdown of Safety-Critical Outputs**

  The user application software must implement shutdown of safety critical outputs based on user application software safety requirements.

- **Strategies to Mitigate Against Corrupted RAM**

  The user has to implement strategies to mitigiate against effects of corrupted RAM, such as checksums, CRCs, or shadow copies of safety-critical data.

- **Non-Volatile Data**

  The application is responsible to ensure that non-volatile data is consistent. This has to be ensured by the application, for example by plausibility checks, range checks, checksums or CRCs, redundant data storage etc. The application is also responsible for ensuring that the write lifetime of the NV data medium is not exceeded.

- **Software Validation**

  The application must be tested for proper function including fault insertion testing. The user application software must be tested for proper response to:
  - Highest frequency input conditions.
  - Highest frequency output conditions.
  - Highest CAN traffic load conditions on the corresponding used CAN buses.
  - The user application software required OSExecTimeout has adequate safety margin

- **Applog (Application Event Logging)**

  The Applog feature (if available) shall not be used for safety-critical data.

- **Fault Manager**

  If faults must be latched, the application shall take care of this operation.

- **Handling of Safe State**

  The system must be designed in a way that it is able to handle outputs suddenly being de-energized, e.g. as a response to a safety-critical failure.

Design Considerations

- **Output Shutdown Verification**

  The user application software must verify that the system is capable of disabling the safety related outputs.

- **Functional Safety Assessment**

  A Functional Safety Assessment must be conducted before the hazards associated with any safety related system constructed using the XL104 Controller are present.

- **Delay Time From Failure Detection**

  The maximum delay time from the onset of a failure to the time at which the outputs reach the safe state is the diagnostic time interval plus 10 ms. The diagnostic time interval (loop time) is defined by the application.

- **Restart Interval**

  It must be ensured that the XL104 Controller is restarted at least every 12 hours.

- **Current Output Periodic Reset**

  If the user application allows it, the current output must periodically be set to zero to allow the zero offset to be recalculated. The zero current offset calculation can take up to 200 ms. For optimal performance, the output current should be set to zero after large temperature changes (>25° C [77° F]) to allow the zero offset to be re-calculated.

- **High Inductance Valves**

  When a high-inductance valve is switched off, false alarms may occur inside the safety layer because the decay of the PWM output current is too slow. This safety monitoring of PWM outputs can be disabled to improve compatibility with high-inductance valves. To do this, set DisableCurrent-DecayRateMonitoring whereby it now becomes the responsibility of the application to monitor the output current for unintended short (overcurrent) conditions. When such a condition is detected, the application must immediately disable (turn off) the output. By default, DisableCurrent-DecayRateMonitoring is not set and the monitoring is done by the kernel.

Environmental Limits

The designer or integrator of a safety critical function must verify that the PLUS+1® XL104 Controller is rated for use within the expected environmental limits of the target application. Refer to the *PLUS+1® XL104-XXXX Controller Technical Information* **BC320261740866** for controller environmental limits.

Application limits

The designer or integrator of a safety critical function must check that the PLUS+1® XL104 Controller is rated for use within the expected application limits. Refer to the *PLUS+1® XL104-XXXX Controller Technical Information* **BC320261740866** for controller limits.

Design verification

Refer to **Failure rates** for a summary of failure rates for the PLUS+1® XL104 Controller.

The achieved Safety Integrity Level (SIL) of an entire Safety Critical Function design must be verified by the designer or integrator via a calculation of PFH considering the I/O required, demand mode, any implemented diagnostics, safety time, and architecture.

The failure rate data listed the FMEDA report is only valid for the useful lifetime of a PLUS+1® XL104 Controller. The failure rates will increase sometime after this useful lifetime period. Reliability calculations based on the data listed in the FMEDA report for mission times beyond the lifetime may yield results that are too optimistic; in other words, the calculated Safety Integrity Level will not be achieved.

Design Considerations

SIL capability

Systematic capability

The systematic capability of the PLUS+1® XL104-XXXX Controller family is SC 2 per IEC 61508.

Random capability

Refer to *Component description and failure rates* on page 7 for a summary of circuit failure rates for the PLUS+1® XL104 Controller. For each user application, the failure rates for that particular configuration should be determined and compared to the allowable failure rate for a given SIL target.

Connection to sensors and actuators

The connection of the PLUS+1® XL104 Controller to the required sensors and actuators must be performed in accordance with the *PLUS+1® XL104-XXXX Controller Family Technical Information*, **BC320261740866**. Machine wiring should be done in a way to minimize EMI and EMC susceptibility.

Safety function requirements

- The system's response time must be less than the process safety time defined by the user application.
- The worst-case response time for a change of value of an analog input or contact signal (measured at the terminals) through the complete system to the completion of change of state of the analog output or contact output (measured at the terminals) will be a maximum of two times the actual loop execution time OS.ExecTime, as measured to the standard outputs. This worst-case time must be determined for the worst-case loading of the safety controller.

Description	Worst case time	Additional information
Diagnostics and Response Times	10 ms	
Flash ROM or SRAM ECC error detect from onset to safe state	10 ms	
Change of input to output	10 ms	Not including ExecTimeOut
Diagnostic error detection time from onset to safe state	10 ms	Diagnostics are based on demand during execution loop

- The maximum delay time from the onset of a failure to the time at which the outputs reach the safe state is the diagnostic time interval plus 10 ms.
- Results from the functional tests and diagnostics must be recorded and reviewed periodically.
- All safety related system components, including the PLUS+1® XL104 Controller, must be operational before machine operation.
- Personnel performing testing on the PLUS+1® XL104 Controller must be competent to perform such testing. Functional Safety Training is provided by Danfoss Power Solutions, and details can be found on the Danfoss Power Solutions Learning website at: **https://www.danfoss.com/en/service-and-support/learning/**

Installation and operation considerations

Installation

The PLUS+1® XL104 Controller must be installed per standard practices outlined in the *PLUS+1® XL104-XXXX Controller Family Technical Information*, **BC320261740866**. The environmental conditions must be verified to not exceed the controller environmental ratings. Instructions on installation of latest version of the safety controller HWD file are found in *How to Install PLUS+1® GUIDE Upgrades Operation Manual*, **11078040**.

Design Considerations

Physical loction and placement

The PLUS+1® XL104 Controller must be mounted in accordance with the *PLUS+1® XL104-XXXX Controller Family Technical Information*, **BC320261740866**., in a low vibration environment. If excessive vibration is expected, special precautions must be taken to ensure the integrity of electrical connections or the vibration should be reduced using appropriate damping mounts.

Repair and placement

The PLUS+1® XL104 Controllers are not repairable and no maintenance of them is required.

Useful life

The useful life of the PLUS+1® XL104 Controller is 30 years. No proof tests are required.

Software/hardware version numbers

See the relevant PLUS+1® XL104 Controller *Data Sheet*.

Security considerations

The PLUS+1® XL104 Controller does not use data that the user can configure externally, for example, by the PLUS+1® Service Tool. The user application software may contain data that is configured externally. If this is the case, then suitable security should be provided. The *PLUS+1 ® GUIDE Software User Manual*, **10100824** provides a description of how to handle parameters in a safe way.

Danfoss Power Solutions notification

Any failures that are detected and that compromise functional safety should be immediately reported to Danfoss Power Solutions. Any change suggestions for future improvements or new features can be forwarded to Danfoss Power Solutions:

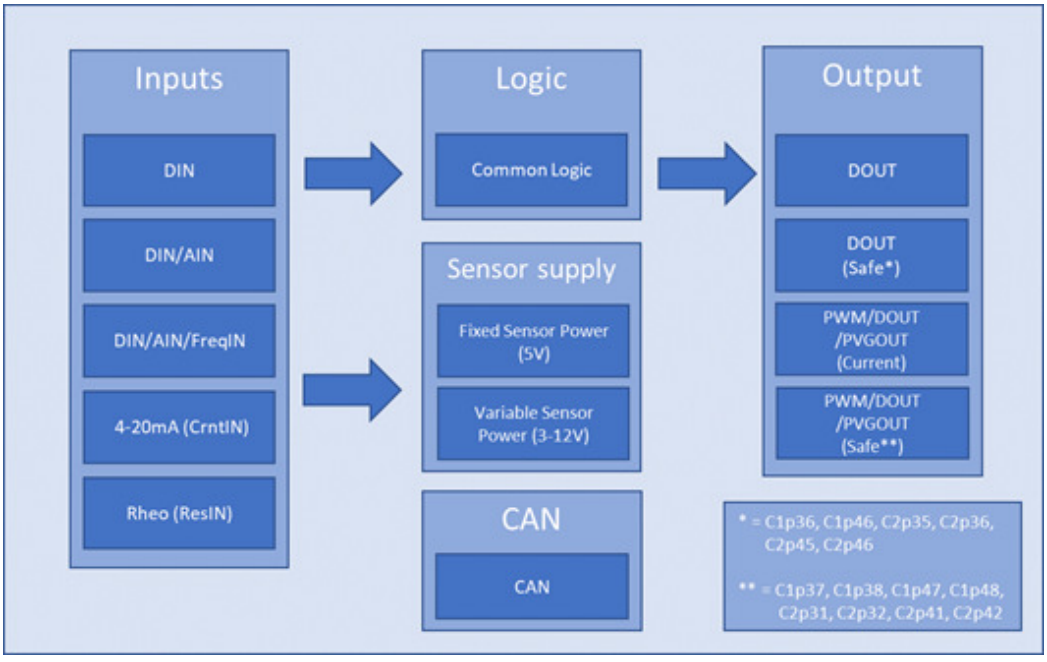
Contact information is online at: **https://www.danfoss.com/en/contact-us/**

Using the FMEDA results

PFH calculation or PFD_{AVG} calculation

This chapter explains how the results from the FMEDA analysis can be used to calculate the contribution of the XL Controller in a safety critical application.

The PFH calculation total will include the failure rate of all sensors and actuators that are required to perform the function as well as the elements of the PLUS+1® XL104 Controller that are utilized. The different function groups from Inputs, Logic, Power Supply and Outputs are illustrated in the safety block diagram below:

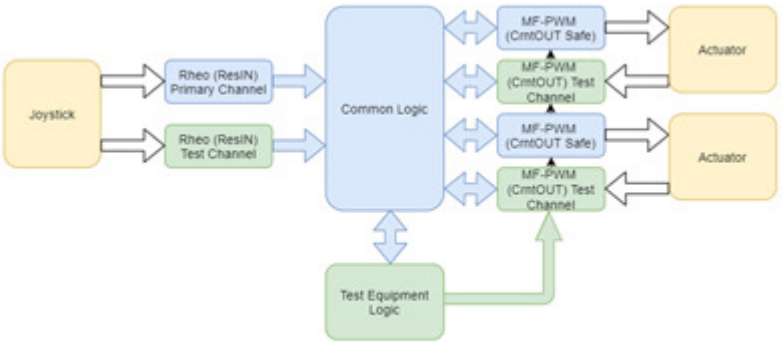


The failure rates for each subsystem are listed in the section *Component description and failure rates* on page 7.

Example application, failure rate analysis

To demonstrate how to calculate the contribution of the PLUS+1® XL104 Controller, consider the example of a steering function that is safety critical. The steering function relies on a Steer Command that is transmitted by a joystick utilizing two redundant Rheo (ResIN) – resistance inputs. The controller processes the input and controls the movement of the machine through a dual path control subsystem utilizing four PWM (current) outputs.

This Safety Function uses a 1oo1D architecture, with diagnostic/test equipment and secondary shutoff/de-energization methods.



Using the FMEDA results

This safety critical function uses one of the inputs as a test channel for comparison with the primary channel. The output actuators are driven in a half-H-bridge MF-PWM output configuration that uses the return MF-PWM output to provide a comparison of the current measurement from the driving channel, as well as a de-energization disconnection.

The safety critical function has an overall failure rate that is the sum of controller subsystems used directly for the function. Test equipment and test channels do not directly contribute to the failure rate of the safety critical function. A Beta-factor may be used to describe the probability of a failure in the test channel at the same time as a failure in the safety function.

- (1x) Rheo (ResIN)
- (1x) Common Logic
- (2x) PWM (CrntOUT Safe)
- (1x) Rheo (ResIN) Test Channel
- (1x) Test Equipment Logic
- (2x) PWM (CrntOUT) Test Channel

In a machine application, the safety critical function could be operating in high demand. In a high demand function, only the dangerous undetected failures are included when calculating the PFH.

PFH (The Probability of Failure on Demand per Hour) is the probability that a system will fail dangerously, and not be able to perform its safety function when required. To be considered a high demand application, the diagnostics must be executed 10 times faster than the process safety time. Care must be taken when modeling a function as high demand. It is recommended that the designer or integrator review the requirements with Danfoss Power Solutions to help avoid understating PFH.

As a system metric, IEC 61508 defines SIL ratings based on the PFH_D of the safety function. Each SIL rating has an associated PFH which increases an order of magnitude for each increase in SIL rating. ISO 13849 defines Performance Level ratings, based on the PFH_D of the safety function. In addition, the Performance Level rating requires a level of Diagnostic Coverage.

Performance Levels and Safety Integrity Levels for Category 2 High Demand Systems

Performance Level (PL)	Probability of dangerous failure per hour (PFH_D)	Diagnostic Coverage	Safety Integrity Level
--	>=10^{-8} to <10^{-7}		SIL 3
d	>=10^{-7} to <10^{-6} ($MTTF_D$=High)	90%< DC <99% (Medium)	SIL 2
c	>= 10^{-6} to < 3x10^{-6} ($MTTF_D$=Medium to High)	60% < DC <90% (Low to Medium)	SIL 1
b	>= 3x10^{-6} to <10^{-5} ($MTTF_D$=Medium)	60% < DC <90% (Low to Medium)	SIL 1

A Probability of Failure per Hour (PFH) must be determined for each Safety Critical Function.

Failure rate analysis for the example function (FIT)

Controller Subsystem	Qty	λ_S	λ_{DD}	λ_{DU}	Total λ_D (λ_{DD} + λ_{DU})	DC	Beta Factor
Rheo (ResIN) primary	1	0	20.5 *(.99*20.7)*	0.21 *(.01*20.7)*	20.7 *(13.6+7.1)*	99%*	
Common Logic	1	95.5	1420	176	1596	88.9%	
MF-PWM (CrntOUT w/Safety FET)	2	33	66.2 *(.99*66.9)*	0.67 *(.01*66.9)*	68.6 *(57+11.6)*	99%*	
Primary Subtotal		**161.5**	**1573**	**177.6**	**1754**		
Rheo (ResIN) Test Channel	1	0	20.5 *(.99*20.7)*	0.21 *(.01*20.7)*	20.7 *(13.6+7.1)*	99%*	2%
Test Equipment Logic	1	27.9	123	8.5	131.5	93.6%	2%

Using the FMEDA results

Failure rate analysis for the example function (FIT) (continued)

Controller Subsystem	Qty	λ_S	λ_{DD}	λ_{DU}	Total λ_D (λ_{DD} + λ_{DU})	DC	Beta Factor
MF-PWM (CrntOUT) Test Channel	2	19.8	57.6 *(.99*58.2)*	0.58 *(.01*58.2)*	58.2 *(48.6+9.6)*	99%*	2%
Test Equipment subtotal		**67.5**	**259**	**9.9**	**269**		
Safety Function Total (Primary + Test Equipment*Beta factor)		**270.2**	1573 + 0.02*259 = **1578**	177.6 + 0.02*9.9 = **177.8**	1757 + 0.02*269 = **1759**	1578 / 1759 =**89,7%**	

*= The implementation of the recommended diagnostics (see the section *Recommended diagnostics* on page 8) affects the system failure rate. In this example, the two input Rheo (ResIN) functions individually have a DC of 69.5%, but when used in a redundant configuration and checked against each other, the diagnostic coverage is raised to 99%. Similarly, the PWM (CrntOUT) functions will have a DC of 99% when connected as an H-bridge to an actuator.

In this example the PFH is the undetected failure rate λ_{DU}, which is **177.8 FIT** (failures per 10^9 hour) or 1.778×10^{-7} dangerous failures per hour. The function diagnostic coverage is 89.7%.

Since the Diagnostic Coverage for this Safety Function is below 90%, the simplified procedure for determining PL shown in IEC13849 Sec 4.5.4 Table 6 cannot be used. Instead, the function PFH (λdu) must be low enough to achieve PL d according to IEC13849.1 Annex K Table K.1. In Table K.1 the maximum allowed dangerous failure rate (PFH) for a Category 2, PL d function with Low (60%) DC is 1000 FITs.

The total contribution of the XL104 controller to the PFH of this function is 177.8 FITs or 17.8% of the maximum allowable PL d failure rate. The machine sensors and actuators can use the remaining 82% of the allowed failure rate to build the complete safety function.

Common cause failure mitigation

ISO 13849-1 Appendix F defines an estimation of the effect of Common Cause Failures (CCF) in Table F.1 The PLUS+1® XL104 Controller scores 65 in measures against CCF in Design/Application/Experience per sections 3, 4, 5 and 6. Sections 1 and 2 are highly dependent on the machine and application implementation and are not included in the score for the PLUS+1® XL104 Controller. A score of 65 or higher is needed to meet the requirements of ISO 13849-1.

Section 1 of Table F.1 mentions various measures against CCF based on Separation and Segregation. The following discussion can be used to implement better CCF separation when using the PLUS+1® XL104 Controller's Input and Output circuits.

Digital Outputs on Safebank groups

The PLUS+1® XL104 Controller DOUT (4A) Safebank groups are implemented in pairs of outputs. The Safebank will enable or disable battery power to both Digital Outputs on that Safebank.

Safe Bank	Digital Output
1	C1p36
	C1p46
2	C2p35
	C2p45
3	C2p36
	C2p46

Common cause failure mitigation

Multifunction Current output safety function pairing recommendations

The PLUS+1® XL104 Controller Multifunction Current outputs are implemented as groups of four, sharing common amplifier and digital IC's. Their current feedback signals are grouped onto different A-D converters on the MCU for peripheral and package CCF separation. The best CCF separation for a H-bridge function uses two Current outputs from different CCF groups, different ADC groups, and different MCU Package Groups.

Source Groupings (with Safety FET)			
SFF Group 1			
ADC	**MCU**	**PWM**	**Output**
ADC G0	PKG G1	PWM G1	C1p37
			C1p38
			C1p47
			C1p48
SFF Group 2			
ADC	**MCU**	**PWM**	**Output**
ADC G3	PKG G3	PWM G2	C2p31
			C2p32
			C2p41
			C2p42

Sink Groupings			
SFF Group 3			
ADC	**MCU**	**PWM**	**Output**
ADC G3	PKG G3	PWM G5	C2p39
			C2p40
			C2p49
			C2p50
SFF Group 4			
ADC	**MCU**	**PWM**	**Output**
ADC G0	PKG G1	PWM G3	C1p31
			C1p32
			C1p41
			C1p42

The recommended combination for an half H-bridge function should use one output from SFF Group 1 and one output from SFF Group 3, or one output from SFF Group 2 and one output from SFF Group 4.

The Multifunction Current outputs in PWM Group 4 (C1p39, C1p40, C1p49, C1p50) have less MCU package separation from the other PWM groups and are thus less desirable to use for a safety function. If used in a H-bridge configuration, they should be used as a sinking output paired with a Source output from SFF Group 1 or Group 2.

Analog Input Safety Function CCF information

Analog Input signals (DIN/AIN) are implemented in groups of four, sharing common amplifier IC's and circuit pathways. The analog inputs are grouped onto different A-D converters on the MCU for peripheral and package CCF separation. Inputs for the same safety function should use as many different groups as possible. It is not recommended to use two inputs from the same DAGx group together due to poor package CCF separations. MCU package group APG2 has insufficient package separation from either APG1 or APG3 to overcome MCU package CCF considerations.

Common cause failure mitigation

Analog Input SFF Group 1			
Input	**ADC**	**MCU**	**Signal**
DA G1	ADC G0	PKG G1	C1p06
			C1p07
			C1p11
			C1p12

Analog Input SFF Group 2			
Input	**ADC**	**MCU**	**Signal**
DA G2	ADC G0	PKG G1	C1p26
			C1p27
			C1p28
			C1p29

Analog Input SFF Group 3			
Input	**ADC**	**MCU**	**Signal**
DA G3	ADC G3	PKG G3	C2p05
			C2p06
			C2p07
			C2p08

Analog Input SFF Group 4			
Input	**ADC**	**MCU**	**Signal**
DA G4	ADC G3	PKG G3	C2p01
			C2p02
			C2p03
			C2p04

Analog Input SFF Group 5			
Input	**ADC**	**MCU**	**Signal**
DA G5	ADC G0	PKG G1	C1p05
			C1p15
			C1p25
			C1p30

Analog Input SFF Group 6			
Input	**ADC**	**MCU**	**Signal**
DA G6	ADC G1	PKG G2*	C1p10
			C1p20
			C1p21
			C1p22

* MCU group PKG G2 has less package separation from either APG1 or APG3 and cannot be considered as fully independent.

Common cause failure mitigation

Analog Input SFF Group 7			
Input	**ADC**	**MCU**	**Signal**
DA G7	ADC G2	PKG G3	C1p16
			C1p17
			C1p18
			C1p19

Digital Input safety function CCF information

Digital Input signals (DIN) are implemented in groups of four to eight, sharing common receiver IC's and input registers. Package CCF for signals on one input register require using non-adjacent pins; the pin order is shown in the Reg Pin column. A good rule is to allow for a 2-pin separation, for example, pins 1 and 3. Signals with Reg Pin A can be used with any other signal in their Register Group as their pin location is further away from any of the other pins.

Input	Register	Reg Pin	Signal
G1	A	A	C2p25
	A	1	C2p23
	A	2	C2p24
	A	3	C2p15
	A	4	C2p14
	A	5	C2p21
G2	A	6	C2p22
	A	7	C2p11
	B	A	C2p12
	B	1	C2p13
	B	2	C2p19
	B	3	C2p20
G3	B	4	C2p30
	B	5	C2p17
	B	6	C2p18
	B	7	C2p27
	C	A	C2p28
	C	1	C2p29
G4	C	2	C2p26
	C	3	C2p16

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