

CIP Safety: Safety networking for today and beyond

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Communication networks changed the look of today's automation systems by distributing processing, sensors, and actuators where they are required. The CIP Safety¹ network is providing the same benefits to safety systems. CIP Safety extends the industry standard CIP network base services by adding CIP Safety² services to transport data for CIP based networks such as DeviceNet and EtherNet/IP with high integrity. This paper presents this scalable, network independent approach to safety networking, where the safety services are described in a well defined layer, allowing the underlying network services to be changed. This approach enables the seamless routing of safety data, allowing the user to create end to end safety chains across multiple links.

Introduction

The same motivations for greater distances, increased flexibility, reduced cost and maintainability which originally moved communication networks into the industrial environment are also driving the development of industrial safety networks, along with the realization of the limitations of traditional hardwired safety solutions³.

Hardwired safety systems employ safety relays which are interconnected to provide a safety function. Hardwired systems are difficult to develop and maintain for all but the most basic applications. Furthermore, these systems place significant restrictions in the distance between devices. As safety system developers progressed beyond basic E-stop functions, they found themselves forced to fall back to hardwired logic techniques, which have been out of widespread use since the early 1970s. Even when they were successful in developing a significant size safety system, they were often costly and difficult to maintain.

Because of these issues, as well as distance and cost considerations, it is desirable to provide safety services on standard communication networks. The key to these developments was not to create a network which couldn't fail, but to create a system where failures in the

network would cause safety devices to go to a known state. If the user knew to which state the system would go, they could make their application safe. But this meant that significantly more checking and redundant coding information would be required. Fortunately communication networks evolved and more capable inexpensive microprocessors became available to implement these additional functions.

To clarify the additional safety requirements, an existing railway standard⁴ was used and later extended by the Germany Safety Bus committee⁵. This provided design guidelines to safety network developers to allow their networks and safety devices to be certified to IEC61508⁶.

However, since the first safety networks were intricately tied to a particular media type or media access scheme, users were forced to change their approach to safety when they changed media or network. This also meant that users who needed a safety chain to span more than one network link, would need to employ complex safety gateways, which now became part of the safety function.

Fortunately, CIP Safety™ is based upon the Common Industrial Protocol (CIP™)⁷, which allows network independent routing of standard data. These base

services were extended to allow high integrity^a safety services, by the addition of the CIP Safety protocol. This paper presents a solution for a scalable, routable, network independent safety layer, thus removing the requirement for dedicated safety gateways. Since all safety devices execute the same protocol, independent of which media on which they reside, the user approach is consistent and independent of media or network used.

CIP Safety: Safety Services built on a Common Industrial Protocol

The Common Industrial Protocol (CIP) is designed to allow different networks to be used with a common protocol. Since it is designed to be media and data link independent, it allows for expansion to future networks. CIP Safety is the TÜV certified^b extension to the standard CIP protocol. It extends the model by adding CIP Safety application layer functionality, as shown in Figure 1.

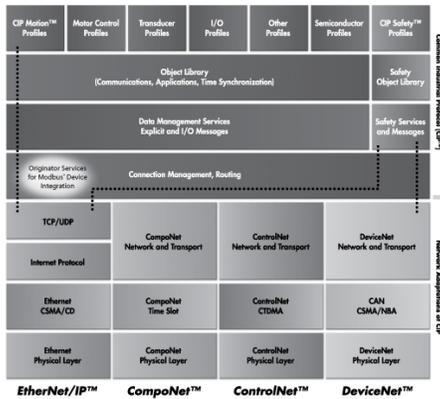


Figure 1: CIP communications layers

Because the safety application layer extensions do not rely on the integrity of the underlying standard CIP services and data link layers, single channel (non-redundant) hardware can be used for the

^a Integrity is defined as the ability to perform a function on demand. IEC61508 requires that the probability of failure on demand be less than 10⁻³ for high integrity SIL3 safety applications.

^b The CIP Safety concept has been approved by TÜV Rheinland for use in IEC61508 SIL3 and EN954-1 Cat. 4 applications.

data link communication interface. This same partitioning of functionality allows standard routers to be used to route safety data, as shown in Figure 2. The routing of safety messages is possible, because the end device is responsible for ensuring the integrity of the data. If an error occurs in the transmission of data or in the intermediate router, the end device will detect the failure and take an appropriate action.

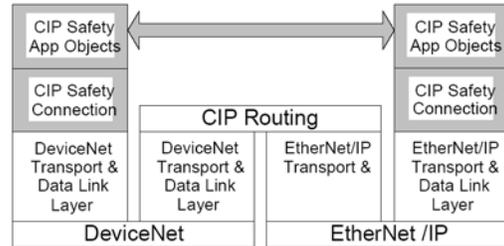


Figure 2: Routing of safety data

This routing capability allows the creation of CIP Safety cells with quick reaction times on DeviceNet, for example, to be interconnected with other cells via other networks such as EtherNet/IP, as shown in Figure 3. Only the safety data that is needed is routed to the required cell, which reduces the individual bandwidth requirements. The combination of fast responding local safety cells and the inter-cell routing of safety data allows users to create significant safety applications with fast response times.

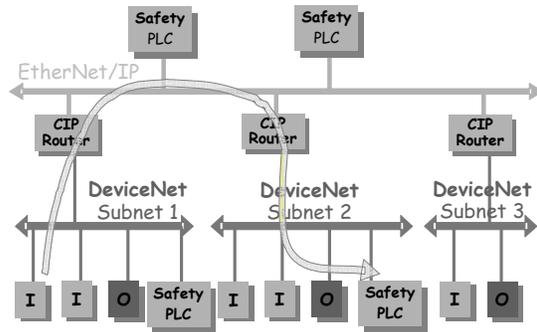


Figure 3: Network Routing

Implementing Safety

The CIP Safety application layer is specified using a Safety Validator object. This object is responsible for managing

the CIP Safety connections and serves as the interface between the safety application objects and the link layer connections, as shown in Figure 4. The Safety Validator ensures the integrity of the safety data transfers.

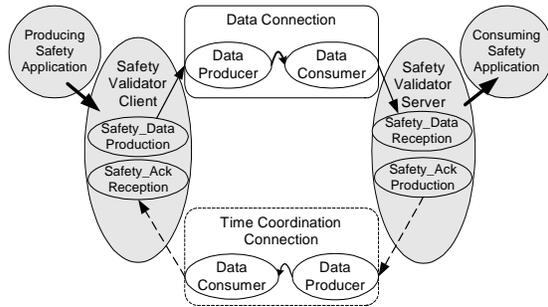


Figure 4: Relationship of Safety Validators

- The producing safety application uses an instance of a client validator to produce safety data and ensure time coordination.
- The client uses a link data producer to transmit the data and a link consumer to receive time coordination messages.
- The consuming safety application uses a server validator to receive and check data.
- The server uses a link consumer to receive data and a link producer to transmit time coordination messages.

The link producers and consumers have no knowledge of the safety packet and fulfill no safety function. The responsibility for high-integrity transfer and checking of safety data lies within the Safety Validators.

Safety Validators Ensure Integrity

CIP Safety does not prevent communication errors from occurring, but it ensures transmission integrity by detecting errors and allowing devices to take appropriate actions. The Safety Validator is responsible for detecting these communication errors. The nine communication errors which must be

detected are shown in Table 1^c along with the five measures CIP Safety uses to detect these errors.

Com. Errors	Measures to detect communication errors				
	Time Expectation via time stamp	ID for send and receive	Safety CRC	Redundancy with Cross Checking	Diverse measure
Message Repeat	X		X*		
Message Loss	X		X*		
Message Insertion	X	X	X*		
Incorrect Sequence	X		X*		
Message Corrupt			X	X	
Message Delay	X				
Coupling of safety and safety data		X			
Coupling of safety and standard data	X	X	X	X	X
Increased age of data in bridge	X				

* The Safety CRC provides additional protection for communication errors in fragmented messages.

Table 1: Error detection measures

Time Expectation via a Timestamp

All CIP Safety data is produced with a timestamp which allows safety consumers to determine the age of the produced data. This detection measure is superior to the more conventional reception timers. Reception timers can tell how much time has elapsed since a message was last received, but they do not convey any information about the actual age of the data. A timestamp allows transmission, media access/arbitration, queuing, retry and routing delays to be detected.

^c Initially based on Draft proposal test and certification guideline, safety bus systems, BG Fachausschuß Elektrotechnik 28-May-2000.

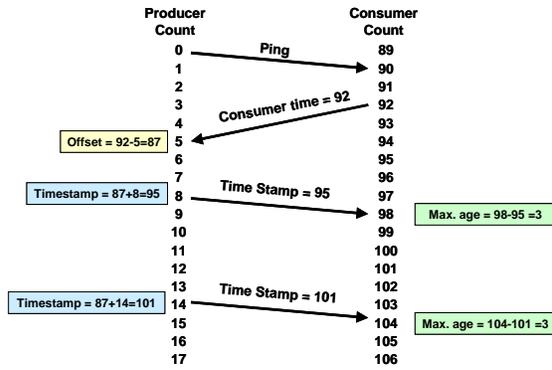


Figure 5: Timestamp

Time is coordinated between producers and consumers using ping requests and ping responses, as shown in Figure 5. After a connection is established, the producer will produce a ping request, which causes the consumer to respond with its consumer time. The producer will note the time difference between the ping production and the ping response and store this as an offset value. The producer will add this offset value to its producer time for all subsequent data transmissions. This value is transmitted as the timestamp. When the consumer receives a data message, it subtracts its internal clock from the timestamp to determine the data age. If the data age is less than the maximum age allowed, the data is applied, otherwise the connection goes to the safety state. The device application is notified so that the connection safety state can be appropriately reflected.

The ping request and response sequence is repeated periodically to correct for any drift in producer or consumer crystal drift.

Time stamps provide availability

A safety network is only useful for production if it is available. False trips reduce availability and limit the useful applications of a network. CIP Safety provides tolerance to minor disturbances by allowing retransmissions. As long as the retransmission is received before the expected time interval expires, the network connection can continue to operate.

Production Identifier (PID)

A Production Identifier is encoded in each data production to ensure that each received message arrives at the correct consumer. The PID is derived from an electronic key, the device Serial Number and the CIP Connection Serial Number. Any device inadvertently receiving a message with the incorrect PID will go to a safety state. Any device that doesn't receive a message within the expected time interval with the correct PID will also go to a safety state. This measure ensures that messages are routed correctly in multilink applications.

Safety CRC (Cyclic Redundancy Code)

All safety transfers on CIP Safety use Safety CRCs to ensure the integrity of the transfer of information. The Safety CRCs serve as the primary measure to detect possible corruption of transmitted data. They provide detection up to a Hamming distance^d of 4 for each data transfer section, though the overall Hamming distance coverage is greater for the complete transfer due to the redundancy of the protocol. The Safety CRCs are generated in the safety producers and checked in the safety consumers. Intermediate routing devices do not examine the Safety CRCs. Thus by employing end-to-end Safety CRCs, the individual data link CRCs are not part of the safety function. This eliminates certification requirements for intermediate devices and helps to ensure that the safety protocol is independent of the network technology. The Safety CRC also provides a strong protection mechanism which allows underlying data link errors such as bit stuffing⁸ or fragmentation errors to be detected.

The individual link CRCs are not relied on for safety, but they are still enabled. This provides an additional level of protection and noise immunity, by allowing data retransmission for transient errors at the local link.

^d Hamming distance is used in communication theory to measure the minimum number of bit errors required before a transmission error may not be detected.

Redundancy and Crosscheck

Data and CRC redundancy with cross checking provides an additional measure of protection by detecting possible corruption of transmitted data. They effectively increase the Hamming distance of the protocol. These measures allow long safety data packets, up to 250 bytes, to be sent with high integrity. For short packets of 2 bytes or less, data redundancy is not required; however, redundant CRCs are cross checked to ensure integrity.

Diverse Measures for Safety and Standard

The CIP Safety protocol is present only in safety devices; this prevents standard devices from masquerading as a safety device.

Safety Connections

CIP Safety provides two types of safety connections:

- Unicast
- Multicast

A unicast connection, as shown in Figure 6, allows a Safety Validator Client to be connected to a Safety Validator Server using two link layer connections.

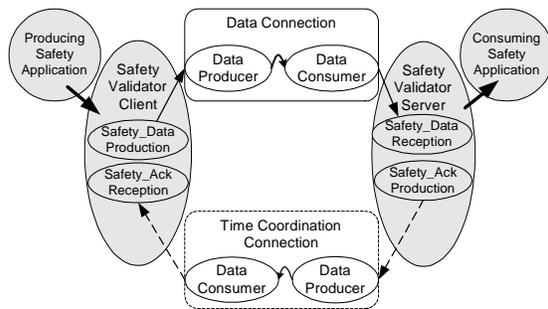


Figure 6: Unicast Connection

A multicast connection, as shown in Figure 7, allows up to 15 Safety Validator Servers to consume safety data from a Safety Validator Client. When the first Safety Validator Server establishes a connection with a Safety Validator Client, three link layer connections are established: one for data, one for time correction and one for

time coordination. Each new Safety Validator Server will use the existing data and time correction connection and establish a new time coordination connection with the Safety Validator Client.

When multicast messages are routed off link, the router combines the data and time correction messages from DeviceNet and separates them when messages reach DeviceNet. Since the safety message contents are unchanged, the router provides no safety function.

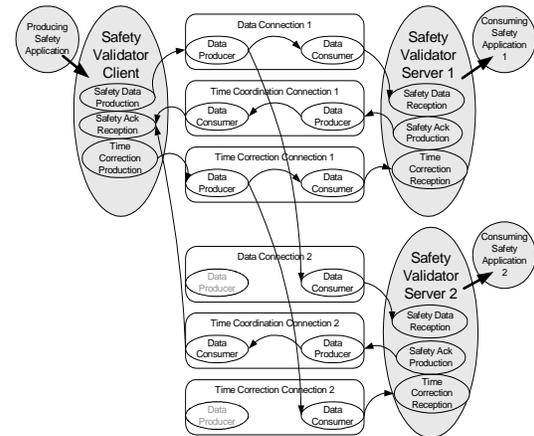


Figure 7: Multicast Connection

Message Packet Sections

CIP Safety has four message sections:

- 1) Data section
- 2) Timestamp section
- 3) Time correction section
- 4) Time coordination section

CIP Safety supports two formats for the data section. The short format, shown in Figure 8, provides high integrity transmission for up to 2 bytes of safety data and serves as the primary format for most safety data messages. It includes a single instance of the safety data, an 8-bit Safety CRC and an 8-bit Safety CRC calculated on an inverted image of the data.

Short Data Section			
Actual Data	Mode Byte	Actual CRC	Comp. CRC
1-2 Bytes		CRC-S1	CRC-S2

Figure 8: Short Data Section Format (1-2 bytes)

The long format, shown in Figure 9, provides high integrity transmission for up to 250 bytes of safety data. In the long format the original safety data and inverted safety data are sent along with a 16-bit Safety CRC and a 16-bit Safety CRC of the inverted safety data. This strong protection mechanism allows safety messages to be as long as 250 bytes.

Long Data Section				
Actual Data	Mode Byte	Actual CRC	Complemented Data	Comp. CRC
3-250 Bytes		CRC-S3	3-250 Bytes	CRC-S3

Figure 9: Long Data Section Format (3-250 bytes)

The Timestamp section of the protocol, as shown in Figure 10, is used to mark the production time of all safety productions.

Time Stamp Section		
Mode Byte	Time Stamp	CRC_S1

Figure 10: Timestamp Section

The time correction section, shown in Figure 11, is used only for multicast messages. It is used to adjust an individual consumer's time count for multicast connections. This section is not needed in unicast messages because each producer is only associated with a single consumer.

Ack_Byte	Consumer_Time_Value	Ack_Byte 2	CRC-S3
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Figure 11: Time Correction Section (multicast only)

The time coordination section, shown in Figure 12, contains the information sent from consumers to producers to correct the time value.

MCast_Byte	Time_Correction_Value	MCast_Byte 2	CRC-16
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Figure 12: Time coordination section

The Complete Message Telegrams

The individual message sections are appended together to form complete message telegrams. Figure 13 and Figure 14 show the message packets for short data messages (1-2 bytes).

The unicast message packet, shown in Figure 13, appends the data section to the timestamp section to form the producer to consumer message packet. The consumer to producer message packet consists entirely of the time coordination message section.

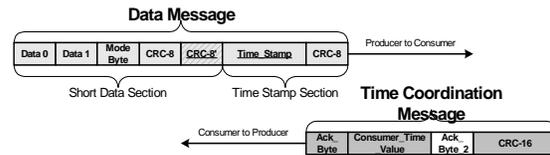


Figure 13: Unicast Message Packets

In the multicast message packet, as shown in Figure 14, an additional Time Correction message is added from the producer to consumer to provide time synchronization among the multiple consumers.

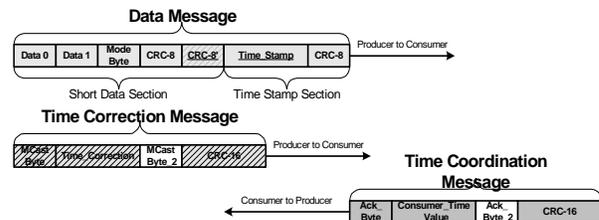


Figure 14: Multicast Message Packets

The complete message telegram for long messages is formed by replacing the short data section in Figure 13 and Figure 14 with the long data section shown in Figure 9.

Configuration

Before safety devices can be used in a safety system, they must first be configured and connections must be established. The process of configuration requires configuration data from a configuration tool to be placed in a safety device. There are two possible sequences for configuration:

- configuration tool directly to device, or
- via an intermediate device.

In the configuration tool to device case, as shown in Figure 15, the configuration tool writes directly to the device to be configured (1) (2).

In the case of intermediate device configuration, the tool first writes to an originator (1) and the originator writes to the target using an Originator to Target Download (3) or a *Safety_Open* service (4). The *Safety_Open* service (4) is unique in that it allows a safety connection to be established at the same time that a device is configured.

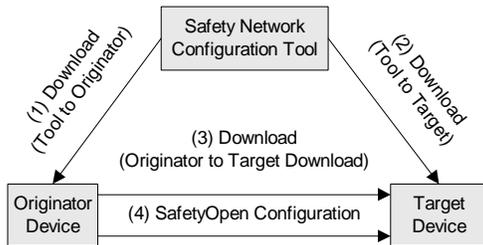


Figure 15: Configuration Transfers

Connection Establishment

The DeviceNet and EtherNet/IP protocols provide a connection establishment mechanism, using a *Forward_Open* service which allows producer to consumer connections to be established locally or across multiple links via intermediate routers. An extension of the *Forward_Open*, called the *Safety_Open* service has been created to allow the same multi-link connections for safety.

There are two types of *Safety_Open* requests:

- Type 1: With configuration
- Type 2: Without configuration

With the Type 1 *Safety_Open* service, configuration and connections are established at the same time. This allows rapid configuration of devices with simple and relatively small configuration data.

With the Type 2 *Safety_Open* service, the safety device must first be configured and the *Safety_Open* service then establishes a safety connection. This separation of configuration and connection establishment allows the

configuration of devices with large and complex configuration data.

In both cases, the *Safety_Open* service establishes all underlying link layer connections: across the local link as well as any intermediate links and routers.

Configuration Implementation

CIP Safety provides the following protection measures to ensure the integrity of configuration:

- Safety Network Number
- Password Protection
- Configuration Ownership
- Configuration Locking

Safety Network Number

The safety network number provides a unique network identifier for each network in the safety system. The safety network number combined with the local device address allows any device in the safety system to be uniquely addressed.

Password Protection

All safety devices support the use of an optional password. The password mechanism provides an additional protection measure, prohibiting the reconfiguration of a device without the correct password.

Configuration Ownership

The owner of a CIP Safety device can be specified and enforced. Each safety device can specify that its configuration is configured by a selected originator or that the configuration is only configured by a configuration tool.

Configuration Locking

Configuration locking provides the user with a mechanism to ensure that all devices have been verified and tested prior to being used in a safety application.

Safety Devices

The relationship of the objects within a safety device is shown in Figure 16. Note that CIP Safety extends the CIP common object model, with the addition of Safety I/O assemblies, Safety Validator, and Safety Supervisor objects.

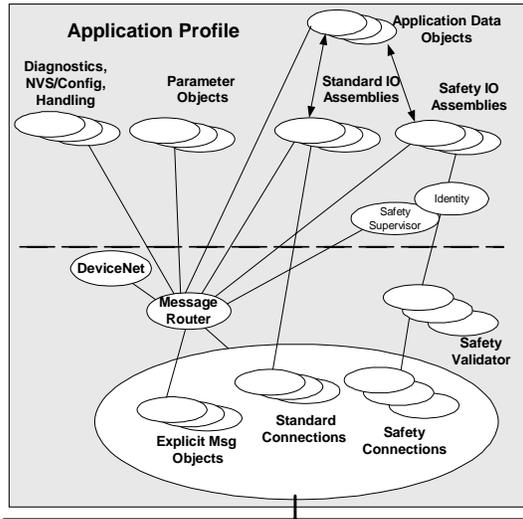


Figure 16: Safety Device Objects

Safety Supervisor

The Safety Supervisor object provides a common configuration interface for safety devices. The Safety Supervisor object centralizes and coordinates application object state behavior and related status information, exception status indications (alarms and warnings), and defines a behavior model which is assumed by objects identified as belonging to safety devices.

Summary

Communication networks have changed how today's automation systems operate by distributing processing, sensors, and actuators where they are needed. The CIP Safety provides these same benefits to safety systems, by providing a scalable, routable network independent safety protocol. Functions such as multicast messaging provide a strong foundation that enable users to create fast responding local cells that are required for today's safety applications, while advanced functions such as

multilink routing permit the seamless interconnection to remote cells to meet the expansion needs of the future.

References

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- ⁷ ODVA: CIP Common Specification, Volume 1, Edition 2.1, January 2005
- ⁸ Eushiuan Tran, May 1999 Multi-Bit Error Vulnerabilities in the Controller Area Network Thesis, CMU

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