IO-Link Safety System Description

Technology and Application

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Introduction

Purpose of this document is to provide an overview of the capabilities and limits of IO-Link Safety to

- Managers,
- Designers,
- Implementers, and
- Integrators

of automation systems requiring risk protection with the help of functional safety equipment.

IO-Link Safety is based on the IO-Link technology standardized within the international standard IEC 61131-9. This standard specifies a single-drop digital communication interface technology (SDCI) for sensors, actuators and mechatronics. It extends the traditional switching input and output interfaces as defined in IEC 61131-2 towards a point-to-point communication link using coded switching. This technology enables cyclic exchange of digital input and output process data as well as acyclic exchange of parameter and diagnosis data between a Master and its associated Devices. A Master can be coupled via gateway to an upper level system such as a fieldbus with programmable logic controllers.

Main benefits of IO-Link as a “black channel” for safety communications are

- Extremely low cost and smallest dimensions
- No special ASICs required
- Any Device with only one interface
- Robust digital communication
- Gateways to all fieldbuses
- Uniform engineering of Devices

IO-Link is a precondition for Industry 4.0 and Internet-of-Things. It is just going to change the classic automation architecture with separated classes of sensors and actuators at the lowest level towards mechatronic modules with integrated sensors and actuators.

IO-Link Safety is an extension to IO-Link by using an additional safety communication layer on top of both the Master and the Device sides, thus becoming an FS-Master and an FS-Device. Concept has been approved by TÜV-SÜD.

All technologies are supported by the international IO-Link Community. Additional information and the IO-Link Safety specification can be found on www.io-link.com.

1 Safety in automation

Functional safety communication in automation is now proven-in-use for more than 20 years and for fieldbuses several profiles - called FSCP, are standardized in the IEC 61784-3-x series (see www.iec.ch).

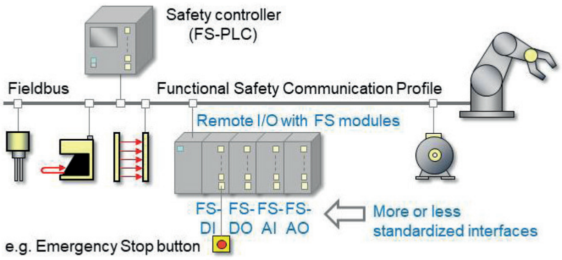

Fig. 1: FS communication

Typically, safety functions according to IEC 62061 or ISO 13849-1 (see www.iso.ch) are realized using safety sensors such as a light curtain, safety logic controllers such as an FS-PLC, and safety actuators such as a drive or other final element. These devices are exchanging safety process data using any of the chosen FSCPs.

Figure 1 also shows functional safety modules such as an FS-DI on a remote I/O that allows connecting electronic safety devices via redundant signals, so-called OSSD ("output switching sensing device"). Pure simple electro-mechanic devices, for example Emergency-Stop buttons, can also be operated on such FS-DIs.

Similarly, other module types are available for functional safe digital outputs to drive, for example, relays. Functional safe analog inputs are used for measurement devices as shown in figure 2.

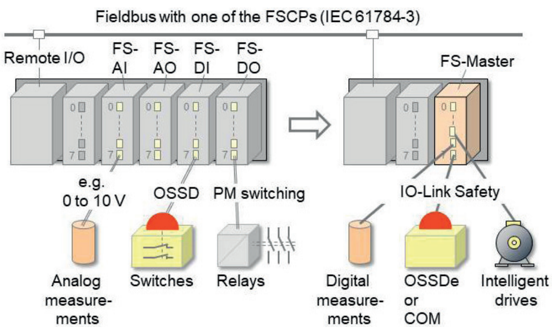

Fig. 2: Remote I/O

There are a number of more or less standardized interfaces for those module types and device manufacturers are able to distribute just one model of each safety device worldwide for operation on remote I/Os.

2 Why IO-Link Safety?

In case of innovations of their safety devices, manufacturers are considering two main strategic aspects:

- Microcontrollers are getting cheaper and cheaper and new features could be incorporated in my product. However, interfaces such as OSSD do not support this.
- An FSCP could be the solution. However, the product is sold worldwide and as a consequence, several FSCPs would be required to be implemented and supported as illustrated in figure 3.

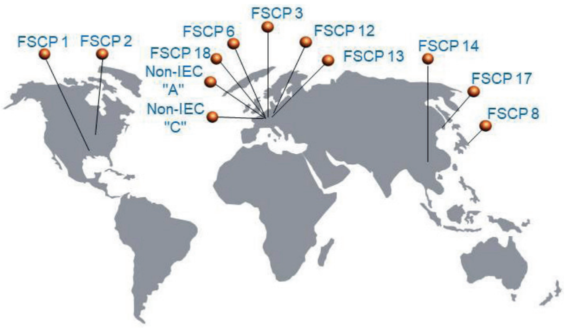

Fig. 3: FSCP world

"Tunneling" one of the FSCP protocols across base IO-Link does not help since implementation and support of several device models for other FSCPs would still be necessary.

A separate dedicated IO-Link Safety communication with one FS-Device is the solution for those manufacturers as illustrated in figure 4.

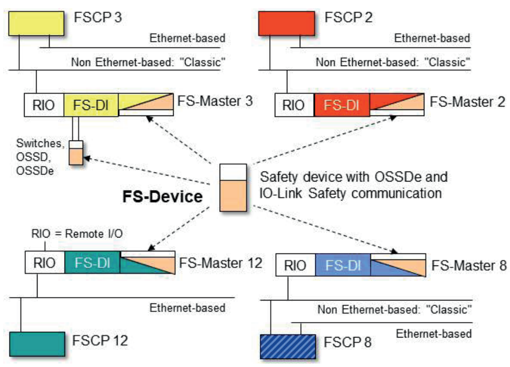

Fig. 4: Single platform solution

Since IO-Link Safety also provides a standardized OSSD interface (OSSDe), the FS-Device can be deployed on classic FS-DI modules thus avoiding a broad model range. Of course, at least one FS-Master "x" including the gateway to a particular FSCP is required to deploy such an FS-Device within that FSCP "x" domain.

IO-Link Safety is even more important for compact remote I/O since an FS-Master can support any type of FS-Device be it a sensor, actuator, or complex mechatronic type at any of its communication ports as illustrated on the right side of figure 2.

This allows for new types of safety applications, for example through local safety logic within the FS-Master in conjunction with higher level safety functions.

In addition, mixed safety and non-safety data transmission allows for e.g. control panels with an E-Stop button.

The point-to-point communication nature of IO-Link Safety reduces effort for the customer (see chapter 4).

3 IO-Link as "Black Channel"

3.1 Principle

Most of the FSCPs are following the "Black Channel" principle. An existing fieldbus is used as a carrier for special types of messages containing safety process data and additional safety code. Purpose of the safety code is to reduce the residual error probability of the data transmission to the level required by the relevant safety standards such as IEC 61784-3 or better. Handling of those messages is performed by a safety communication layer (SCL) on top of the fieldbus.

IO-Link Safety follows this principle as shown in figure 5.

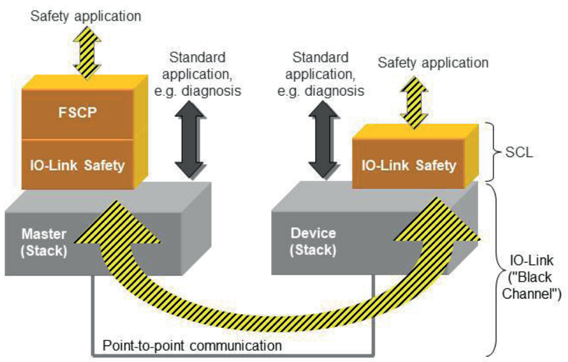

Fig. 5: "Black Channel" principle

The IO-Link SCL are located on top of the FS-Device and FS-Master stack. Exchange of safety process data with an upper level FSCP system takes place via gateway on FS-Master side. Usually, IO-Link SCL instances, FSCP layer and gateway can be realized in software within one unit of redundant microcontrollers.

3.2 Preconditions

IO-Link fulfils the requirement of cyclic process data exchange and a 1:1 relationship between sender and receiver through its point-to-point communications. There are no storing network elements and wireless transmissions permitted between FS-Master port and FS-Device.

FS-Devices usually require more than the maximum permitted wake-up readiness time due to extensive safety testing after power on. Thus, basic IO-Link has been modified slightly and the FS-Master delays the wake-up procedure until the FS-Device is ready ("Ready pulse").

At each port start-up, the FS-Master sends a "Verify Record" such that the FS-Device is able to check correctness of stored parameters, the authenticity (FSCP, port number), and the I/O data structure.

This allows IO-Link Safety to use the Data Storage mechanism of IO-Link in an unchanged manner. Defect FS-Devices can be replaced without tools.

Port power can be switched OFF and ON by the FS-Master to overcome dead-lock situations when OSSD operation is involved.

3.3 OSSDe and SIO

IO-Link Safety specifies the secondary signal line of IO-Link ("Pin 2") for redundant signal operation together with the primary signal line ("Pin 4"). This standardized version is called OSSDe and shown in figure 6.

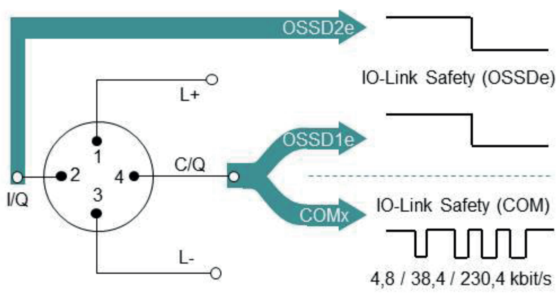

Fig. 6: Port interface extension

Safety communication uses the primary signal line solely and runs on all three transmission rates COM1, COM2, and COM3.

4 IO-Link Safety communication

4.1 Objectives

Three major attributes of safety communication have influence on its residual error probability:

- Timeliness (data arrive just in time),
- Authenticity (data from correct sender),
- Integrity (updated and correct data arrive).

Various errors may occur when messages are transferred between an FS-Master and an FS-Device such as loss, delay, corruption, and alike. IEC 61784-3 is a source of knowledge on such errors and how to calculate residual error probabilities under certain assumptions. The following safety measures have been chosen so that the residual error probability of the data transmission is reduced to the level required by the relevant safety standards such as IEC 61784-3 or better. That means IO-Link Safety communication is suitable for safety functions up to SIL 3 or PL e respectively.

4.2 Safety measures

The safety measures include:

- Numbering of messages between both the FS-Master and FS-Device. FS-Master uses a recurring 3-bit counter value. FS-Device has its own counter, synchronized at protocol start, and responds with a one's complement value.
- Time expectation with acknowledgement via watchdog timer that is always restarted whenever a new IO-Link Safety message with a new subsequent number arrived.
- Authentication at protocol start-up: FS-Device is connected to the correct FS-Master (FSCP's unique connection-ID) and correct FS-Master port ("PortNum"). Cyclically, only the port number is checked.
- Cyclic Redundancy Check (CRC) signature across process data and safety code.

IO-Link Safety uses the so-called explicit transmission of safety measures.

4.3 Formats and data types

Messages from FS-Master and messages from FS-Device are illustrated in figure 7. They consist of two parts. The first part with 4 partitions contains the safety protocol data unit (SPDU) and the last one an optional non-safety PDU.

The first partition holds the functional input or output safe process data depending on the transmission direction: FS-PDout/FS-PDin. They can be coded as BooleanT (bits), IntegerT(16), or IntegerT(32). Most significant octets and/or bits are sent first. Padding bits are "0".

From FS-Master to FS-Device

Output PD	CRC signature	Control&MCnt	PortNum	FS-PDout
	Signature across FS-Output data, PortNum, and Control & counting	Including 3 bit counter	FS-Master port number	0 to 3 octets, or 0 to 25 octets
32 to 0 octets	2/4 octets	1 octet	1 octet	3/25 octets

From FS-Device to FS-Master

FS-PDin	PortNum	Status&DCnt	CRC signature	Input PD
0 to 3 octets, or 0 to 25 octets	Port-number inverted	Including 3 bit counter inverted	Signature across FS-Input data, PortNum, and Status & counting mirror	
3/25 octets	1 octet	1 octet	2/4 octets	32 to 0 octets

Fig. 7: Messages with Safety PDU

IO-Link Safety knows two formats. One is designed for short process data such as bits of shut down signals requiring high speed processing. Size of this partition can be 3 octets maximum. The other one is designed for longer process data such as for measurement or setpoint values. Size of this partition can be 25 octets maximum.

Next three partitions comprise the so-called safety code. Here, the first one (1 octet) holds the port number the FS-Master knows of, or one the FS-Device received during commissioning.

Second partition of the safety code holds Control and Status information (1 octet) to manage and synchronize the protocol activities and the 3-bit recurring counters.

Third partition of the safety code holds a CRC signature. For short process data a 16 bit CRC signature (2 octets) is sufficient, for longer process data a 32 bit CRC signature (4 octets) is defined.

4.4 Services

Sender and receiver of SPDUs are located in layers above the "black channel" communication stacks as shown in figure 5 and 8. Core parts of the layers are specified as state machines controlling the regular cyclic processing of SPDUs and the exceptions such as start-up, power OFF/ON, CRC signature error handling. Figure 8 illustrates how the Safety Communication Layer (SCL) interacts with the technology part in FS-Devices and the SCL instances with the FSCP gateway within the FS-Master.

Main services within the FS-Master provide exchange of FS-PDout and FS-PDin. During start-up, or in case of errors, the actual process data are replaced by default safe data (SDout, SDin). These values shall be all "0" to force the receiver into a safe state, for example de-energize.

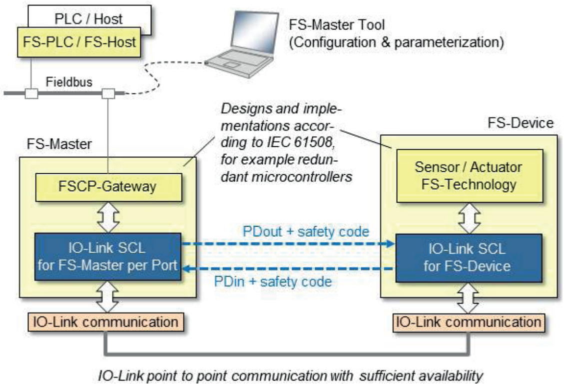

Fig. 8: SCL layer stacks

For FS-Devices where de-energize is not the only possible safe state but rather low speed instead, IO-Link Safety provides additional services via a flag in Control Byte ("Activate safe state"). In return, an FS-Device can inform the receiver via a flag in Status Byte that its safe state has been activated ("Safe state activated").

IO-Link Safety communication errors cause the FS-Master SCL (see figure 8) to switch into a safe state. A safety function is usually not allowed to automatically switch from a safe state to normal operation without human interaction. An additional service informs the FSCP about pending operator intervention and acknowledgement ("…AckReq…"). In turn the FS-Device receives this service also for indication via LED (optional). An operator acknowledgement can be passed over from FSCP to the FS-Master SCL via corresponding service ("…Ack…").

The services for FS-Device technology include the corresponding exchange of FS-PDin and FS-PDout, the extra possibility to activate and report safe data (SD), and the already mentioned operator request indication.

The duration of demand of an FS-Device for a safety reaction shall be long enough to be transmitted by IO-Link Safety communication (at least two increments of the counter). A special service informs technology about new counter values in order to facilitate the realization of this requirement.

Diagnostic information from FS-Device SCL can be passed over to technology via special "SCL Fault" service.

4.5 Protocol parameters

Protocol parameters in IO-Link Safety carry the prefix "FSP_" or "FSCP_" in case of the FS-Master authenticity. Purpose of these parameters is to adjust the SCL behavior to particular application requirements and to check correctness of assignments. They all are arranged in three records within their particular Indices.

The *authenticity record* consists of:

- FSCP_Authenticity1/2
- FSP_Port
- FSP_AuthentCRC

The first one contains the connection-ID of the FS-Master as a participant of the FSCP network. An FS-Device is able to detect incorrect connection to an FS-Master.

The second one contains the port number and allows for checking correct connection to an FS-Master port.

The third one contains a CRC-signature to secure correctness of the values.

The *protocol record* consists of:

- FSP_ProtVersion
- FSP_ProtMode
- FSP_Watchdog
- FSP_IO_StructCRC
- FSP_TechParCRC
- FSP_ProtParCRC

FSP_ProtVersion contains the protocol version in use. FSP_ProtMode defines whether short or long SPDUs to be used. FSP_Watchdog specifies a number of milliseconds for a watchdog timer that monitors the reception of next valid SPDU.

FSP_IO_StructCRC contains a signature across the process data structure of the FS-Device.

FSP_TechParCRC contains a signature across the technology parameters of the FS-Device (see chapter 6).

The signature in FSP_ProtParCRC secures the values of the record.

The *record* in FSP_VerifyRecord serves as hidden diverse verification means at FS-Device start-up. This mechanism is invisible to the user (see chapter 5 and figure 9).

Protocol parameters are set during commissioning with the help of an FS-Master Tool and an IODD with safety parameters of the particular FS-Device.

Some parameters such as Authenticity and FSP_TechParCRC require special values during commissioning scenarios for locking and unlocking. Commissioning is supposed to be monitored operation by personnel.

5 Configuration & verification

Figure 9 illustrates most of the activities at start-up of an FS-Device. After power-on and extensive safety self-tests, which usually may last longer than the standard IO-Link limit, the FS-Device indicates its readiness for wake-up. The FS-Master establishes communication and after the parameterization check of the FS-Device (Data Storage), the FS-Master sends the verification record for safety checks (see chapter 4.5).

FS-Master and FS-Device enter the state "cyclic Process Data exchange" in case of correct authentication and parameterization and automatically the safety communication layer (SCL) will start operating.

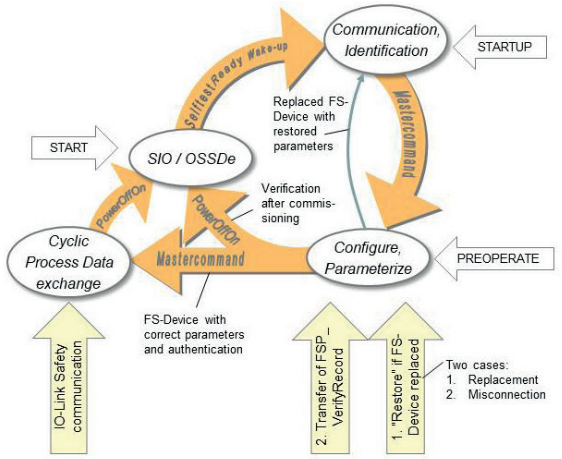

Fig. 9: Start-up of FS-Device

IO-Link Safety considers several scenarios besides the above described regular start-up:

- OSSDe operation (see chapter 7)
- Commissioning - testing
- Commissioning - armed
- FS-Device replacement
- Misconnection of configured FS-Devices

They all are specified within the IO-Link Safety specification.

6 Technology parameters

6.1 IODD

The IO Device Description of IO-Link is the common place for parameters and their permitted ranges for the particular FS-Device technology such as light curtain, laser scanner, proximity switch and etc. are defined within the IODD. They should carry the prefix "FST". User adjusts parameter values within the FS-Device with the help of a FS-Master Tool during commissioning and testing.

6.2 Dedicated Tool

A simple PC program, "Dedicated Tool", comes with the FS-Device and its IODD. Its task is to calculate a CRC signature across all instance values of the technology parameters in a safe manner. The result can be copied into the FSP_TechParCRC.

FS-Device can compare the locally calculated signature with this reference signature.

6.3 Device Tool Interface (DTI)

IO-Link Safety specifies an easy Device Tool Interface (DTI) for the invocation of Dedicated Tools and parameter value transfer.

6.4 Off-site parameterization

IO-Link knows tools such as "USB-Master" for off-site parameterization and testing of Devices. This is possible for FS-Devices also if the corresponding PC program "Master Tool" is upgraded to "FS-Master Tool" for interpretation of IODDs with safety protocol parameters.

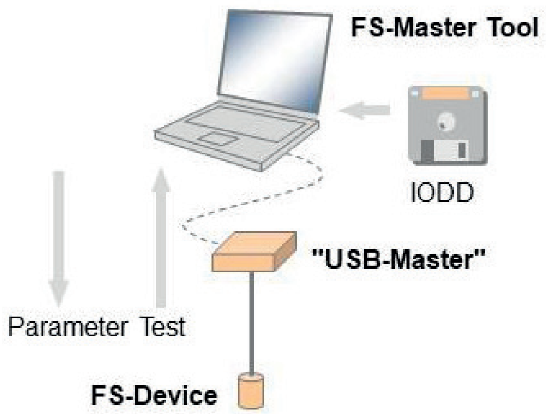

Fig. 10: Off-site parameterization

7 OSSDe operation

OSSDe as specified in IO-Link Safety and shown in clause 3.3 for FS-Devices assumes the following:

- redundant and equivalent switching signals,
- created from solid state electronics,
- test pulses limited to maximum test pulse length of 1000 µs according type C and class 1 requirements of ZVEI position paper CB24I.

These limitations care for less complexity within FS-Master ports or FS-DI modules, for example due to possible use of fixed filter times.

It is possible for safety devices - intended to be used with FS-DI - to use build-in standard IO-Link communication solely for parameterization. IO-Link Community rules as stated in clause 10.1 must be observed.

8 Gateway to FSCP

8.1 Positioning of IO-Link Safety

Figure 11 shows how IO-Link Safety is embedded in the automation and information technology (IT) hierarchy. Safety gateways include but are not limited to Functional Safety Communication Profiles (FSCP).

Embedded controllers such as in drives can use IO-Link Safety technology as well.

8.2 Standardized Master Interface

A new technology in standard IO-Link is the Standardized Master Interface (SMI). It facilitates Master implementations and allows safety concepts to be assessed in a comprehensive and easier manner.

In addition it provides the preconditions for Master Tools to support Masters of different brands.

SMI specifies services for

- Master identification
- Configuration Management (CM)
- Data Storage (DS)
- Acyclic communications (Read/Write)
- Diagnosis (Events)
- Process Data Exchange

Some services are extended in case of IO-Link Safety.

Services for CM take also care for access authorization and the verification record.

Services for acyclic communications provide port power OFF/ON.

Services for Process Data Exchange support exchange of SPDUs in addition to non-safety Process Data.

8.3 Splitter/composer

Part of the Process Data Exchange unit is a so-called splitter and composer. Purpose of the splitter is to extract the SPDU from an incoming IO-Link message.

Purpose of the composer is to combine an SPDU and non-safety Process Data to an outgoing IO-Link message.

In both cases qualifiers are maintained.

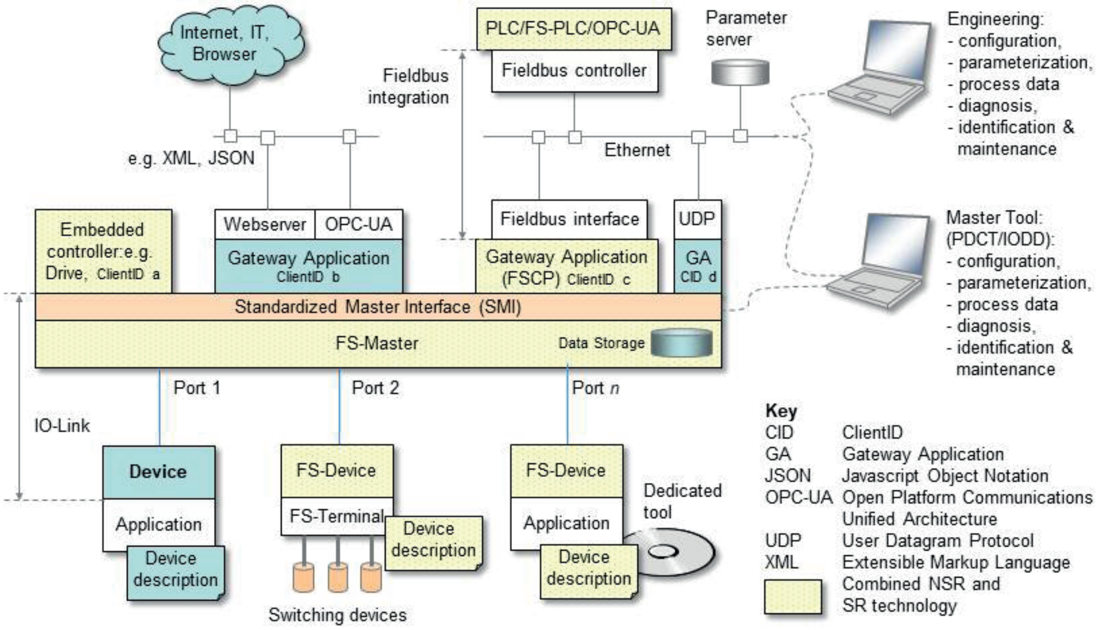

Fig. 11: Positioning of IO-Link Safety

8.4 I/O data mapping to FSCP

Figure 12 shows the role model for mapping of the FS-Device's safety and non-safety Process Data to FSCP and fieldbus virtual remote I/O.

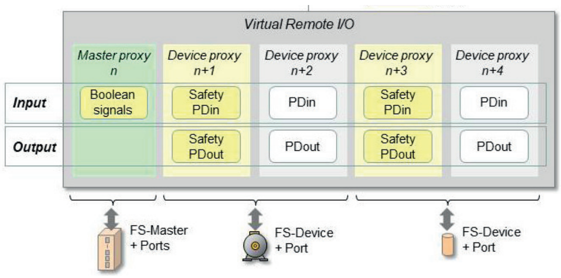

Fig. 12: Role model for mapping

This model allows for an efficient mapping of bit based data structures into one FSCP message similar to for example an FS-DI module. More complex data structures of FS-Devices can be mapped to separate FSCP messages.

The model also provides means for mapping of non-safety Process Data as well as diagnosis information (Events).

8.5 Port specific passivation

In case an FSCP supports channel granular passivation, mapping should consider port specific passivation of IO-Link Safety.

9 Development

9.1 Technology components

In addition to the possibility of implementing the IO-Link Safety specification from scratch, technology components on the market are an alternative. The IO-Link Community does not provide common development kits for FS-Devices, FS-Masters and FS-Master Tools. Technology providers as member companies rather provide technology components. Information is available at www.io-link.com or in workshops.

The advantage of using technology components is obvious: Pre-certified software modules, additional valuable information for example with respect to IODD design, tools, and support.

9.2 FS-Device

Even though IO-Link Safety is suitable for safety functions up to SIL 3 or PL e, it may not be necessary to design and develop the FS-Device also for these safety classes.

IO-Link Safety enables new possibilities for FS-Devices and applications:

- Sensors for proximity, strain, torque, pressure
- Encoders
- Light curtains and Laser scanners
- Digital cameras
- Emergency stop devices with self-testing to avoid yearly inspections

- Operator panels
- Intelligent grippers
- Switchgears
- Motor-starters
- Intelligent drives

9.3 FS-Master

In the meantime, a number of companies are familiar with integration into fieldbuses. Many of them offer FSCP development kits for safety devices such that integration of FS-Master stacks is pretty straight forward if safety development processes are already established.

9.4 Test

Test specification and test equipment are currently in progress. Test patterns for automated protocol testers are ready, generated automatically from protocol state machines.

10 Assessment and certification

10.1 Policy

In order to prevent and protect the IO-Link community from possibly misleading understandings or wrong expectations and gross negligence actions regarding safety-related developments and applications, the following shall be observed by anybody who is dealing with IO-Link Safety, be it a trainer, consultant, designer, implementer, or user of IO-Link Safety devices:

- Any non-safety device will not automatically be applicable for safety-related applications just by using IO-Link and a safety communication layer.
- In order to enable a product for safety-related applications, appropriate development processes according to safety standards shall be established and/or a certification from an assessment body shall be achieved.
- The manufacturer of a safety product is responsible for the correct implementation of the safety communication layer technology (according to IEC 61508 or ISO 13849-1), the correctness and completeness of the product documentation and information.
- The information provided in IO-Link specifications is excluding any liability for correctness and completeness.
- The usage of IO-Link brand names and brand pictures is protected by copyrights and requires a special agreement.

10.2 Safety assessment

Safety assessments according IEC 61508 or ISO 13849-1 must be performed with the help of assessment bodies such as:

- TÜV (worldwide)
- IFA (Germany)
- SP (Sweden)
- SUVA (Switzerland)
- HSE (United Kingdom)
- FM, UL (USA)

10.3 Certification

The IO-Link Test Specification provides information on testing and certification and how manufacturer declarations can be used.

10.4 EMC and electrical safety

IEC 61000-6-7 provides requirements for EMC testing of FS-Master and those FS-Devices for which no product standards exist.

IEC 61010-2-201:2017 provides requirements for electrical safety especially with respect to SELV/PELV.

11 Deployment

11.1 FSCP guidelines

Usually, fieldbus organizations provide design and installation guidelines covering peripherals such as remote I/Os. They also provide security guidelines or refer to the IEC 62443 series respectively.

These guidelines may require updates in case of IO-Link Safety specialties.

11.2 IO-Link guidelines

The IO-Link Community provides a Design Guideline that can be downloaded from the website www.io-link.com.

12 Benefits

12.1 IO-Link general

Benefits of IO-Link, as described in chapter "Introduction" and within the "IO-Link System Description" downloadable from the website www.io-link.com, also apply for IO-Link Safety.

However, the migration strategy is from OSSDe to IO-Link Safety instead of SIO to IO-Link.

Figure 13 shows the major benefits of IO-Link Safety.

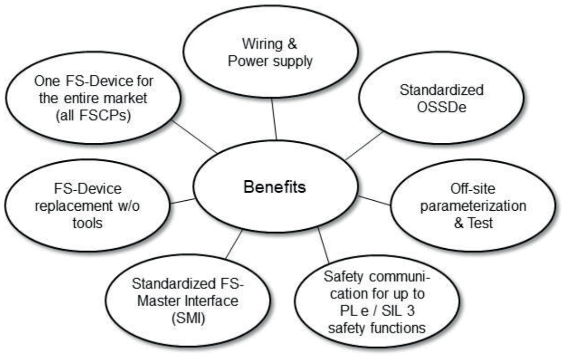

Fig. 13: Major benefits

Benefits for device manufacturers include but are not limited to:

- One standard technology without license fee
- One type of device for FS-DI and FS-Master
- Bidirectional exchange of safety data
- Mixed safety and non-safety process data
- Prewired complex mechatronic modules
- Built-in diagnostics support Condition Monitoring and Predictive Maintenance
- Verification support through authentication
- Simplified engineering via IODD and Dedicated Tool
- Preconditions for Industry 4.0, IoT, and Smart Manufacturing

12.2 Integrators and users

Benefits for integrators and users include but are not limited to:

- One FS-Master Tool for several FS-Master brands possible through SMI
- Holistic engineering of safety functions possible through IODD with information on
    - › Systematic safety (PL / SIL)
    - › Probability of a dangerous failure per hour (PFH)
    - › Device response time

12.3 Future investments

IO-Link Safety has been developed by the IO-Link Community, a fast growing worldwide operating organization of renowned companies.

13 Glossary

Black Channel	Communication channel without available evidence of design or validation according to IEC 61508 [IEC 61784-3]
Condition Monitoring	Major component of predictive maintenance monitoring a parameter of condition in machinery (vibration, temperature etc.).
DTI	*Device Tool Interface*; a software interface for navigation to and invocation of Dedicated Tools including parameter transfer
FS-AI / AO	*Functional Safety Analog Input / Output* module in a remote I/O
FSCP x	*Functional Safety Communication Profile* for a particular fieldbus x, specified within the IEC 61784-3 series
FS-Device	Single passive peer such as a functional safety sensor or actuator to a Master with functional safety capabilities
FS-DI / DO	*Functional Safety Digital Input / Output* module in a remote I/O
FS-Master	Active peer with functional safety capabilities connected through ports to one up to *n* Devices or FS-Devices and which provides a Standardized Master Interface to the gateway to the upper level communication systems (NSR or SR) or controllers with functional safety capabilities
Gateway	Network node equipped for interfacing with another communication system that uses different protocol
Industry 4.0 /IoT	Current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems, the Internet of Things and cloud computing.
IODD	Electronic device description (*IO Device Description*)
IO-Link Safety	Functional safety communication extension for IO-Link
NSR	*Non safety-related*
OSSDe	Output Switching Sensing Device interface standardized in IO-Link Safety according to ZVEI recommendations
Port	IO-Link communication channel on a Master /FS-Master
Predictive Maintenance	Techniques to help determine the condition of in-service equipment in order to predict when maintenance should be performed
Remote I/O	(Fieldbus-) Gateway with (DI/DO) modules to switching devices or with (AI/AO) modules for measuring/analog controlled devices
Safety function	Safety-related system of safety input elements, safety processing, and safety final elements to achieve or maintain a safe state of controlled equipment in respect of a specific hazardous event
SCL	*Safety Communication Layer* representing the safety protocol engine
SMI	*Standardized Master Interface* between (FS-) Master and gateway to an upper level system, thus harmonizing the behavior of Masters and providing uniform access for Master Tools
SPDU	*Safety Processing Data Unit* consisting of safety input/output process data and associated safety code
SR	*Safety-related*

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