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Industry 4.0 for the process industry: Using OPC UA to implement an information model for follow-up of safety instrumented systems

Mary Ann Lundteigen
Engineering Cybernetics, NTNU, Norway. E-mail: mary.a.lundteigen@ntnu.no

Einar Omang
Cognite, Norway. E-mail: einar@omang.com

Maria V. Ottermo[1,2] Stein Hauge[1,2] Shenae Lee[1,2]
[1] *Software Engineering, Safety and Security, SINTEF, Norway.*
[2] *E-mail: maria.v.ottermo@sintef.no, stein.hauge@sintef.no, shenae.lee@sintef.no*

Assurance of functional safety of safety instrumented systems includes monitoring of reliability performance throughout the operational phase. Currently, collecting and analyzing failure data and re-calculating reliability performance are manual and work-intensive tasks. The main objective of this paper is to present a new information model that structures equipment and failure data so that the analysis can be more automated. In addition, some practical challenges in implementing the model with OPC UA, an Industry 4.0 technology platform, and underlying source systems. The work presented has been part of the research-based innovation project "Automated process for follow-up of safety instrumented systems," involving several industry partners. The paper gives a novel contribution to the Industry 4.0 strategy, and the results can be transferable to other sectors. forsan ongoingon

Keywords: Safety instrumented systems, functional safety, maintenance management, OPC UA, information modelling, Industry 4.0.

1. Introduction

Programmable safety systems, commonly called safety instrumented systems (SIS) in the process industry, are vital for controlling hazardous processes and preventing damage to personnel, assets, and the environment. The SIS design must comply with functional safety standards like IEC 61508 (2010) and IEC 61511 (2016), which includes defining performance targets for reliability. Facility owners must maintain SIS reliability according to these targets throughout the operational phase by applying SIS follow-up activities. Here, an essential task is collecting and analysing failures and their impact on the reliability. With digitization and an increased degree of automation, the amount of data is continuously growing.

As of today, the mentioned data is stored in a variety of source systems and documents, such as engineering systems, computerized maintenance management systems (CMMS), safety, and automation systems (SAS), vendor technical documentation, information management systems (IMS), and condition monitoring systems (CMS). The ability to extract and combine the information from these sources is confined, and consequently, considerable manual resources are needed to exploit the data fully. In the Norwegian joint industry project: "Automated process for monitoring of safety instrumented systems" (APOS) (SINTEF, 2023), the goal has been to reduce this manual effort by introducing specifications to data formats and classification for source systems that interact or be interoperable, to automatically update reliability parameters, such as failure rates, with operational data. As part of this work, we developed the first version of the APOS information model, referred to as APOS IM. The foundation for the APOS IM was the newly developed specification on standardization of equipment grouping (Hauge et al., 2023) published by the APOS project.

To demonstrate the implementation of the APOS IM, it was necessary to select an open

data storage and exchange platform advocated by Industry 4.0. The Open Platform Communication - Unified Architecture (OPC UA) published by OPC Foundation (2020a) has been widely adopted within the process industry sector. One of the strengths that is highlighted, for example, by Jaskó et al. (2020), is the interoperability achieved for data exchange from devices located within the physical processes at the lowest level to the information systems at higher (enterprise) levels. However, the most common focus of OPC UA is for monitoring operations with process measurements, historical trending, and alarms. A master project (Omang, 2021) supervised by the APOS project was carried out to demonstrate how the APOS IM could be integrated into an OPC UA environment. This paper incorporates results from this work, including practical challenges experienced when interfacing the OPC UA environment with underlying source systems. The paper gives new insight into the transformation of traditional work processes in process industries to more digitalized processes within the Industry 4.0 framework. A specific case from the oil and gas industry is used in this work, but the results and approaches are transferable to other sectors with similar equipment types.

2. OPC UA for information modelling

OPC UA enables data storage and exchange at all network levels using OPC servers and clients. The aim of OPC UA has been to improve interoperability, both on the transport layer using OPC UA communication protocols and the semantic layer using graph-based data models as emphasized by (Schiekofer et al., 2018).

The use of OPC UA has increased rapidly since its release in 2008, and even more intensively with the publisher-subscribe functionality that came in 2018. Improving the capability of data utilization has become of more focus with digitization efforts. For example, the pairing of real-time and real-world data with digital representations, or twins of the assets for more extensive analyses and optimization are among the objectives of the joint industry efforts like Industry 4.0. Fan et al. (2021) propose an architecture for implementing digital twins (DT) in flexible manufacturing systems using OPC UA. Mourtzis and Vlachou (2018) present cloud-based adaptive scheduling and condition-based maintenance of machine tools, using OPC UA to exchange monitoring data from the shop floor. In Latif et al. (2019), a case study shows how OPC UA protocols are used to enable data exchange between a process controller and a simulator in a chemical process plant, as an approach to facilitate real-time process optimisation. Evidence of the wide adoption of OPC UA in Norwegian process industry is the newly established OPC UA user forum organized by the Norwegian Association for Electrical and Automation Engineering (NFEA).

3. Specification of the APOS IM

The APOS IM is dependent on data from the CMMS system, where operational personnel register, classify, and document SIS failures revealed during operation, testing, and maintenance. The implemented structure of the CMMS largely decides how failure data are reported, and the flexibility of such systems is in most cases limited. The first step is to report the failure against the correct equipment tag. Secondly, when the correct tag is identified, the failure must be reported with sufficient detail and into categories according to the priority and severity of the failure. When reporting SIS failures, it is therefore essential to have (1) a well-structured equipment hierarchy that incorporates the properties/attributes that are expected to affect the equipment reliability, and (2) well-defined and intuitive set of failure parameters to report on, and additional fields for free text to enter other relevant information about the failure. In practice, this process of reporting is considered time-consuming and subject to uncertainty. Many CMMS systems in the oil and gas sector implement ISO 14224 (2016) categories for reliability and maintenance data for equipment. However, operational personnel have pointed out that determining the correct ISO categories can be difficult. The new specification developed by the APOS project (Hauge et al., 2023) has focused on solving some of these issues for SIS equipment. The specification became the foundation of the

supported structured implemented in the APOS IM, which are further elaborated in the following.

3.1. *Equipment hierarchy*

The APOS specification divides each equipment hierarchy into three levels (L1, L2, and L3) with increasing specificity, explained briefly in the following and in more detail in Hauge et al. (2023).

Level 1 (L1) for main equipment groups: L1 groups equipment by primary function. Primary functions may be monitoring and transmitting of process measurements, detection of hydrocarbon gases, stopping of process flow, and facilitating evacuation. Members of the same L1 group generally share the same primary function and will have some common failure modes. Examples of L1 equipment groups are process transmitters and valves. Data collected at L1 level may be applied when a coarse reliability analysis is needed for the equipment. However, current industry practice does not usually rely on L1 data alone when evaluating whether or not the reliability performance is adequate. Instead, L2 (or even L3) data is normally applied (see below). The definition of equipment groups is based on a review and comparison of different company practices and corresponds roughly to the ISO 14224 equipment class ISO 14224 (2016).

Level 2 (L2) for safety-critical elements (SCEs): L2 groups equipment by core operating principle or design. Gas detectors, for example, are divided by gas type and detection mechanism, whereas for process transmitters are split into subgroups for pressure, level, flow, temperature, and vibration transmitters. Members within the same L2 group often experience comparable failure rates, meaning that it is reasonable to calculate failure rates at the L2 level.

Level 3 (L3) for equipment properties: The third level L3 is a further refinement of L2 according to a pre-defined set of attributes or properties with the potential to significantly impact the reliability performance. Analysis of data at the L3 level can reveal differences in reliability-related to specific properties. For process transmitters, an important property is the measuring principle. For instance, level measurement can be based on principles like displacer, differential pressure, free-space radar, nuclear, guided-wave radar, ultrasonic, or float transmitters. Unfortunately, industry standards and guidelines are not aligned in naming attributes/properties and, e.g. radioactive, gamma, or nuclear level transmitters all refer to the same technology. Different naming of the same technology may seem like an unimportant detail, but in reality, it represents an obstacle in the application of open digital platforms for the seamless exchange of data. ISO 14224 (2016) and IEC 61987 (2016) are examples of key references for the listing and naming of relevant properties and attributes. Equipment classified at L3 inherits properties and attributes from its L1 and L2 groups, and an important design criterion to avoid duplication is to place information at the highest possible level in the hierarchy.

3.2. *Failure classification hierarchy*

Failure mode (F) and detection method (D) are two key parameters to distinguish less severe (or safe) failures from severe (or dangerous) failures. Failure cause (C) is an important parameter to decide whether the failure is random or systematic. The APOS IM implements the suggested hierarchy for each of these three parameters in the APOS guideline Hauge et al. (2023), designated D0-D2, F0-F2, and C0-C2 respectively.

Detection method: The detection method generally refers to the process that triggered the investigation of a possible failure. This may be a scheduled test, casual observation, or a failure to function on demand. D0 splits between events that were immediately detected on occurrence and events that were hidden for some time before detection. D1 further splits undetected (hidden) events into scheduled and unscheduled tests, while D2 splits each of these even further based on the specific type of test.

Failure mode: The failure mode refers to the method by which the component failed, such as too low or too high output, minor irregularities, or loss of containment. F0 divides failures into

"critical", where the safety function has been impaired, and "other" if the component was still able to perform its primary function. F1 provides a further division into 1) Safety Function Impaired, 2) Safe/spurious failure, and 3) Non-critical failure, whereas F2 contains specific failure modes. Each L1 equipment group has a list of legal F2 failure modes, used for simplifying the event classification process.

Failure cause: Finally, the failure cause refers to the direct or underlying cause of a failure. Again, there is a division from C0-C2 with increasing specificity. Unlike failure modes and detection methods, the list of failure causes is generally not exhaustive since it is difficult to predict all possible underlying causes. There are four C0 groups and nine C1 groups, and all possible causes should fit within one of the C1 groups. For example, at C0 level, it is distinguished between causes related to degradation/stress, component inadequacies (non-degradation related), operator and user related, and documentation/management.

4. APOS IM with OPC UA

The implementation of the APOS IM is based on the base OPC UA standard (OPC Foundation, 2020a) and the ISA 95 companion standard (OPC Foundation, 2020b), with some new suggested extensions not covered by any of these.

4.1. *Use of existing features*

An OPC UA information model is a node graph that can organise and link both static and dynamic data. The nodes are connected with references, which may be hierarchical or non-hierarchical. Nodes may be simple containers for static or dynamic data or represent physical or logical elements. The different purposes of nodes are indicated by their Node Class, and OPC UA defines eight different Node Classes. Six of these were used in the implementation of the APOS IM : object, variable, object type, variable type, reference type, and data type.

One challenge of the base OPC UA information model is that it is very generic, and hence a lot of work is required to apply it to a specific industrial application. For this reason, several companion standards have been developed. The process industry therefore developed an ISA-95 companion standard based on ISA-95(ISA, 1995), a standard developed by the International Society of Automation on organising plant data, including its equipment and related work processes for operation and maintenance. The ISA-95 companion standard allows a hierarchy of classes represented by object types in OPC UA, so that some common properties that are described for a larger group of similar equipment. For example, ISA-95 companion standard specifies OPC object types for e.g. valves and sub-categories of these, like on/off valves, which can inherit the valve properties while adding some that are more specific. The main advantage of this approach is less duplication of information in the information model. The ISA-95 specific object for on/off valves can present data such as the type of valve, required traveling time, whether the valve is fail-open or fail-close, and the type of medium that flows through the valve.

As mentioned previously, the APOS IM was based on selected node classes of OPC UA *and* the ISA-95 companion standard, but further extended with new capabilities for organising safety critical equipment and classifying failure events according to safety standards, like IEC 61511 (IEC 61511, 2016). For the realisation of the APOS IM, it was important to decide how to integrate the new types and ISA 95 classes with existing existing information models already deployed in an OPC UA server or server architecture. It was also important to specify a suitable setup for clients (i.e. receivers of data for monitoring and analysis) that need to access or browse the server data.

For simple servers, the node hierarchy will generally be a static part of the server, while live values are read from device inputs or outputs. A more complex server might provide a static node hierarchy for each underlying device and serve as a master for several distributed devices. This first implementation of APOS IM relied on establishing interfaces for information and data exchange with underlying (source) systems that did not have an OPC UA interface; however, other implementations could be possible if relaxing this

requirement.

4.2. *New APOS IM extensions*

Two types of extensions were needed to complement the ISA-95 companion standard: Extensions to model equipment hierarchies and extensions needed to classify failures. Each of these are described in the following.

Extensions for equipment hierarchy: The APOS IM implements the three-level hierarchy of equipment (L1 - equipment group, L2 - equipment function, and L3 - equipment properties) by adding new extensions named APOSBaseClassType to the already pre-defined templates of ISA-95 companion standard. ”APOS Equipment types are ISA-95 Physical Asset Classes, so the equipment hierarchy is added as a subtype of PhysicalAssetClassType. A base class AposBaseClassType was added as root, and L1 types are added as subtypes of this as shown in Fig. 1. For example the L1 type FireDetectors.” Properties are added at each level to indicate common properties for subtypes. A property added to FireDetectors would apply to all L2 and L3 FireDetector types, and similarly for L2 types. For example, heat detectors have a ”MeasuringPrinciple” property, that does not apply to other fire detectors. This would be added as a property to the L2 group ”HeatDetectors”, with an enumeration of two legal values: ”0: FixedTemperature” and ”1: RateOfRise”. At L2 this is not set, as L3 heat detectors may take either of these values. If all heat detectors had the same principle, the value would be set at L2.

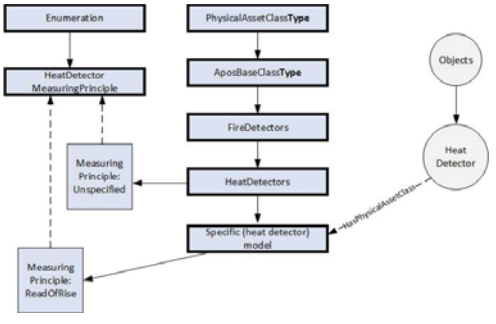

Fig. 1. Equipment hierarchy.

Extensions for failure classifiers: Neither OPC UA nor the ISA-95 companion standard explicitly defines a concept that can be used to represent the hierarchy for classifying failure mode, failure cause, and detection method (F1, F2, and F3). Since failure classifiers are abstract, the approach was to apply the generic OPC UA Object Type definition to generate these hierarchies. A new extension for the APOS purpose, BaseFailureClassifier, was developed for this purpose to distinguish it from other object types. The three additional Object Type extensions BaseDetection, BaseFailureMode, and BaseFailureCause inherit their fields from the BaseFailureClassifier, as shown in Fig. 2.

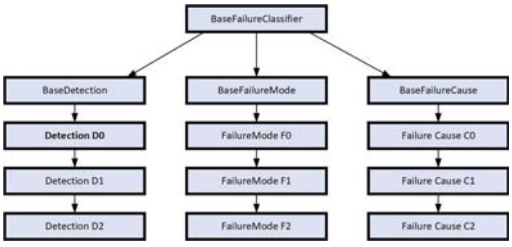

Fig. 2. The failure classifier hierarchy

The specific data values to be structured and classified according to the BaseFailureClassifiers stem from the descriptions of failure events. OPC UA represents events as a collection of types. Each event type has a set of fields defined by its type and supertypes. For our purpose, we create a subtype of the OPC UA BaseEventType, named APOSFailureEvent, containing three fields with datatype NodeId indicating the choice of detection, failure mode, and failure cause.

For our purpose, we have applied the generic OPC UA BaseEventType as illustrated in Fig3 with a fixed set of fields. One of these fields is the SourceNode, which is the node where the event originated.

This will typically be the node representing the device that failed. The values of the failure classifier properties are set to each respective base class to indicate that they must be set to a subtype of that value. Fig. 3 also illustrates that a new

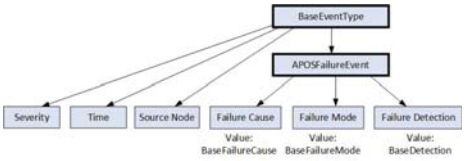

Fig. 3. Failure event types

APOS extension called APOSFailureEvent has been introduced to relate failure events to failure classification. As the new APOSFailureEvent inherits its fields from its parent, all fields present on the BaseEventType node must be specified when creating an instance of an APOSFailureEvent. As events cannot have references, a datatype of NodeId is used to reference the classifiers to the event as illustrated in Fig. 4.

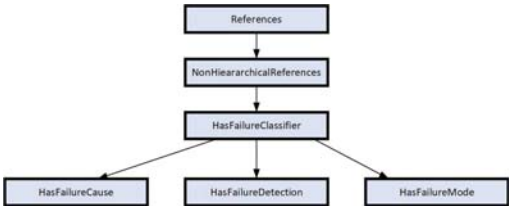

Fig. 4. Failure classifier reference types.

Finally, APOS defined a number of valid failure modes for each equipment group. The OPC UA information model represents this by creating references from the equipment hierarchy to the failure classifier hierarchy as illustrated in Fig5.

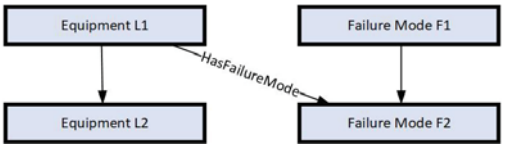

Fig. 5. Failure classifiers referenced by the equipment hierarchy.

There were no suitable non-hierarchical reference types in base OPC UA, hence; a few custom reference types were defined. Although the APOS IM only limits possible failure modes, it is reasonable to extend the model to also limit possible failure causes and detection methods. The practical use of this is shown in Fig5. Just like attributes, references are inherited, so it is possible to define valid failure modes for L1, L2, and L3 depending on the required level of detail.

4.3. *Implementation of the APOS IM*

The OPC UA server implementing the APOS model needed the following information from underlying systems, at a minimum:

- Data about available equipment models
- History of failure events
- Instances of equipment connected to each equipment model

Representing the APOS IM in OPC UA required modelling of the relationship between equipment instances and equipment classification hierarchies and between equipment instances and instances of failure events (with the underlying models for failure classification). This work was quite challenging because it depended on how existing information models for underlying systems could be translated into a one-to-one relationship with the APOS IM.

Starting with the equipment classification hierarchy, it was necessary make an algorithm that assigned each equipment type to an L2 group. This was done manually or using pattern matching, which is explained in more detail in Omang (2021). Such a script requires sufficient information in the underlying systems to properly assign the equipment to an L2 group. This could be problematic if some of the necessary information is not available in a suitable digital format.

Similarly, failure events must be classified by translating information from the classification system used by the underlying systems to the APOS IM model. However, in our case, the interface server used to set up the APOS IM was used also to store the classification.

The APOS project does not define how equipment instances should be modeled, and therefore the requirement for the specification of equipment instances is not defined as part of the APOS IM model beyond what is written in the ISA-95 companion standard. Ideally, they would replicate the

underlying systems as directly as possible, but exactly how they are implemented is not important as long as each physical piece of equipment is uniquely identified by a node in OPC UA, so that they can be linked to the equipment hierarchy in a consistent manner.

5. Discussion

The APOS IM server was implemented as a thin interface exposing data from several underlying systems as OPC UA. In the implementation of the APOS IM, we faced several challenges in interfacing underlying systems. Some of these were caused by the requirement *not* to change the way the data was stored in the existing IT infrastructure.

Lack of suitable APIs: All source systems must have an accessible, efficient API, but we experienced that this was not always the case. OPC UA requires accessing data in very specific ways, and to preserve the slimness of the interface, the APIs should allow searching the data in some way. Otherwise, the server and the network load might be too high.

Lack of consistency: There is generally a lack of standardisation and, therefore consistency in data formats and naming. Assigning equipment to the correct L2 group in the APOS IM required the possibility of identifying the same equipment in the underlying systems, but we experienced that naming and formats could differ substantially. There are many (sometimes conflicting) industry standards specifying which fields should be available for each equipment type. Part of the value of the APOS project is the effort to arbitrate between these and compile the results in a single place. A machine-readable standard would add further value, as it would enable the development of applications based on APOS without translating human-readable standards to machine-readable formats every time. Standardisation and representation of information in machine-readable and standardised formats are necessary and ongoing initiatives like common data dictionaries (CDD) (CDD, 2023) are welcomed.

"Holes" in data: Some source systems had data fields corresponding to failure classifiers implemented in the APOS IM, for example, related to "detection method", "failure mode" and " failure cause".Unfortunately, and perhaps due to lack of use without an APOS like information model, these fields are often left empty, or set to "other" or "unknown". If they had been filled in, it would still be necessary to translate them automatically to the APOS IM, meaning that they must be assigned to some mappable value.

Asset administration shell as alternative? The recent Industry 4.0 standard called Asset Administration Shell (AAS) is gaining increased attention across industries (ABB, 2021; Open Industry 4.0 Alliance, 2021; Wagner et al., 2017; Plattform Industrie 4.0, 2020). The idea is to generate a digital twin of an asset by using AAS meta models and modelling rules (Eclipse.org, 2022). The primary construct of the AAS is a *shell* that presents and organizes the asset data, including references to where the data is stored. An asset in relation to APOS IM can, for example, be a safety instrumented function (SIF) carried out by a SIS. A digital representation of the SIF may be a construct of shells, covering both the SIF level and the individual components. Building a AAS IM for a SIF does not require changes in the underlying source systems, except that they align with common data dictionaries (CDD), like IEC (CDD, 2023). Working towards the adoption of APOS IM formats and categories in IEC CDD is an essential next step.

Implementing digital platforms within Industry 4.0 is more than a matter of technology. Applying digital platforms open up new ways of exchanging data throughout the whole lifecycle, and consequently, new ways of interacting among the people and organisations involved. Additional opportunities (and challenges) arise when considering also other aspects of Industry 4.0, for example, as discussed in Di Nardo et al. (2022). APOS 2.0, a project starting up in 2023, is also incorporating human-centric solutions as part of the scope.

6. Conclusions

This paper has proposed how an information model for SIS performance monitoring called APOS IM can be modelled and implemented

using OPC UA with interfaces toward existing source systems. The APOS IM was based on a specification published in a guideline for the classification of equipment and failures. Two types of extensions were needed to implement the APOS IM model using basic OPC UA components and the ISA-95 companion standard. Some of the practical challenges that were faced have been highlighted. Among these is the need to make contributions to initiatives on common data dictionaries to ensure machine-readable and standardised data formats. Such standardisation is necessary for Industry 4.0 platforms like asset administration shell (AAS). So far, the AAS standard has primarily been used to create digital twins of physical equipment and systems. An interesting step for further research would be to investigate how the APOS models and classification can be implemented as a service for SIS follow-up with the AAS framework.

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