

Digitalization of Industrial Inspection Assets through the Asset Administration Shell

Iury Michel Treuk^{*†}, Alexandre O. Júnior^{*}, Rui Pedro Lopes^{*‡}, Gonçalo Mota[§], Joaquim Mira J.[†], Paulo Leita^{*‡}

^{*} Research Centre in Digitalization and Intelligent Robotics (CeDRI), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal, Email: {alexandrejunior, rlopes, pleitao}@ipb.pt

[†] Universidade Tecnológica Federal do Paraná (UTFPR), Campus de Ponta Grossa, 84017-220 Ponta Grossa, Paraná, Brazil, Email: iurytreuk@alunos.utfpr.edu.br, mira@utfpr.edu.br

[‡] Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

[§] Volkswagen AutoEuropa, 2954-024 Quinta do Anjo, Portugal, Email: goncalo1.mota@volkswagen.pt

Abstract—Developments in industrial manufacturing systems, through the use of new digital technologies, are revolutionizing the traditional means by which companies operate in terms of productivity and competitiveness. The adoption of technologies related to Industry 4.0 (I4.0) has led to the possibility of digitizing industrial assets to achieve more responsive, reconfigurable and efficient production systems. The Asset Administration Shell (AAS) corresponds to a form of digital representation of a physical asset, such as, a machine or device, that describes its properties, functionalities, and behaviours, as well as guarantee interoperability between different systems. Implementing AAS in the industrial environment allows the creation of a standard for digitalising asset scenarios, which can be used for intelligent and non-intelligent products. This paper explores modelling geometric inspection assets on an automotive assembly line using AAS standards. Once modelled, the AAS of the assets are applied to a new approach for reactive AAS based on a REST API for real-time data transmission to a framework focused on Zero Defects Manufacturing. The implications associated with the asset modelling and the creation of the AAS server are presented and discussed, giving a critical opinion on the current status of the technologies associated with AAS in I4.0.

Keywords: *Asset Administration Shell, Industry 4.0, RAMI4.0, Digitalization, Cyber-physical System.*

I. INTRODUCTION

The need for a swift exchange of data and information in the industrial sector, enhancing companies' productive development and flexibility, has promoted the replacement of outdated technologies by disruptive ones that meet this current demand [1]. Over the last two decades, the adoption of cutting-edge technological approaches has driven the Industry 4.0 (I4.0) paradigm, which has enabled the integration of digital systems with physical assets, the digitalization of processes and improved interoperability across systems [2].

In this context, many companies are investing in new technology models that are flexible and compatible with their partners' systems [3]. When there is no support for this interoperability between systems, either due to problems regarding the machine integration or even the existence of different communication protocols, it becomes a challenge for systems to operate collaboratively to achieve a pre-determined goal [4].

Cyber-physical systems (CPS) have emerged to address this problem, effectively integrating physical and digital elements, in a networked manner, using technologies that enable autonomy and control without the human intervention [5]. With the assistance of architectures such as the Reference Architectural Model Industrie 4.0 (RAMI4.0) and the Industrial Internet Reference Architecture, they acquire information and services in real-time [6], allowing machines to be monitored and analyzed in situ.

RAMI4.0 is a three-dimensional coordinate model comprising six layers representing different aspects of I4.0 system architectures: business, functions, information, communication, integration and assets [7]. The asset layer represents components of the physical world, such as processes, machines and products, which can be digitalized in the context of Digital Twin, employing representations that guarantee interoperability in I4.0, such as the Asset Administration Shell (AAS) [8].

Considered a bridge between a physical asset and its digital representation, the AAS encompasses various semantic submodels that describe the main characteristics, functions and particularities of an asset [3] to guarantee standardization in its digital representation, interoperability of systems, transparency and traceability of the asset throughout its life cycle, as well as providing support for real-time monitoring services of the industrial asset and facilitating its management.

The AAS can be classified into three different types according to their level of interaction capability, as described in Figure 1. Classified as a passive model, the type 1 AAS is a static file representing a physical asset. The reactive or type 2 AAS can establish communication between the asset and the AAS model through an API, allowing information access and update. Finally, the proactive or type 3 AAS allows interaction and negotiation among other AAS models, having more intelligent and autonomous skills that enable the processing and predicting events and actuation on the asset's system [9].

Standardizing AAS syntaxes and semantics guarantees its interoperability, with templates for the AAS submodels currently being developed and made available by the Indus-

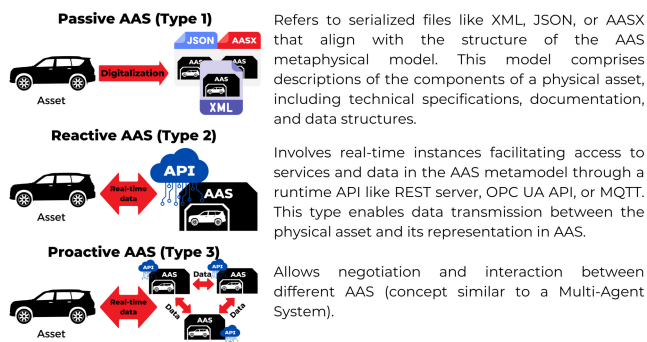


Figure 1. Description of passive, reactive and proactive AAS.

trial Digital Twin Association (IDTA) [10]. Despite several simplified models already available, advanced definitions are required to effectively model complex industrial systems, particularly for AAS's reactive and proactive types. The proactive type still needs clear definitions, with only a few studies addressing it. For the reactive type, on the other hand, despite already having some open-source API implementations such as AASX Server, Eclipse BaSyx and NOVAAS, none of them yet cover all the AAS specifications, with most only providing basic functionalities such as HTTP communication for writing and reading [11], which fail to synchronize data with physical assets, a severe issue for their deployment in I4.0.

Mindful of the existing lacks and of the benefits that can be achieved by creating AAS in the context of I4.0, and looking to extend the practical deployments of AAS in the literature, this paper aims to present the process adopted for the digitalization of assets in a real scenario in an automotive assembly line as part of the scope of the Horizon Europe project openZDM (openzdm.eu). For this purpose, the developed solution uses the AASX Package Explorer tool for the creation of the type 1 AAS of a geometrical measurement system, as well the development of a type 2 AAS approach for the real-time manager of the data collected by the system for data analysis and failure detection.

The rest of the paper is organized as follows: Section II presents a brief analysis of related work, namely the development and studies of projects involving AAS and its role in industry. Section III describes the automotive case study adopted for implementing industrial AASs. Section IV deals with implementing AAS types 1 and 2 for three geometric measurement systems using the AAS Package Explorer and an AAS server approach based on FastAPI. Section V discusses the lessons learned during the implementation of the AASs, and Section VI rounds up the paper with conclusions and future work.

II. RELATED WORK

Some studies have been carried out in the industrial sector since the first concepts of AAS emerged. The study in [12] reviews AAS development works, analyzing the progress of research and the challenges of AAS in aspects of interoperability, modelling and applicability. Another aspect being

considered is the AAS standardized architecture manifesto, which is divided into two parts: Digital Factory Header and Digital Factory Body [13], where the former refers to the capabilities of an asset, providing information on the use of AAS and the Asset, as well as its identification and the latter informs the properties and characteristics of an asset present in autonomous submodels [14]. By evaluating the potential future research, these studies enable the understanding of the AAS's current competencies and relevance in I4.0.

The research carried out in [15] and [16] evaluates the applicability of Semantic AAS for more outstanding interoperability between elements. For example, [15] addresses the scientific contributions to Semantic AASs that model the communication and information layers in RAMI4.0, aiming to present an understanding of the industrial technologies used in Semantic AASs. Analyzing the components of I4.0, they point out to use the Resource Description Framework as one of the most relevant models for standardizing metadata and semantics, which allows interoperability between machines and, consequently, the exchange of data between them. However, researchers conclude about the need to standardize information models for Semantic AASs, highlighting the necessity for international standardization of these components in a future scenario.

Following the AAS criteria in I4.0, the authors of [17] introduce a solution to integrate business and control level applications through bi-directional data exchange using the AASX Package Explorer. They point out the use of the AASX file to understand all the elements of the AAS, such as 'Submodel' and 'Property', encompassing the information contained in the AAS in a structurally compact form. Validating the research by developing an AASX Package Explorer model for motor control, the authors prove the feasibility of using the AASX Package Explorer for data conversion methods, which has the limitation of requiring the operator intervention to make the solution effective. Finally, the researchers mention the existence of few studies that seek to solve these data exchanges through the AASX Package Explorer.

Using an agent-based AAS approach, the study in [18] improves a physical asset digitalization process by developing an intelligent and collaborative AAS, addressing the proactive type. Applied to an industrial automation system, the authors develop a framework for agent-based AAS that enables the synchronous and asynchronous communication in the system, using the OPC UA communication protocol for the first case and REST-based communication for a more specific case study. Although the study illustrates the feasibility of using AAS and communication protocols, the researchers refer the need for understandable specification of some essential submodels for this operating environment, requiring the greater complexity for constructing the agent-based AAS architecture.

The following study, described in [19], seeks to simplify the integration between milling machines and other components in a production plant to validate AAS in the industrial sector. The authors describe the RAMI4.0 architecture and some of the singularities present in the AAS, one of which is its adapt-

ability to use distinct communication and data transmission technologies for implementation, e.g., XML language, JSON data format and OPC UA communication standard. By testing the possible interoperability between two AAS assets, the researchers attest the AAS's effectiveness, concluding that it is a promising standardization initiative for the industrial sector.

Recently, [20] and [21] adopted an approach using the open-source platform Eclipse BaSyx to implement an AAS in the context of I4.0. In [20], the authors extend the concept of Artificial Intelligence (AI) AAS introduced in previous works to gain practical experience for developing the standardization stage of the result of the AI AAS information model. With the help of BaSyx, the application obtained the necessary means to carry out the case study, allowing access to specific submodels contained in the AAS. However, the study warns about the compatibility of using the BaSyx platform between different structures, referring the importance of considering a standard approach to allow data access in different architectures.

In [22], the authors introduce the NOVAAS reference implementation of AAS in I4.0, based on the latest technological developments in industrial internet technologies, and techniques and methods available in software engineering. This platform digitalizes physical entities and is responsible for the AAS structure's security, authentication and monitoring. The researchers highlight the level of development of NOVAAS that is suitable for implementation in industrial equipment to develop new optimizations of NOVAAS in the long term.

Although some of the work carried out addresses standardization and semantics in the construction of AAS, it is still necessary to expand the understanding of how these definitions can be correctly adopted in the modelling of highly complex industrial systems, and especially how AAS can be efficiently adopted in the management and standardization of real-time data provided by physical assets.

III. AUTOMOTIVE CASE STUDY

The developments carried out in this work are within the scope of the Horizon Europe project openZDM, which seeks to promote the development of an open-source platform to enable the realization of production processes in Zero Defects Manufacturing (ZDM). Combining existing research solutions and advances in the field of ZDM with new developments, the openZDM platform will be validated through five different industrial pilots in diverse and authentic operating conditions.

This work embraces an automotive assembly line as a case study. For a vehicle assembly line, the geometric layout of the car's components is one of the leading quality indicators, being necessary to measure and control the gap (distance between surfaces) and flush (alignment between surfaces) points at different stages of the production process.

At the initial stage of the assembly process (body shop), the gap and flush points are measured at different stations using automated robotic systems equipped with geometric laser measuring equipment. Within the scope of the openZDM project, this data will be analyzed using different data analysis tools in order to identify not only alignment problems between

the car components but also the influence and correlation between points and tolerance limits across distinct points and stations, supporting the prediction of how such points can lead to problems at later stages of the assembly so that they can be mitigated avoiding costly rework processes.

To ensure the data interoperability on the openZDM platform, the AAS was adopted to digitalize the industrial assets due to its standardized structure, which allows the data analysis tools to easily adapt to the various data inputs, as well as taking advantage of AAS's compatibility with different communication protocols, such as REST, MQTT and OPC UA. As such, this paper focuses on the digitalizing process of the geometric measurement system in three different inspection stations in the automotive body shop through the use of AAS, as well as the implementation of a type 2 AAS approach for the integration of real-time data from the measurement inspection system with the data analysis tools of the openZDM platform.

IV. IMPLEMENTATION

This section presents the digitalization of the industrial assets of interest using AAS types 1 and 2 to standardize their functionalities and descriptions. The methods used to achieve the real-time operational data connectivity between these assets and the openZDM platform are also highlighted.

A. Development of the Type 1 AAS

The modelling and definition of the structure for the passive AAS of the automotive assembly line inspection assets was developed using the AASX Package Explorer, a C-based editor with a graphical interface specific for AAS creation, being one of the highly diffused tools found in the literature for this purpose. For structuring the AAS passive model, example templates provided by the AASX Package Explorer repository and the different submodels specifications published on the IDTA platform were adopted as a reference.

The structure of the AAS for the geometric inspection systems is shown in Figure 2, where the adopted submodels (SM) contain all the relevant information related to the particularities and functionalities of the physical asset following the IEC 61360 standard [23]. The adopted submodels are the *Identification*, *Technical Data*, *Capabilities*, *Ethernet Communication Skill*, *Documentation* and *Operational Data*. The 'Identification' submodel contains the properties with general information about the system, such as brand, year of production, and localization in the body shop, and the 'Technical Data' submodel comprises the technical specifications of the system, such as nominal values for voltage, current and power, operating frequency, measurement accuracy. The 'Capabilities' and 'Ethernet Communication Skill' submodels describe the asset's communication capabilities, and the 'Documentation' submodel is responsible for containing different technical documentation files of the system such as manuals and datasheets.

The 'Operational Data' submodel is responsible for defining the data structure to be collected by the measurement inspection system to guarantee the interoperability between the three stations in the body shop. This submodel has properties

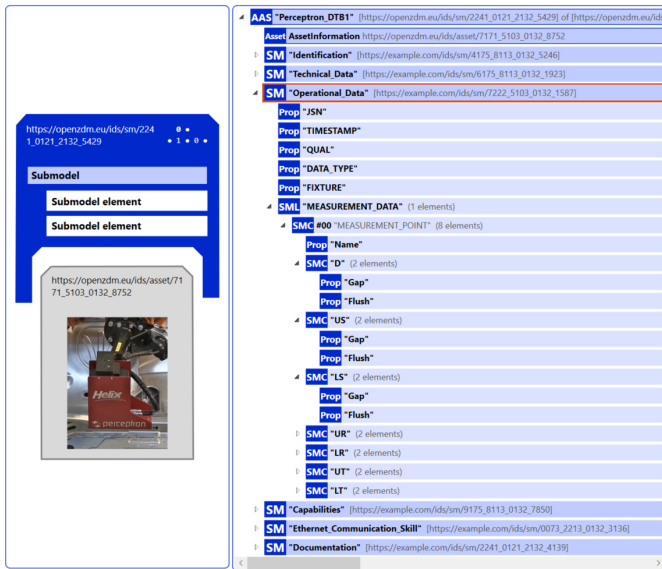


Figure 2. AAS type 1 structure of the geometric inspection system implemented in the AASX Package Explorer.

(Prop) that describe the measurement quality parameters, the vehicle identification and the measurement timestamp. The Submodel Element List (SML) named as ‘Measurement Data’ inserted in this SM acts as a template for the measurement points, being a list that can be replicated for n numbers of points. Each element in this list will always have the same parameters, namely the ‘Name’ of the measured point and seven measurement parameters associated with the gap and flush values. The ‘D’ parameter represents the value measured by the inspection system, the ‘US’ and ‘LS’ parameters correspond respectively to the upper and lower limits for the measurements, the ‘UR’ and ‘LR’ parameters corresponds to the upper and lower measurement rejection values, and the ‘UT’ and ‘LT’ parameters correspond to the upper and lower tolerance limits.

Among the adopted specifications, it is possible to highlight the IDTA 02003-1-2 Generic Frame for Technical Data for Industrial Equipment in Manufacturing [24] and IDTA 02008-1-1 Time Series Data [25]. The first specification details the AAS Technical Data submodel for the technical information structure of physical assets, detailing the asset data through elements and properties. These elements are organized into main sections and subsections to facilitate the human reading, following the ECLASS or IEC CDD standards. The clarity and independence of the information are emphasized and identified by the semantic IDs of the submodel elements. Conversely, the second standard aims to provide a template for the semantic description of data series throughout the asset’s life cycle, providing a perspective for standardising queries and data entries over time.

Figure 3 shows a part of the JSON structure of the ‘Operational Data’ submodel and its elements, such as the identifier of each property (idShort) and the corresponding data type (valueType) essential for data standardization. As previously

mentioned, the ‘Measurement Data’ SML acts as a template for the parameters that make up each point to be measured by the asset; in the reactive type of AAS, this template can be replicated internally in the list structure of the SML according to the number of points to be measured, assigning the actual values collected by the asset.

```

{
  "idShort": "Operational_Data",
  "id": "https://example.com/ids/sm/7222_5103_0132_1587",
  "kind": "Instance",
  "submodelElements": [
    {
      "category": "VARIABLE",
      "idShort": "JSN",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:long",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "TIMESTAMP",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:datefime",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "QUAL",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:string",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "DATA_TYPE",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:string",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "FIXTURE",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:string",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "D",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "US",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "LS",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "UR",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "LR",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "UT",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    },
    {
      "category": "VARIABLE",
      "idShort": "LT",
      "id": "https://example.com/ids/sm/7222_5103_0132_1587",
      "valueType": "xs:float",
      "modelType": "Property"
    }
  ]
}

```

Figure 3. JSON structure of Operational Data submodel.

B. Development of the Type 2 AAS

Figure 4 shows the reactive AAS implementation approach developed for the case study. The data collected by the geometric measurement system at each station and for each vehicle is retrieved via a CSV file and immediately uploaded to a shared folder on the company’s internal network, with different identifiers for each of the three measuring stations. A Python-based Filewatcher service monitors the folder for new data entries, serving as the starting point for the type 2 AAS server.

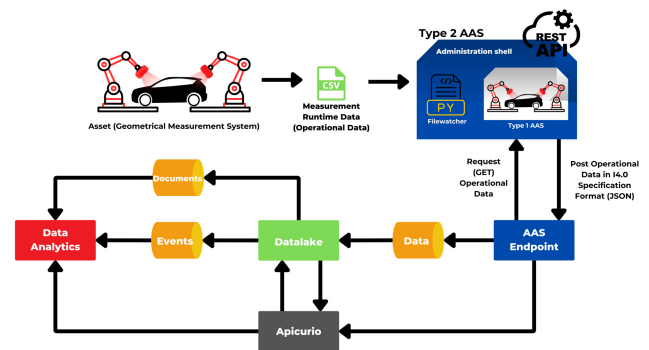


Figure 4. AAS Type 2 architecture for the openZDM project

The AAS server was implemented based on the FastAPI framework to act as a REST endpoint responsible for continuing the system’s data pipeline. The server provides an HTTP GET method that allows the access to the passive AAS

models of the inspection system, as well as their respective submodels. In this way, the Filewatcher service can retrieve the data structure in the ‘Operational Data’ submodel, scan the CSV file and parse the data according to the specifications established in the AAS. Since the data schema for the point’s parameter structure in the SML has been defined generically, the Filewatcher service can replicate it while maintaining the data interoperability between the different stations despite measuring different points.

Once the data has been converted into the standard data schema, the AAS server performs an HTTP POST method to make the retrieved data available through the openZDM microservice platform via the AAS endpoint. This microservice platform, which architecture description is out of scope of this paper, is responsible for coordinating data analysis activities by adapting the services based on the structure of the input data. The data provided by the AAS server is stored in a data lake that can be accessed via events by the data analysis tools. The analyzed data structure is also stored in the Apicurio registry, allowing microservices to retrieve for posterior analysis.

Figure 5 shows the Filewatcher service based on the reactive AAS, where the AAS server implemented with the FastAPI framework is running, making the type 1 model of the measurement systems available. At the same time, the Filewatcher service is monitoring the shared directory. When a new file is detected, the service requests the AAS server to parse the data into the JSON structure defined for operational data since the direct output of the geometric inspection system does not meet the data specifications in the I4.0 language format. Once the parser has been carried out, the data is updated and sent via the AAS server to the endpoint on the openZDM platform.

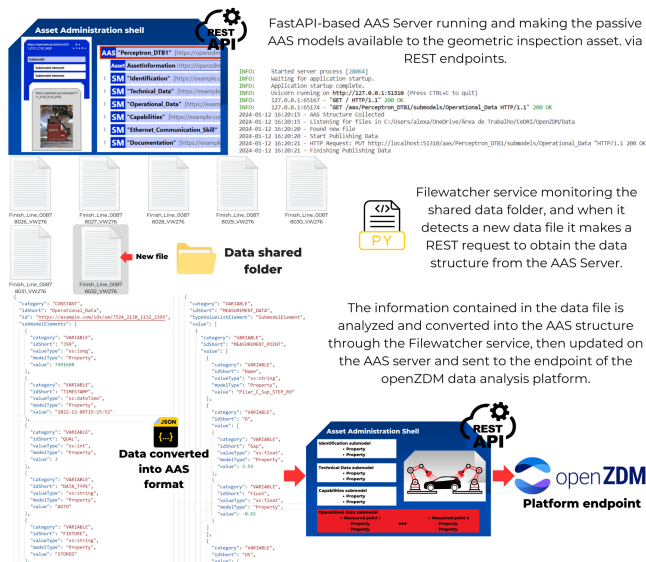


Figure 5. Representation of the operation of the reactive AAS through the Filewatcher service.

V. DISCUSSION AND LEARNING LESSONS

By developing the passive AAS model for the digitalization of the geometric measurement inspection systems, it was

possible to validate the AASX Package Explorer tool. The platform’s graphical interface simplifies the task of creating AAS submodels than other tools that do not have them, such as Eclipse BaSyx. However, it still needs to be improved to make more user-friendly and to solve existing errors and bugs. On the tool’s GitHub page (github.com/admin-shell-io), different examples of already implemented AAS are available that can help the user to understand better the composition needed to create their models. There is still a need for better documentation that relates the tool’s functionalities to the standards defined by Platform Industrie 4.0 and IDTA. However, some video tutorials are also available for the earlier versions of AASX Package Explorer.

The example templates available in the AASX Package Explorer Github repository and the specifications provided by IDTA proved essential for modelling the passive AAS for geometric inspection assets. Many specifications published in the IDTA platform must be expanded and validated in real and more complex industrial cases; however, the platform is constantly being updated by the community with new specifications that can meet this demand in the future. Even the template for the Capability submodel used in the passive model of the inspection asset, which aims to define the ontologies of the asset’s operational resources, is currently under development.

During the realization of this work, a new version of the AASX Package Explorer (V3.0.1, released in September 2023) introduced additional features to the platform. One notable enhancement was the ability to create the SML. Before the addition of the SML on this release, we encountered challenges when modelling the ‘Operational Data’ submodel in passive AAS for the parsing data task through the reactive AAS since updating the set of measured points required the addition of a new submodel for each point, for the AAS be capable of accommodating this data.

Since the geometrical inspection assets deal with a substantial number of points and their associated parameters, with measurement points also being dynamically created and removed, it was impossible to create and remove submodels in the AAS and transmit the data in real-time due to computational load. Something that was exacerbated in preliminary tests that involved the use of the AASX server to create the reactive AAS. In this scenario, creating new submodels to adapt to the dynamism of the measured points required excessive REST requests due to the structure of the endpoints for the submodels defined by the AASX Server, making the processing non-real-time. The inclusion of the SML feature has allowed for more suitable modelling of the asset’s operational data, making it possible to encapsulate the data and its update in real-time through the reactive AAS.

The adoption of the FastAPI framework to develop the AAS server proved to be a robust approach, easily adaptable to the openZDM data analysis architecture and more responsive than the AASX Server. Although the AASX Server is already at an advanced stage of development, based on our experience, improvements are still needed in the structuring of the available

endpoints for accessing the AAS data and submodels, as well as extending the functionality of REST requests (such as GET, PUT, POST and DELETE), in order to allow more suitable and real-time control of the data streamed from the physical asset. Another important aspect is that the functionalities of the AASX Server API through the MQTT and OPC UA protocols still need to be adequately implemented and documented. In particular, the OPC UA protocol would be more suited to implementations in industrial environments that depend on a more secure and reliable exchange of information and allow a wider interoperability between systems.

VI. CONCLUSION

The digitalization process and the rapid exchange of information in I4.0 have led to investment in technology models compatible with different companies' systems. Due to the inadequate integration of machines, the lack of interoperability between these systems makes more difficult the shared work. In this context, the AAS is recognized as a digital representation of the physical asset that is suitable for standardization and interoperability between systems in I4.0 environment.

This paper demonstrates the process adopted to digitalize industrial inspection assets for a real scenario on an automotive assembly line. The processes of implementing the passive and reactive models of the geometric inspection system of different stations in the body shop were discussed using the AASX Package Explorer tool and the FastAPI framework concerning the specifications and submodels published on the IDTA platform. The implementation of the type 2 AAS approach allowed to guarantee the interoperability of the data collected from the assets and its transmission via the AAS server for further analysis to detect and predict faults related to gap and flush measurements.

Future work will focus on implementing proactive AAS for the industrial inspection assets disposed along the assembly line and will be expanded to other sectors of the assembly line. For this purpose, Multi-Agent Systems will be adopted to enable the autonomous interaction and information exchange between the different assets. Further analysis of the IDTA standards will also be considered to model the assets correctly and adopt the OPC UA communication protocol for communication between the assets and the AAS server.

ACKNOWLEDGMENTS

This work was partially supported by the HORIZON-CL4-2021-TWIN-TRANSITION-01 openZDM project, under Grant Agreement No. 101058673. Also, it has been supported by the Foundation for Science and Technology (FCT, Portugal) through national funds FCT/MCTES (PIDDAC) to CeDRI (UIDB/05757/2020 and UIDP/05757/2020) and SusTEC (LA/P/0007/2021).

REFERENCES

[1] A. Oliveira, H. Assumpcao, J. Queiroz, L. Piardi, J. Parra, and P. Leitao, "Hands-on learning modules for upskilling in industry 4.0 technologies," in *5th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*, 2022, pp. 1–6.

[2] J. H. Ortiz, *Industry 4.0: Current status and future trends*. IntechOpen, 2020.

[3] PI4.0, "The asset administration shell: Implementing digital twins for use in industrie 4.0, platform industrie 4.0," zVEI: Die Elektroindustrie.

[4] D. Gürdür and F. Asplund, "A systematic review to merge discourses: Interoperability, integration and cyber-physical systems," *Journal of Industrial information integration*, vol. 9, pp. 14–23, 2018.

[5] R. Alguliyev, Y. Imamverdiyev, and L. Sukhostat, "Cyber-physical systems and their security issues," *Computers in Industry*, vol. 100, pp. 212–223, 2018.

[6] D. G. Pivoto, L. F. de Almeida, R. da Rosa Righi, J. J. Rodrigues, A. B. Lugli, and A. M. Alberti, "Cyber-physical systems architectures for industrial internet of things applications in industry 4.0: A literature review," *Journal of manufacturing systems*, vol. 58, pp. 176–192, 2021.

[7] B. R. Martin Hankel, "Industrie 4.0: The reference architectural model industrie 4.0 (rami 4.0)," v1.0, Apr. 2015, ZVEI: Die Elektroindustrie.

[8] J. Neidig, A. Orzelski, and S. Pollmeier, "Asset administration shell reading guide," jan. 2022, PLATFORM INDUSTRIE 4.0 in cooperation with IDTA.

[9] X. Ye, S. H. Hong, W. S. Song, Y. C. Kim, and X. Zhang, "An industry 4.0 asset administration shell-enabled digital solution for robot-based manufacturing systems," *IEEE Access*, vol. 9, pp. 154 448–154 459, 2021.

[10] Z. Fan, D. Shi, O. Meyer, J. Seidelmann, and H. Wang, "Asset administration shell-based flexible manufacturing system," in *6th IEEE Intl Conference on Industrial Cyber-Physical Systems (ICPS)*, 2023.

[11] M. Jacoby, M. Baumann, T. Bischoff, H. Mees, J. Müller, L. Stojanovic, and F. Volz, "Open-source implementations of the reactive asset administration shell: A survey," *Sensors*, vol. 23, no. 11, 2023.

[12] K. Wei, J. Sun, and R. Liu, "A review of asset administration shell," in *2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 2019, pp. 1460–1465.

[13] R. Drath, M. Rentschler, and M. Hoffmeister, "The automationml component description in the context of the asset administration shell," in *24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2019, pp. 1278–1281.

[14] F. Pethig, O. Niggemann, and A. Walter, "Towards industrie 4.0 compliant configuration of condition monitoring services," in *15th IEEE Intl Conf. on Industrial Informatics (INDIN)*, 2017, pp. 271–276.

[15] S. R. Bader and M. Maleshkova, "The semantic asset administration shell," in *Semantic Systems. The Power of AI and Knowledge Graphs: 15th Interl Conf., SEMANTICS 2019*. Springer, 2019, pp. 159–174.

[16] S. Beden, Q. Cao, and A. Beckmann, "Semantic asset administration shells in industry 4.0: A survey," in *4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*, 2021, pp. 31–38.

[17] X. Ye, W. S. Song, S. H. Hong, Y. C. Kim, and N. H. Yoo, "Toward data interoperability of enterprise and control applications via the industry 4.0 asset administration shell," *IEEE Access*, vol. 10, pp. 35 795–35 803, 2022.

[18] L. Sakurada, P. Leitao, and F. De la Prieta, "Agent-based asset administration shell approach for digitizing industrial assets," *IFAC-PapersOnLine*, vol. 55, no. 2, pp. 193–198, 2022.

[19] M. A. Inigo, A. Porto, B. Kremer, A. Perez, F. Larrinaga, and J. Cuenca, "Towards an asset administration shell scenario: A use case for interoperability and standardization in industry 4.0," in *NOMS 2020-2020 IEEE/IFIP Network Operations and Management Symposium*, 2020.

[20] L. Rauh, M. Reichardt, and H. D. Schotten, "Ai asset management: a case study with the asset administration shell (aas)," in *27th IEEE Intl Conf. on Emerging Technologies and Factory Automation (ETFA)*, 2022.

[21] V. Nagrath, T. Blender, N. Shaik, and C. Schlegel, "Industry 4.0 asset administration shell (aas): Interoperable skill-based service-robots," *arXiv preprint arXiv:2208.01273*, 2022.

[22] G. Di Orio, P. Maló, and J. Barata, "NOVAAS: A Reference Implementation of Industrie4.0 Asset Administration Shell with best-of-breed practices from IT engineering," in *45th Annual Conference of the IEEE Industrial Electronics Society (IECON)*, vol. 1, 2019, pp. 5505–5512.

[23] IDTA, "Asset Administration Shell Specification - Part 3a: Data Specification - IEC 61360, Industrial Digital Twin Association," 2023.

[24] S. Bader *et al.*, "Generic frame for technical data for industrial equipment in manufacturing (version 1.2)," 2022.

[25] IDTA, "Time Series Data (Version 1.1), Industrial Digital Twin Association," 2023.