Single Source of Truth: Integrated Process Control and Data Acquisition System for the Development of Resistance Welding of CFRP Parts

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Keywords: Thermoplastic Composites, Resistance Welding, Process Control, Data Acquisition, SCADA.

Abstract: For the development of a novel (industrial) process, in particular within a research environment, a very flexible and adjustable control and data acquisition system is required. Traditional SCADA systems often are not designed for frequent changes. To facilitate the development process, the storage of all relevant data from process parameters to measurement data at a single location, as a "single-source-of-truth" is desirable. This paper introduces an integrated process control and data acquisition system that is built around the open-source central data storage system "shepard" which facilitates the evaluation of the process and offers potential for inline-optimization. The system is evaluated by the example of the production of a thermoplastic component. As part of the European Clean Sky II large passenger aircraft project, the German Aerospace Center produces the 8-meter long upper shell of the multifunctional fuselage demonstrator (MFFD) made from thermoplastic composites. The frames are attached to the skin by resistance welding, which is done using an actuated gantry system. This novel process has the potential to disrupt standard aircraft assembly by dust-less welding in a fully automated yet interactively customizable manner which is hence relevant for every process development context.

1 INTRODUCTION

The development of a novel production process usually requires a large number of experiments which need to be documented and later evaluated carefully. During the evolution, different sets of process parameters may be required and a large amount of measurement data can be aggregated. To facilitate this process, the German Aerospace Center (DLR) has created the *shepard* software (storage for heterogeneous product and research data)(Haase et al., 2021; Krebs et al., 2021). Using a REST (Representational State Transfer) interface, data can be stored and retrieved from shepard in a structured way. Connections between different data items can be created, both in a semantic way (e.g. as predecessor and successor relation) and in a temporal way. A key concept of shepard is the ability to store a vast amount of different data at a single location, therefore employing a "single-source-of-truth" approach. Furthermore, shepard is developed as an open-source project for maximum reach and features an on-premises approach to store sensitive data locally, which can be vital in research projects.

In industrial applications, SCADA (Supervisory Control and Data Acquisition) systems are very common. Using these systems, the operator can control and monitor the production process and modify relevant process parameters (often called *recipes*). Aggregated data can also be provided to a MES (manufacturing execution system) for further processing. Common industrial solutions are for example WinCC (Siemens) or Aveva. For use in research applications, these solutions have some drawbacks. They usually are tailored to a specific process, which does not change much after being commissioned, whereas in research the development of a process often is a primary concern. Furthermore, licenses can be very cost intensive. There have been some approaches creating low-cost and/or open-source SCADA systems, both for industrial (e.g. (Phuyal et al., 2020), (Merchán et al., 2017)) and academic use cases (e.g. (Vargas-Salgado et al., 2019), (Şahin and İşler, 2013)). Several of these systems are build around an open architecture using the OPC/UA (Open Platform Communications/Unified Architecture, (OPC Foundation,

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Vistein, M., Mayer, M., Endraß, M. and Fischer, F.
Single Source of Truth: Integrated Process Control and Data Acquisition System for the Development of Resistance Welding of CFRP Parts.
DOI: 10.5220/0012161500003543
In *Proceedings of the 20th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2023) - Volume 1*, pages 592-599
ISBN: 978-989-758-670-5; ISSN: 2184-2809

2022)) protocol for a vendor-independent communication between different components and the control system.

This paper introduces a flexible, open-source SCADA system called *ProcessControl* together with a real-time monitoring system called *ProcessMonitoring* that are based on top of the shepard data storage system. This allows to benefit from the advantages of shepard, in particular from the single-source-of-truth approach that avoids scattering process parameters, measurement logs and documentation over several places. A large number of experiments can be tracked exactly with the parameter sets that have been used in combination with measurement data, which allows the process engineer to improve the process continuously. This paper describes the SCADA system using the example of a resistance welding application within the Clean Sky II project "Multifunctional Fuselage Demonstrator" (MFFD).

The remainder of this paper is organized as follows: Section 2 provides an overview of the resistance welding use-case. In section 3 the SCADA system is explained in detail. Section 4 evaluates the benefits of the process control system from the process engineers point of view. Finally, section 5 draws a conclusion and provides an outlook of further improvements.

2 MULTI FUNCTIONAL FUSELAGE DEMONSTRATOR

The DLR, together with Premium Aerotec, Airbus and Aernnova are part of the Clean Sky II project Multifunctional Fuselage Demonstrator and responsible for single part manufacturing and the assembly of the 8-meter long upper shell structure, made from carbon fiber-reinforced low-melt Polyaryletherketone (CF/LM-PAEK). The single part manufacturing and assembly combines several innovative production technologies such as in-situ consolidation with automated fiber placement (AFP_{ISC}), ultrasonic welding (spot and continuous) and electrical resistance welding(Fischer et al., 2022; Endraß et al., 2022a). To validate all processes, a full-scale, but in length to 1 meter reduced test shell has been manufactured on track towards the upper shell manufacturing as part of the de-risking strategy for technology validation. Because the whole structure is made from CF/LM-PAEK, thermoplastic welding technologies are key enablers for dustless assembly. During assembly, the shell is first stiffened by stringers using continuous ultrasonic welding. Next step is the integration of frames to the skin by resistance welding. The connecting surfaces of the frames are

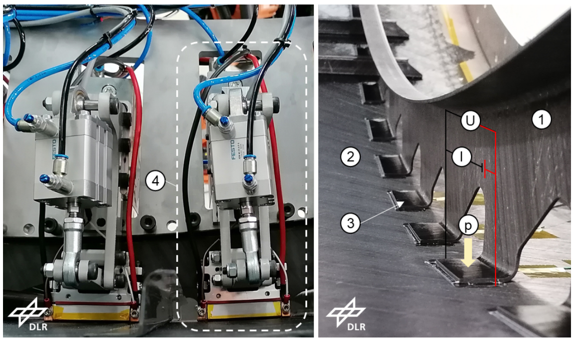

Figure 1: Custom-made weld modules for resistance welding of frames to skin (left). Resistance welded composite frame within the test shell (right).

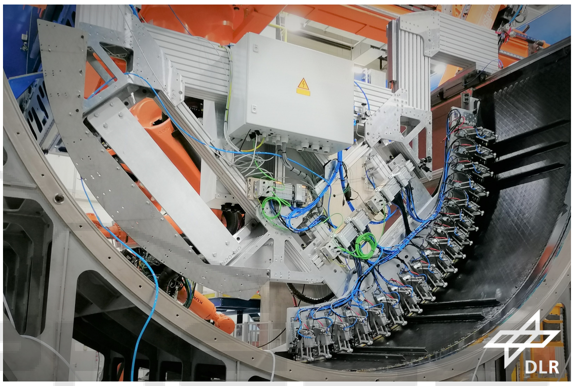

Figure 2: Weld bridge anchored to the placement tooling.

called "attached flanges" and are directly welded to the skin laminate using resistance welding. The integral frames in the upper shell are split in the keel region, in order to enable the integration. Therefore, frame-couplings are welded to the frame ends to connect both sides. Finally, right-angled elements (cleats) are welded to certain stringer and frame intersections to further stiffen the structure. In this section, the manufacturing hardware and the resistance welding process for frame integration, which is focused in this paper, are explained.

2.1 Overview

In order to validate the custom-made welding infrastructure, processes, data acquisition and the manufacturing execution system six frames have been welded to the test shell. Each frame ① (cf. figure 1) is connected to the skin laminate ② by up to 18 welded attached flanges ③ using a unique weld-module ④ which provides both the necessary welding current, as well as mechanical pressure to join both composite parts.

Due to a reduced stringer pitch towards the fuselages horizontal split, different length configurations of the attached flanges have to be encountered and thus require individual process parameters for the welding process (i.e. current, voltage and time) with the necessity to be even optimized and adopted in value and sequence during test shell manufacturing. The welding modules (cf. figure 1 left) are attached to a one degree-of-freedom gantry system. This so-called *weld bridge*, cf. figure 2 can be positioned accurately using a rack and pinion system. Every frame is aligned into a fixture on the weld bridge and subsequently positioned on the accurate location on the skin in flight-direction. Afterwards, the attached flanges are welded to the skin one by one.

2.2 Resistance Welding for Shell Assembly

Resistance welding is, besides induction and ultrasonic welding, known as one of the most matured welding technologies applicable for joining of high-performance thermoplastic composites. In resistance welding a welding strip, the so-called welding element, is placed in the bondline. The welding element consists out of a conductive implant (e.g. stainless-steel mesh or carbon fibers) and in case of electrically conductive adherents (the skin and the attached flanges) additional insulation (e.g. glass-fiber or neat resin layer) above and below the implant. While maintaining the adherents under weld pressure, an electrical current flow through the conductive implant leads to joule heating, melting of the bondline while increasing the polymer chain mobility under reduced viscosity and allows for polymer diffusion between welding element and adherents(Ageorges et al., 2000; Yousefpour et al., 2004). Since heat is generated in between the adherents the introduced power can be balanced to the polymer needs, and a structural join is generated under minimal invasive component deformation. Processing parameters for resistance welding of LM-PAEK were matured on coupon level at DLR's static resistance welding test bench, based on a sophisticated Design of Experiments (DoE) study. Numerous welds were performed validating attenuation losses during water coupled ultrasonic testing, fracture load in single lap shear testing and failure mode by fracture surfaces analyses. For detailed information the reader is referred to our publications (Endraß et al., 2020; Endraß et al., 2022b; Thomè, 2021). However, process parameters need to be adopted at transfer from coupon to full scale level due to changes in boundary conditions, e.g. different thermal conductivity of components and tools and transition resistance. Thus, flexible process parameter modification is essential during this early development phase. Within the MFFD's upper shell manufacturing frames, frame-couplings and cleats are integrated by electrical resistance welding. In total 652 resistance welding operations are performed varying in geometrical dimensions of part and bondline, weld tool configurations and positions within the structure. Hence, the allocation of the defined weld parameter sets to its respective operation positions and traceable data management is indispensable for the automated assembly and data evaluation.

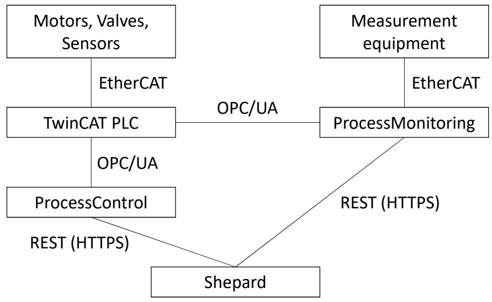

Figure 3: Overview of system architecture.

3 PROCESS CONTROL AND DATA ACQUISITION

The overall system for frame welding of the MFFD test shell consisted of several components which are coupled using standard networking protocols. The project employs three pieces of software that have been developed at DLR: shepard, ProcessControl and ProcessMonitoring. In the following sections, at first the overall architecture is introduced, followed by a more in-detail description of the main components.

3.1 Architecture

Figure 3 shows the overall architecture of the welding system. The hardware of the weld bridge is controlled using a Beckhoff TwinCAT programmable logic controller (PLC) running on a standard industrial PC. The motor controllers, values, etc. are connected to the PLC using the industrial fieldbus protocol EtherCAT(Jansen and Büttner, 2004). The gantry is actuated by two Beckhoff AM-series motors, driven by an AX8000 servo system. The pneumatic system is controlled using Festo CPX-series valves, and the welding power supply by analog 0 V to 10 V signals.

For quality assurance purposes, measuring equipment is installed. This consists of several high-precision analog input terminals (Beckhoff ELM series) that can measure the voltage and current applied to the welding elements, as well as temperatures from thermocouples. Data for the pressure measurand is collected via OPC/UA. The measurements are taken by the specialized ProcessMonitoring software, which collects data from different sources, performs a live visualization of the process and stores the measurement data in the central shepard database.

The overall process is controlled by the ProcessControl software. This software communicates with the PLC using the OPC/UA protocol and uses the shepard database as central data store.

3.2 Shepard Data Storage

During the execution of a manufacturing process a large variety of process data accrues, often from a multitude of different sensors. The acquisition and structured storage is essential for quality assurance steps, as well as for inline process optimization. A precise annotation of time and location for all data is essential for later analysis, as well as a concise knowledge of all process parameters that have been used. In order to avoid redundancies, a single central storage ("single source of truth") is desirable.

To facilitate the data storage, the DLR has developed the shepard software(Haase et al., 2021; Krebs et al., 2021). Shepard can be accessed using a REST-based API and provides ready-to-use client implementations for a wide variety of programming languages (e.g. Java, C++, Python, ...). The recently developed shepard ecosystem has been selected as base technology to evaluate the usability and suitability of the system within a larger research use-case.

The shepard system data model consists of two entities: *Collections* and *DataObjects*. Collections aggregate DataObjects and serve as a container for a single project, workpiece, etc. A DataObject represents a single step, action, result, etc. within a project. A hierarchical structure can be formed among DataObjects by using a parent/child relation (every DataObject can have exactly one parent and an arbitrary number of children). Furthermore, a temporal relation between two DataObjects can be modeled using the successor relationship. DataObjects can contain references to further data such as *StructuredData* (arbitrary data in JSON (JavaScript Object Notation) format), *Timeseries* (temporal sequence of data points) or *Files* (binary files).

3.3 Process Control

The overall process is controlled by an additional in-house developed open-source software called ProcessControl, which acts as SCADA system. A major goal during the development of the ProcessControl software was the concept of a "single source of truth". To achieve this goal, ProcessControl stores all relevant data within shepard.

A main concept of ProcessControl is the recursive decomposition of the production process into smaller parts. Ideally, several small parts share common parameter sets and programs and thus allow for reuse. The frame welding process for the MFFD demonstrator can be decomposed into two layers: frames and attached flanges. The process parameter set for the frames contain the position of the frame, such that the associated program can move the weld bridge into the proper position. The process parameter set for the attached flanges contains all necessary information for the welding process (such as voltage, current, duration and pressure).

Figure 4 shows the overall structure of data that is stored for the demonstrator part. ProcessControl makes use of the shepard DataObjects and StructureData references. On the top level, a single DataObject for the project (i.e. in this case frame welding) is used. Different projects can be stored in the same or in multiple shepard Collections.

The data structure for a project consists of two parts. The first part (left, dashed part of figure 4) is the specification of relevant metadata and is attached to the main ObjectNode as StructuredData. This contains the definition of parameter sets (i.e. names and types of data variables, but no concrete values) and the manufacturing programs necessary for production. For one production step, a single set of process parameters must be defined, but several programs can be specified, which can be useful for multi-stage processes. In the case of the MFFD demonstrator, for each flange of a frame at first a contact measurement is performed before the first actual welding is performed.

The second part (right, solid part of figure 4) defines the structure of the part (i.e. the number of frames and the number of flanges for each frame). Furthermore, at least one instance of (concrete) process parameters must be present for every step. More than one instance may be present if a step is tried several times with varying parameters in an experimental setup. To achieve traceability, no process parameters are ever overwritten, but rather a new instance is added.

The initial setup of the project structure and process parameters is done automatically by the ProcessControl software using a CSV file (comma separated values) and by supplying an appropriate JSON-formatted project definition file. The project defini-

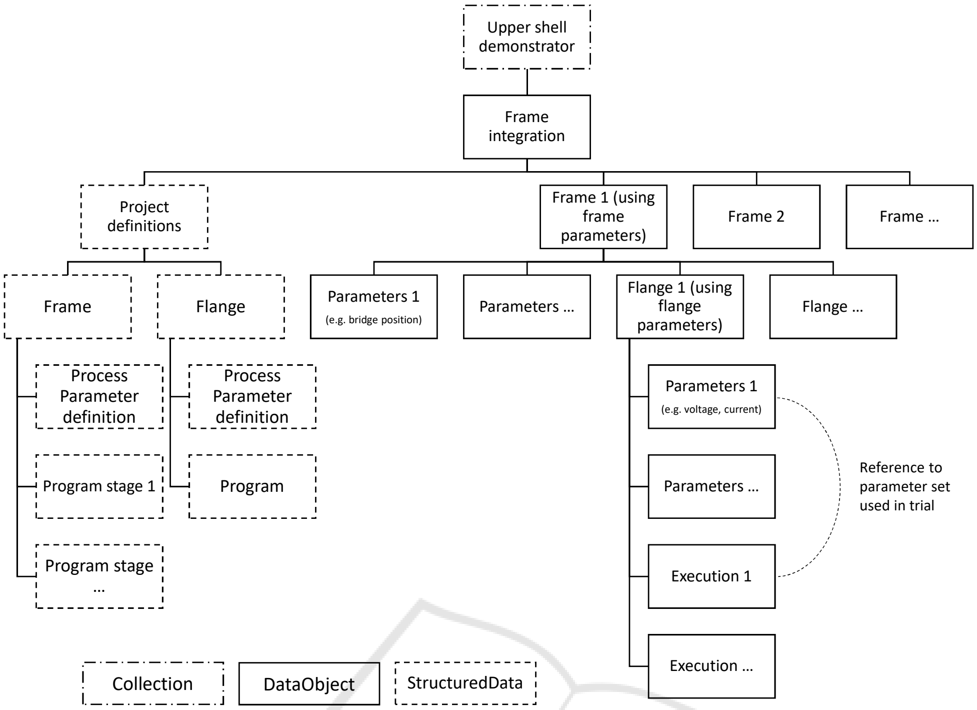

Figure 4: Structure of the MFFD demonstrator project.

tion file contains all programs and requires detailed knowledge about the underlying hardware systems and should be written by an automation expert. The CSV file contains only the process parameters and should be written by a process expert.

The ProcessControl software has been designed as a manufacturing execution system with a strong focus on supporting experimental production scenarios. Therefore, a graphical user interface has been created which allows the user to modify any process parameter during the experiment, and also to execute a single step and stage multiple times with different parameters (provided that the underlying process allows multiple executions). This interface is displayed in figure 5.

Every time a step is executed, a new DataObject node is created in shepard and metadata such as execution time and the concrete parameters that have been used are attached to the new node. In addition, a free text comment can be stored, enabling the expert to comment live on the experiment, allowing for later precise evaluation. Furthermore, this node is also used by the ProcessMonitoring software described in section 3.4 to store measurement data. By combining all relevant data at a single location, refinement of the process or experiment can be facilitated.

The ProcessControl software core is agnostic to the process and the underlying hardware. Extension modules provide hardware connectivity. For the

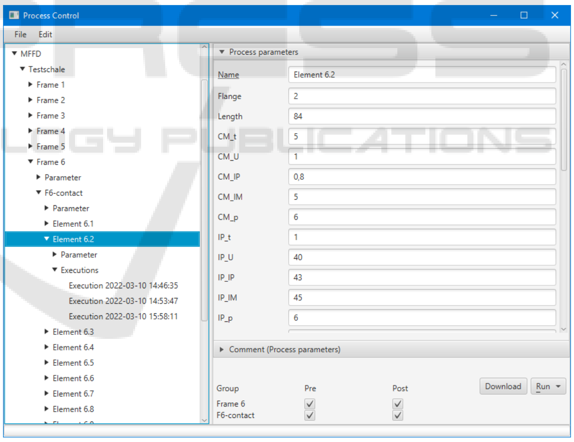

Figure 5: Process parameter editor, showing parameters for two phases of the welding process: CM (contact measurement) and IP (initial voltage pulse). For each phase the time (t), voltage (U), predicted current (IP), maximum allowed current (IM) and applied pressure (p) can be specified.

MFFD demonstrator, communication using OPC/UA has been implemented. The TwinCAT PLC provides an OPC/UA server, while the communication module in ProcessControl acts as OPC/UA client. The communication module provides basic operations such as writing a value to a node or waiting for a node to change value. Using these operations, process parameters can be transmitted to the PLC and a start flag can be set. Further execution can be halted until a

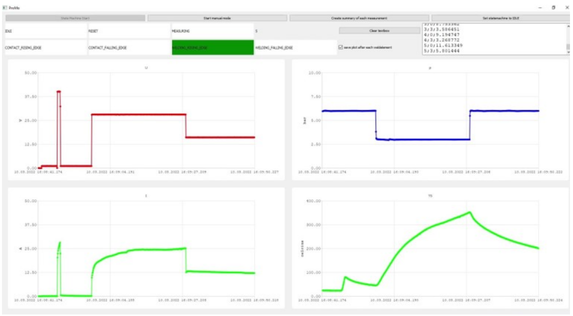

Figure 6: Example for live GUI of ProcessMonitoring. Top left: voltage, top right: pressure, bottom left: current, bottom right: temperature.

success or error flag is returned by the PLC. In the case of an error, the whole process can be interrupted. ProcessControl orchestrates the process and its data flow, hence the main program logic is expected to be implemented in the underlying PLC.

3.4 Data Acquisition and Monitoring

Data acquisition and monitoring of relevant measurands is an important part of a SCADA system. In an industrial production process, this can be highly customized with no need for changes after commissioning. In contrast, an experimental setup or process development demands a flexible solution to adapt to new requirements by means of new data sources and measurands providing other insights into the process.

ProcessMonitoring offers interfaces to handle incoming time series from different data sources and to add consistent timestamps. Important metrics for the quality of welds are voltage, current, temperature and pressure in the weld area that have been applied over time (cf. figure 6). Two different data sources are currently in use: OPC/UA for pressure values and EtherCAT for voltage, current and temperature. Measurements from a National Instruments card can also be acquired simultaneously, but this was not needed in this use case.

The pressure values are retrieved by the TwinCAT PLC from the pneumatic components. ProcessMonitoring receives the values by using the open-source open62541 library for implementing the OPC/UA connection. The OPC/UA communication channel between the TwinCAT PLC and ProcessMonitoring enables (near) real-time communication, reliably achieving latencies of 10 ms or less.

Current and voltage are measured by high-precision analog input terminals (type Beckhoff ELM3704-0000). The temperature between skin and attached flange is recorded by thermocouples connected to Beckhoff EL3314-0002 terminals.

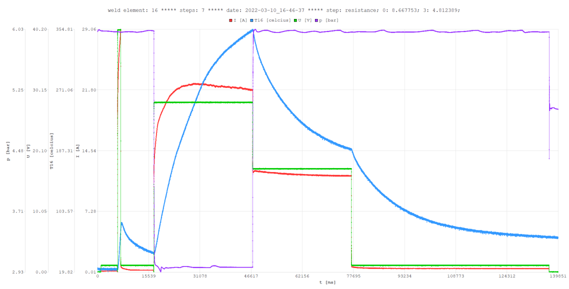

Figure 7: Resulting graph of welding operation generated by ProcessMonitoring.

ProcessMonitoring communicates directly with the Beckhoff measurement equipment by using an EtherCAT master stack based on the Simple Open EtherCAT Master (SOEM)(OpenEtherCAT Society, 2019) project. A temporal resolution of 1 ms for the EtherCAT communication channel has been achieved and is sufficient. Therefore, a cycle loop below 1 ms is crucial and can be accomplished using the Win32 API function “QueryPerformanceCounter” submitting a resolution of 1 µs on a Microsoft Windows 10 PC. So EtherCAT frames can be handled and measured values can be extracted within 1 ms.

During the welding process the values for each measurand are buffered and displayed live in the graphical user interface (GUI, see figure 6). The GUI has been developed using the Qt toolkit.

After the last welding phase has been finished, ProcessMonitoring saves all relevant data in CSV files and creates a graphics file of the measured curves (cf. figure 7). All files are attached to the corresponding ObjectNode in shepard that is also storing the process parameters and comments of the expert.

4 EVALUATION

ProcessControl and ProcessMonitoring have been used heavily during the manufacturing of the test shell. Since the test shell manufacturing was implemented as part of the de-risking strategy towards the manufacturing of the MFFD’s 8m full-scale demonstrator, processing parameters for resistance welding and the weld setup were modified and optimized several times with respect to reliable processing. An extensive Design of Experiments (DoE) -based parametric study targeting the definition of processing parameters (voltage, current, time and pressure) for resistance welding of LM-PAEK within the DLR’s test bench was conducted in order to define a baseline set of parameters for later frame integration(Endraß et al., 2022b). The optimized set of parameters were set as baseline processing parameters within Process-

Control and tuned, varying single parameters during test shell manufacturing within the first 90 weld operations (five of six frames). The very last 18 weld operations on frame six, were conducted using the compiled and optimized parameter set. Since parameter variations from the baseline automatically generate a new tree for the parameter set within ProcessControl linked to the later execution file, transparency and traceability of implemented changes is achieved. This approach facilitates streamlined data retrieval and subsequent analysis, accelerating the research process and fostering reproducibility.

On the other hand, ProcessMonitoring allowed for (near) real-time visualization of the actual process cycle and played a pivotal role in the inline interpretation of the experimental data especially for the process expert.

Using the MFFD frame-welding use-case, it could be demonstrated that the shepard ecosystem is suitable for use in a large research project. With both shepard[1] and ProcessControl[2] being open-source applications, a flexible and cost-effective way of creating a SCADA system in research is provided.

5 CONCLUSION AND OUTLOOK

Using the tools presented in this paper, it was possible to create a control architecture that allowed the process engineer to concentrate on conducting the experiments. The tools were made with the research use-case in mind and allowed the process to be adjusted flexibly. Standard hardware components could be used and integrated with minimal additional cost. The shepard ecosystem has been selected as main data storage for all process steps in the final assembly of the MFFD upper shell demonstrator, not just for frame welding. Main reasons for the development and use of shepard were the on-premises storage capabilities, its ability to adjust flexibly to many different types of data, the possibility to connect different data to each other, and also the availability as open source software. ProcessControl is the first SCADA software based on top of shepard.

The traceability of all experimental data, beginning with the initial process parameters up to the final measurement results has been greatly increased by using a central data storage. The possibility to modify process parameters and to annotate the experiments during the initial setup of the experiment has proven to be very helpful during the manufacturing of the test shell. By storing all relevant information at a single location, the time necessary to evaluate the experiments can be reduced.

Based on the experiments and the data that has been recorded during the manufacturing of the test shell, initial parameters for the production of the final demonstrator could be created by the process expert. To increase the reliability of the welding process, target envelopes for current and voltages have been defined. A recent extension of ProcessMonitoring processes these target envelopes (stored as parameters within shepard) and checks the measured live values against the envelope. If a deviation occurs, a signal is transmitted to the PLC which can react and, if necessary, immediately abort the welding process.

The benefits of centralized data storage in combination with flexible and vendor-independent tools can be useful in many scenarios for process development and research. Currently extensions are being developed which allow to use the tools in projects without a central PLC, for example with industrial robots. Some manufacturers, e.g. KUKA, provide an OPC/UA interface to their controllers which allow to upload robot programs on-the-fly. By using this interface, ProcessControl could not only trigger the execution of programs (as it is usually done by the SCADA system), but also to upload robot programs at the time they are required. This allows to store the reference version of programs together with all other relevant information in shepard and avoids spreading data on multiple systems such as robot controllers, data acquisition systems and developer workstations.

ACKNOWLEDGMENTS

This project has received funding from the Clean Aviation Joint Undertaking (CAJU) under grant agreement CS2-LPAGAM-2020-2023-01. The JU receives support from the European Union's Horizon 2020 research and innovation program.

DISCLAIMER

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

[1]https://doi.org/10.5281/zenodo.5091603

[2]https://doi.org/10.5281/zenodo.8262579

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