# Approach towards process digitalisation and the integration of digital twins into aircraft maintenance shop floor procedures

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**Abstract**

As an ongoing field of research, a lot of work went into the development of digital twins as an elementary part of the aviation industry's digital transformation. (Meyer et al. 2020) These are often asset-based and therefore tailored to an individual part, component or system which they accompany through their complete lifecycle. With respect to the aircraft maintenance, these digital twins are utilized to gain data driven insight and derive corresponding services, like condition monitoring, predictive analysis etc. Besides that, another focus of the maintenance digitalization consists of the digitization of manual-based and paper heavy MRO-procedures (Uhlmann and Otto 2014). Widely unconsidered so far is how shop floor level processes have to be redesigned to meet digital twins interface requirements and enable and highly interconnected physical maintenance procedures. To address this gap, we identified the digitized version of a manual-based maintenance process on the example of an aircraft battery servicing as a reference. The implementation has the quality to serve as a blue print for several different manual-based maintenance processes. By adding a layer of programmatic abstraction onto this identification, we generate a generic solution to expose it to different existing und upcoming digital and mechanic interfaces, e.g. ERP, Smart Tooling, digital twins and XR. Additionally, a well described and easily accessible interface can function as a benchmark for upcoming digital twin efforts and enables the transferability to many other shop floor operations. The result of this project is a user-centered (Abras et.al. 2004) digitized workspace prototype, with a highly flexible and modular process design. A focus of the project is the application of multi-domain, AI-based assistance technologies (e.g. OCR, Object detection or NLP) to relieve the mechanic. Due to this, the mechanic is assisted where it is beneficial and not forced to use assumedly hindering systems. By consideration of clean architecture and open source, this solution is highly convertible to other maintenance processes and independent from used techniques. In this realization, pdf based manual data gets converted into a convenient DICOM1[1] inspired format, from which application units control display, measurement and visual result conditioning. The backend design reduces the data management expense, which comes easily with standardized data formats. The result indicates that the generic linking of digitized shop floor processes to digital twin supports process transformation and optimization efforts.

[1] Current Edition (dicomstandard.org)

**Introduction**

The technological gap between the common paper-based maintenance procedures in aviation nowadays and the idea of digital twins (DT) is large. For the accomplishment of operable DT that gain value to MRO processes, serviceable data is essential. To achieve coherent and serviceable data there is a demand of digitised and automated process solutions. Yet, most MRO processes in aviation are too complex to be automated completely and still demand manual activities.

The challenge of the holistic digital representation of workflows is also described in the Aviation Digitalisation book of Deckert and Dirrler (2021). They also specify opportunities of digitalisation in MRO through ideas like the internet of things, big data, AI, predictive maintenance, 3D printing and DT. In a work of Bortsova et. al. (2021) an overall concept for improvement in aviation MRO is described showing examples of digitialisation opportunities like augmented reality for visual remote guidance and discussing the problem of geographically dispersed locations of different departments.

In addition to overall abstractions and concepts, multiple ideas of digital solutions for individual MRO challenges have been found. For example, the visual assistance for manual scarf repairs by Schmücker et. al. (2020). While these approaches enable individual solutions for MRO problems, they are not brought together in a coherent workflow.

To address the technological gap, an approach towards process digitalisation of aircraft maintenance-manual shop floor procedures is taken. To achieve a holistic system that can be used for any maintenance-manual digitalisation, maintenance-manual processes are considered generally but also on the specific example of the aircraft battery service. This allows for a validation of ideas and brings up challenges that otherwise would stay unconsidered.

The developed system on the one hand is a prototype to show technicians what future maintenance on the example of the aircraft battery service could look like and to validate the digitalisation approaches. On the other hand, it offers an interface for researchers and developers to integrate, exchange and examine new digitalisation tools and approaches easily. This enables the possibility to investigate opportunities and challenges within a specific maintenance process as well as the validation of new concepts. The application is built on the idea of a well described and easily accessible interface that can function as a benchmark for upcoming digital twin efforts and enables the transferability to many other shop floor operations. The result of this project is a user-centred (Abras et.al. 2004) digitized workspace prototype, with a highly flexible and modular process design.

The specific maintenance task is implemented in the application with a state machine approach. This allows the workflow planner to integrate any maintenance-manual task from a maintenance pdf manual into the application. To guaranty the flexibility and interchangeability of any digitalisation approach, the system is implemented on a clean architecture approach.

For a first prototype application the system features the integration of scxml as a state machine, AI based image processing to read the component's part and serial number and optical tool tracking of a torque wrench and the battery.

The application allows for data consistency though the entire MRO process, from the preparation of a maintenance process, to the process itself, including the integration of the mechanic, all the way to the data saved and updated in a digital twin. This is one important step towards digital twins and the digitalisation of the entire lifecycle of an aircraft.

First the digitalisation approach is described in the consideration of user acceptance. Next the structure of the system is described and the approach of scxml to procure an exchangeable and easily accessible manual digitalisation is presented. After that the possibilities of AI as enabler for digitalisation are further reviewed. At the end the conclusion of this work is presented.

**Digitalisation & User acceptance**

At the moment MRO processes are highly paper-based. Those processes that are partly digitized usually are based on computer systems that are mapping the paper-based DIN A4 formats or lists to a computer. Little work went into designing processes that are useful for the MRO mechanics themselves. When diagnosing a component in a MRO process, for example, the mechanic spends most of the time on finding the right manual as well as documenting the findings and just a small fraction of the overall time on his actual work: diagnosing the part.

It has to be understood that digitalisation cannot be achieved by bringing the same paper-based processes on a computer or database, there is more to be done. To have sustainably digitized processes, there is a need of user acceptance and user-centred designed processes. A system that is not used because it is not accepted will not generate any benefit.

Davis (1986) specified that the most important part of user acceptance is the usefulness of the system, since users only engage with a system if it gives access to important functionality. Secondary Davis defined a need of usability. User-Centred design approaching on focusing on the users' needs the usability of the system (Norman 1988). To design and digitize in a user-centred manner, a new perspective has to be taken on the entire as-is process. A perspective that is moving away from paper, PDFs and long non-understandable lists, to having all necessary (not less or more) information visible when and where it is needed.

To improve the mechanics' workflow and optimize the efficiency and usefulness, it is necessary to observe the process from the mechanics' point of view. By integrating the MRO mechanic in the process, it is easier to understand problems, pain points and needs. Research has also shown that the acceptance of new systems is increased by integrating the user in the development process (Foster and Franz 1999).

In the development of the application, a high focus was set on the mechanics' acceptance and the development of a system with great additional value to the process. For this purpose, an experienced former MRO mechanic who is familiar with the battery service process was interviewed and involved throughout the entire process of building the prototype application.

Event storming was used to illustrate the battery service maintenance process. The as-is process as well as the process desired by the MRO mechanic was visualized. Event storming is a technique to visualize software in a non-technical way (Brandolini 2021). It provides a language in which the MRO mechanic, as domain expert, and developers, as software experts, can define the process and understand its requirements, objects and actors. The results were then used to define the application architecture. Periodically, the team of developers, engineers and the former MRO mechanic would get together to discuss new system parts and findings to analyse and revaluate the process. These revaluations then helped to define new requirements and necessary changes. This approach allowed the team to accurately understand and gain knowledge about the maintenance-manual procedures and challenges of bringing old procedures together with new digital tools and automation.

The architectural implementation of the application with the used digital tools is described in the next section.

**Digital Twins**

As a key concept inside the digitalisation of aircraft operations and maintenance, digital twins represent a wide field of ongoing research. They form a virtual instance of a physical entity and their concepts, architectures and functionalities are various. Nevertheless, in most cases they include some kind of data storage or pointing functionality, where manufacturing, operational, maintenance and other data is accessible. Especially the maintenance data, in terms of historic data, reports, manuals etc. are essential within the present work. Their availability on the shop floor level is necessary for the implementation of digital assistance systems and the user-centred redesign of manual processes. In reverse, the acquired information through the digital enriched maintenance procedures has to be fed back to the digital twin and the regarding data records. Hence an important requirement for the systems design can be deduced, the generic capability to mount diverse digital twin configurations to the backend.

As a promising concept, shared digital twins in distributed systems are under active research by Meyer et al. (2022 [in prep]). Here it is considered, that multiple digital twins inside different stakeholder domains have to be incorporated for specific applications. Especially inside the aviation industry, this is a reasonable assumption. Haße et al. (2022) derived key requirements to enable such a concept. Among others, the key requirements demand an automated data acquisition, a M2M communication, a bidirectional data link and a human machine interface for monitoring and interaction. These need to be considered in the present system design to be actual interoperable with the above digital twin concept.

The requirements above coincide with those of many other digital twin concepts (Errandonea et al. 2020), since they can be seen as enabling technologies to connect the digital with the physical assets, which is fundamentally for bidirectional shop floor integration of digital twins. In a state-of-the-art survey on digital twin implementations Liu et al. (2022) elaborated a need of digital models for implementing digital twins. Due to the growing amount of different virtual representations of physical systems, they expect scalability and modularity to become challenging issues, also in the interaction between multiple digital twins on the shop floor. As one possible solution further standardisation efforts are supposed.

Therefore, the present system could serve as a starting point. The backend is encapsulated and functions as an orchestrating link between the attached digital twins and digital shop floor technologies. These are modularized by itself and can be interchanged or extended, depending on the twins demands. The communication is realised with standard protocols and interfaces, that are extensible. Thus, additional resources, e.g. in the form of databases, tools or services, can easily be integrated. Ultimately, this method of a process agnostic digital twin implementation can serve as a testbed for an early stage integration test of upcoming digital twin concepts and therefore help to specify requirements as well as avoid conflicts and incompatibilities early on.

**System**

With the collected information from the event storming process and qualitive feedback, a system architecture design was defined. As implicated in the last sections, digitalisation is a circulating process that changes constantly with the achievement of new knowledge. This has to be approached with a very flexible and interchangeable system. To achieve these requirements, the software architecture is built with the principles of clean architecture (CA) by Martin (2018). The implementation of clean architecture ensures the interchangeability and adaptability of any digital tool, service, device or GUI. Therefore, the application is contributing a general solution on how to digitalise, semi-digitalise and semi-automate MRO-manual processes.

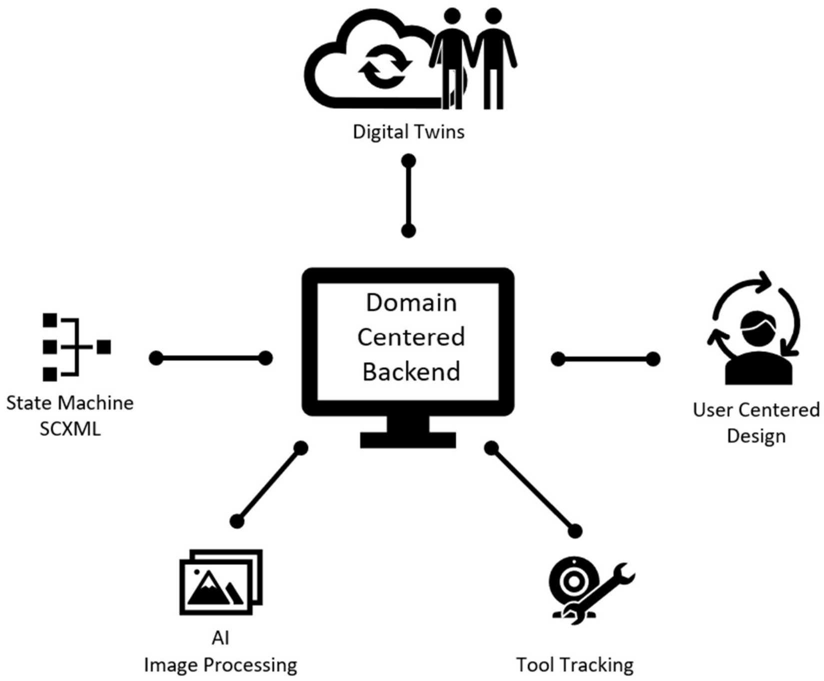


*Fig. 1: CA driven system design*

CA is focusing on the domain rather than on the database, which is an advantage since the data can be very different in various MRO-manual procedures but the domain of the system stays the same. It describes tasks and their descriptions as well as a technician class, since any task is performed by a technician. Any digital tool, GUI or DT is connected to the backend through interfaces which makes them highly flexible. For any new digital tool, only the interface has to be connected. The system is schematically illustrated in Fig. 1.

Since MRO-manuals are usually provided as PDF or printed paper, the approach of state machines for process mapping allows to integrate any MRO-manual procedure to be visualized and integrated into the system.  Each task of the workflow therefore can be defined as needed, so it can overcome the challenges of bringing old procedures together with new digital tools and automated parts.

Though these two approaches of state machines and clean architecture an adaptable application is build. As first implementations an Image Processing module and a Tracking module where connected to the backend though interfaces. The Image Processing module is described in the section AI as enabler. The tracking module was implemented with the ICG (Iterative Corresponding Geometry) 3D object tracking[2] from the DLR Institut of Robotics and Mechatronics, described in the paper of Stoiber et. Al. (2022).

The 3D object tracking allows to track multiple objects at the same time. A developed UDP Publisher sends the pose data of multiple tracked objects in a homogeneous transformation matrix. In the presented application the tracking data is used to reference a handheld tool relative to the position of the maintained batterie. The position data of the handheld tool is than combined with torque data, which is transmitted via Bluetooth. In this way, every screw can be assigned with its torque value automatically.

For the interchangeability of tasks and the possibility of differently filled process tasks the integrated modules can be tested in the holistic process and also be compared to a more manual or more automated approaches of the process.

**State Machine**

In order to face digitalisation of paper-based maintenance procedures, it is crucially important to provide tasks and their binding logic in a software processable format. The current available maintenance manuals in PDF format are suitable for their intended purpose, which is mainly presenting formatted text with images in a manner independent of application, soft- and hardware or printers[3]. Manufacturers include flowcharts into their manuals to visualize the sequence of tasks that have to be accomplished in order to retrieve a correct outcome. Transferring those flowcharts into state machine processable state charts qualifies an assistance system to control its presentation state and data logic based on the demanded maintenance job. SCXML[4] or the “State Chart extensible Markup Language” is an extended state machine language. It extends the pure control flow logic with a data model, executable content, external communications and invoking resources. This specification can be implemented independent from platform or machine. The modules for data and communication handling are pluggable by design. The specification comes with an ECMAScript data model, but platforms are free to define others if they choose. (Dahl 2016) For the purpose of digitizing maintenance-manuals, exchangeability is an important aspect. SCXML’s ability to store a fully decorated work flow in a monolithic form serves this aspect in decreasing the service complexity. (Boyer et al. 2012)

Although it is technically possible to design sophisticated state control till low-level, our approach mirrors solely the highest-level of workflow abstraction, which enables any assistive retail application on top of that layer to display suitable dialogs and information with respect to the manual. This way the high-level control flow can be strictly separated from implementation details, e.g. ai-tools, and modularity is retained.

Fig. 2 shows a graphical representation of a fully functional SCXML state machine, stored in a single file. It contains a simplified version of a battery’s periodical check workflow. States represent the condition of the process. This workflow consists of five main states or tasks: Visual Inspection, Insulation Check, Discharge, Charge and Cell Voltage. General Overhaul is a different state chart, which can be invoked from the periodical check state chart if necessary. A change in state is called transition.

[2] DLR-RM/3DObjectTracking: https://github.com/DLR-RM/3DObjectTracking/tree/master/ICG
[3] Adobe Systems Incorporated, https://opensource.adobe.com/dc-acrobat-sdk-docs/, Nov 2006, p. 33.
[4] State Chart XML (SCXML): State Machine Notation for Control Abstraction (https://www.w3.org/TR/scxml/)

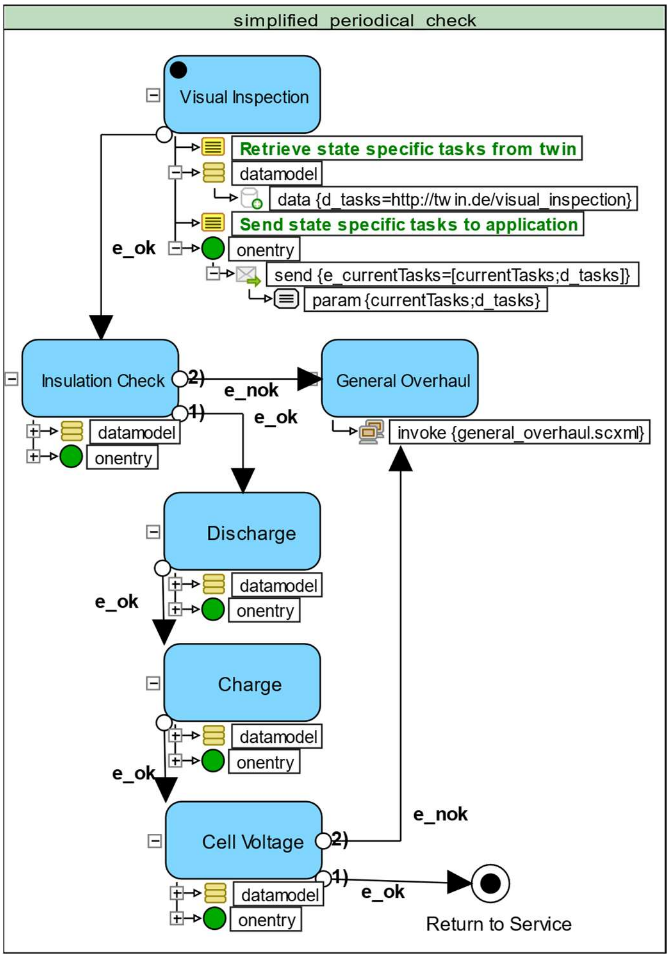


*Fig. 2: SCXML State Machine for periodical check*

All possible transitions are depicted as arrows. Transitions are triggered by events. In this case: e_ok and e_nok. If the state machine is in state Insulation Check, an incoming event e_ok transfers the state machine into its state Discharge. Accordingly, it is the event e_nok which lets the state machine invoke the General Overhaul workflow. Every state has its own data model in its scope. After entering a state, the data model gets initialized and assigned with remote data. In this case the state machine retrieves the specific sub tasks in a rich text format from a remote address via HTTP. After that the state emits an event with the just retrieved state specific subtasks in its body. If the application on top of the state machine listens to this event, it can receive it and present the events body as context to the user. The application on top has access at all times to the state machine's current state and can fetch further information like limits or geometrical data directly from the digital twin or any third party to enable specific tools, which fulfil a subtask automatically or support the user while accomplishing it manually. This clean separation from high-level maintenance procedure and solution specific details empowers reusability. Finally, when the state machine reaches its final state Return to Service it terminates.

**AI as Enabler**

With the tremendous development of AI Technologies in the past decades, especially in the field of Deep Learning, a broad spectrum of tools is available nowadays to increase the degree of digitalisation of manual shop floor maintenance. Especially in the fields of process automation, assistance systems and human machine interaction, AI not only delivers encapsulated applications but rather functions as an enabler to further embed the digital twin in the shop floor processes. On the one hand, this means an enhanced data enrichment of the digital twin in terms of sheer digitization. A vision system, for example, could inspect components for failures or defects (detection & classification), extract information (text recognition) or document the states of (dis)assembly.

On the other hand, a deeper embedded digital twin offers the possibility to utilize the available data in an increased amount of former purely manual tasks. Hereby the vision system can function as an assistance system that supports the mechanic in troubleshooting, assembly checks or information display. This offers the possibility to redesign manual maintenance procedures under utilisation of a user-centred approach. Thus the repetitive workload is reduced and it can be assumed that the cognitive stress during demanding tasks is lowered, which lead to a further user acceptance. The latter is key to actually increase the process efficiency, reduce reworks and finally generate economic benefit.

For the practical demonstration of the previous remarks, a first approach of an above-mentioned vision system is implemented into the battery maintenance process. The build-up should be modular, extensible and be able to perform several computer vision tasks. A Nvidia Jetson AGX Xavier was chosen as the acquisition hardware. This ARM based edge device delivers sufficient computing resources and is especially tailored towards multiple stream processing and deep learning workloads. The fist implemented machine vision task in order to assist the mechanic is the automatic identification of the specific component to be maintained. This is done by gathering the part and serial number of the battery. That combination enables the identification of aircraft components (Meyer et.al. 2022[in prep]) and in case of the battery component, is to be found on the type sign, attached on the casing. Therefore, the task is to gain images of the sign, detect the number positions, read out the characters (optical character recognition - OCR) and hand the information over to the backend. The reason for this CV task to be chosen is the potential to demonstrate the function of AI as an enabler and to realize the above-mentioned benefits. With the component identification, the functional backend is able to gather all necessary documents (e.g. manuals, task sheets, maintenance records) and provide it to the mechanic through a visual interface, as well as yield an event inside the state machine. Thus, the time consuming and monotone paper related work is automated and significantly reduced. The in-depth description of the implementation is given below.

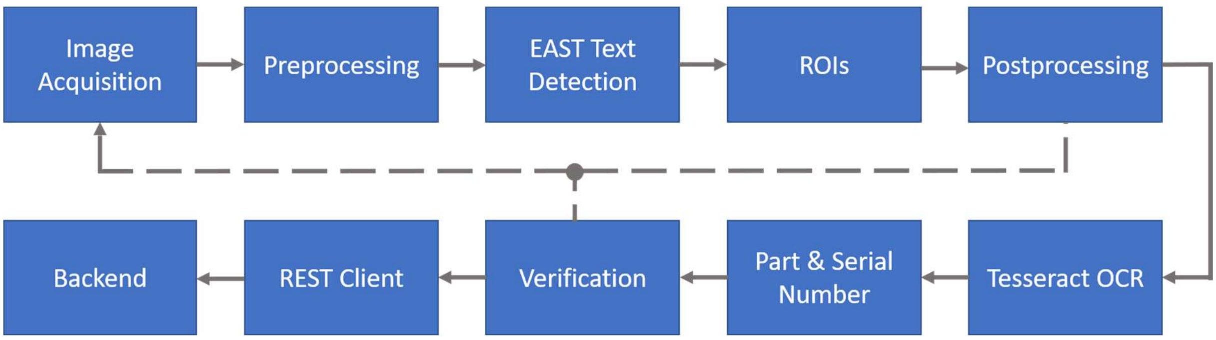


*Fig. 3: Image Processing Pipeline*

In order to automatically extract the part and serial numbers of the battery component, a camera system was integrated in the workplace, which delivers a video stream of the side view of the casing, where the type sign is located. The image processing pipeline is shown in Fig. 3. The frame acquired by the camera undergoes some routine preprocessing steps to tailor it towards the detection model. After that the frame is fed into a pretrained EAST text detection model. A detailed explanation of the model is given by Zhou et al (2017). The pre-trained weight file used is provided by the OpenCV Foundation[5] and is based on EAST (Zhou 2019). The model detects natural text in arbitrary scenes and is known as an accurate and fast method. Furthermore, it is implemented in OpenCV, which keeps the usage as well as the deployment quite simple. The result is a set of bounding box coordinates as the text regions of interest (ROI). A number of routines were implemented, to refine the results with respect to the wanted part and serial numbers. This was done by merging the ROIs that only include fragments of a number and also discard regions that contain unwanted information of the type sign. Thereby the downstream processing effort is narrowed and the performance of the OCR engine is increased. The difference between the raw ROI outputs of the EAST model and the postprocessed ones is shown in Fig. 4. Without that refinement, the OCR engine was not able to deliver meaningful results. Another part of the postprocessing consists of some check-ups of the ROIs as early stop criteria. In that case, the pipeline starts again with the processing of the next available frame (dashed line in Fig. 3).

The used OCR Engine, into which the refined ROIs are fed, is the Tesseract OCR Engine Version 5.1.0. Originally developed by Hewlett Packard, it was open sourced in 2005 and its development mainly has been sponsored by Google since 2006. A further model explanation is given by Smith (2007). The Engine offers a LSTM-based character recognition model, which is widely used in a variety of applications nowadays[6]. The model delivers a character string for each of the fed in ROI. The strings are passed through some final check functions to verify the patterns in terms of their content, length and completeness. In case of a non-conforming part or serial number, the strings are discarded and the loop starts again with the processing of the next available frame (dashed line in Fig. 3). In the event of a correct character string extraction (Fig. 4, right) the part and serial numbers are sent to the state machine as json strings through a REST API via HTTP. This triggers further transitions in the state machine. A database lookup fetches the matching maintenance manual and its regarding process information to initialize the subsequent process steps and provide the visual information to the mechanic at the workspace digital interface. The final approval of the right battery recognition and process selection has to be confirmed by the mechanic and therefore keeps the human in place as the highest-level decision authority.


*Fig. 4: Type sign image, raw EAST ROI output, refined ROIs, part and serial number from Tesseract OCR (left to right)*

As an advantage, the presented approach offers the opportunity for a modular interchange of specific pipeline modules. In case of performance issues for instance, other detection models or OCR libraries can easily be implemented. Furthermore, the ROI postprocessing provides the possibility to tailor the ROIs to include additional information on the type sign, if needed. This is one important reason why

[5] https://www.dropbox.com/s/r2ingd0l3zt8hxs/frozen_east_text_detection.tar.gz?dl=1
[6] Tesseract OCR https://tesseract-ocr.github.io/tessdoc/User-Projects-%E2%80%93-3rdParty.html

the barcodes were not used at all, neither for direct information decoding, nor for the localization of the numbers. Another reason is the fact that a large amount of type signs does not have a barcode printed on. So, a solely text-based recognition provides the greatest potential of adaptability to other maintenance procedures, according to the fundamental concept of the presented work.

As ongoing work to further utilize AI capabilities and enhance the functionality of the vision system, additional cameras are being integrated. For instance, one camera shall acquire a top down view of the battery to assist the visual inspection (defect detection and classification), the (dis)assembly status (part localisation) and the automatic documentation of the process steps. The backend design, as explained above, provides the opportunity to easily interchange or implement additional tools into the maintenance process. Besides of computer vision tasks, upcoming research will also address the implementation of AI assistance in further domains, for instance on the field of natural language processing (NLP). Here, a speech-controlled menu navigation, task confirmation or annotation functionality are conceivable, to lower work flow interruptions and keep the mechanics' focus up and in place.

**Conclusion**

A smart combination of humans and systems is more important than ever before. With the presented prototype the first step towards a futureproof approach of maintenance-manual procedures has been taken. The ability to generate a huge amount of usable data in an until now analogue workspace, brings the opportunity to streamline processes and bring efficiency on the next level. Thinking in the perspective of the MRO technician is necessary to get profitable real-world data for DT.

The clean architecture approach enabled an easily accessible backend structure, that allows a great interchangeability of the connected modules. Therefore, it was possible to easily define an interface for the ICG tracking and use it in a maintenance task.

The use of state machines made it possible to bring pdf manual data into a usable digitized format. They allow the visualization of process sequences which enables an individual implementation of digitalisation tools into different tasks. Any change to the process sequence can simply be implemented.

On the example of image processing it was shown that ai can be used as enabler to digitalised manual heterogenic shop floor procedures. AI can also support generating data for DT, as well as provide data to be implemented in assistance systems.

All over the application prototype gives the opportunity for MRO mechanics to try out future processes and design them with the researches though a feedback loop. For researchers it gives a base on which any new digitalisation tool for maintenance procedures can be easily integrated and tested. In the future this system is supposed to support research though user studies and direct verification of digitalisation ideas.

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