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Development of a multi-sensor concept for progress detection in the site assembly of electrolysis units

Lukas Büsch[*,a], Julian Koch[a], Thorsten Schüppstuhl[a]

[a]Hamburg University of Technology, Institute of Aircraft Production Technology, Denickestraße 17, 21073 Hamburg, Germany

* Corresponding author. Tel.: +49 40 428 78 - 4241; *E-mail address:* lukas.buesch@tuhh.de

Abstract

Green Hydrogen is a promising energy carrier for the future industry. To meet the accompanying increase in demand for electrolyzers, an equivalent increase in production capacity is essential. This can be achieved through efficient assembly orchestrations based on continuous assembly progress detection. This paper contributes to the necessary data acquisition during the assembly process. Various methods from the state of the art are presented, evaluated and compared against each other. Finally, a modular concept for data acquisition on the construction site of electrolysis plants based on data fusion is proposed.

Keywords: Assembly Progress Detection; Internet of Things; Multi-Sensor Data Acquisition; Hydrogen Production; Green Energy

1. Introduction

Green Hydrogen [1] is an environmentally friendly option to replace fossil energy carriers for a wide range of applications in various industrial sectors [2]. Therefore, the demand for electrolyzers that produce green hydrogen is tremendously and rapidly growing. To meet this demand, a successful ramp-up of production capacities for scalable electrolysis plants is essential. For this purpose, efficient assembly orchestrations based on continuous assembly Progress Detection (PD) is required. A flexible assembly orchestration is also necessary to adapt to delivery bottlenecks typical for this industry. Three steps are required for automated PD: data acquisition, data preparation, and data evaluation [3].

For efficient PD to succeed, the boundary conditions of the electrolyzer assembly and erection process must be taken into account: This is divided into a part that takes place inside closed factory buildings and a part that takes place on the open construction site. First, individual parts and components are assembled indoors into modules before they are transported to the construction site. On the construction site, these modules are combined to large-scale electrolysis plants [4]. The manufacturing of a complex and large-scale product from modular assemblies can also be found in the production of aircrafts or large electrical transformers. However, when large-scale modules are assembled outdoors, unique challenges for data collection remain. These are, for example, weather influences such as rain, the variable lighting conditions outsides, or other factors such as the vastness of the construction site. This makes the first step of PD especially challenging and, thus, a good starting point for developing an automated PD. Hence, we focus on data acquisition on the construction site of hydrogen plants in the scope of this work.

For this purpose, we outline this paper as follows: First, the fundamentals of the application domain and its underlying processes are investigated in Sec. 2. In the subsequent Section 3, data acquisition methods from the corresponding state-of-the-art are presented and discussed. For this purpose, not only data acquisition methods used in conventional manufacturing processes are considered, but also methods from the construction industry. Finally, a modular concept based on data fusion of different acquisition methods for the application of modular and large-scale hydrogen plants is proposed in Section 4. The results are discussed, and an outlook for further research efforts is given in Section 5.

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2. Use case and application domain

With Green Hydrogen as a promising energy carrier for the future industry, several concepts for large-scale electrolysis plants are arising. Such a plant is being developed, for example, in HyPLANT100 [4] as part of the H_2Giga lead project of the German Federal Ministry of Education and Research (BMBF) [5]. Its assembly concept is depicted in Fig. 1. This section presents the fundamentals and, subsequently, the structure and the resulting assembly processes of a large-scale hydrogen plant.

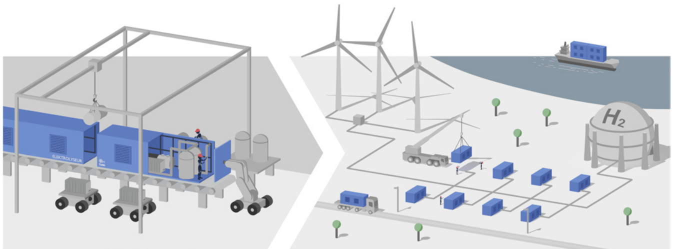

Fig. 1. Modular assembly concept for large-scale electrolysis plants from HyPLANT100 [4].

2.1. Fundamentals

Industrially established electrolysis techniques differ mainly in the electrolyte design and the water supply. There are many research efforts in the field of upscaling existing technologies and developing more efficient techniques [5]. However, current production capacities cannot meet the market demand [6]. Since the total system power targeted in large-scale electrolysis plants reaches the megawatt range, it is associated with a high demand for electrolyzers. Thus, in the example of HyPLANT100, several technologies available on the market are considered for collaborative use in an overall system. The total system output is scalable by the number of electrolysis modules. The plant is assembled from pre-assembled modules to enable a fast and efficient installation at the site. Pre-assembly can be conducted in efficient environments such as factory buildings.

These modules can be manufactured as standard dimensions, e.g., the size of 40-foot ISO containers, to simplify logistics and space planning. A distinction needs to be made between electrolysis modules, producing the hydrogen, and Balance-Of-Plant (BOP) modules. The BOP modules contain the process technology required to operate the electrolyzers, such as the power electronics and process media supply. Commercially available systems achieve an electrolysis capacity of approximately one megawatt at the size of a 40-foot ISO container. Thus, to achieve a total system capacity of one gigawatt, about 1 000 electrolysis modules and the corresponding BOP modules are required.

However, not all modules can be scaled efficiently to this defined size, so in addition to the standard modules, modules with special sizes must also be installed on the construction site. This is the case for, e.g., large transformers and rectifiers. In addition, it is reasonable for certain components to deviate from defined module sizes. Functions that are fulfilled by large standard components with little installation effort can be assembled cost-efficient directly on the construction site. Furthermore, depending on the layout of the plant, buildings and enclosures will also be erected.

2.2. Structure and assembly of large-scale hydrogen plants

In the following, the structure and assembly processes of a modular large-scale electrolysis plant are described on the example of HyPLANT100. The electrolysis and BOP modules are pre-assembled in a shop floor environment (Fig. 1 on the left). Subsequently, these modules are combined on a construction field to form an electrolysis plant (Fig. 1 on the right). The system configuration, such as the total power and the boundary conditions for installation and operation, are variable through modularization.

The processes on the construction site can be divided into two categories. Preparation of the construction site and construction of buildings form the first category. This category includes classic civil engineering processes such as water retention, deep foundation, concrete construction, and building and steel construction. Here, tasks such as, e.g. measuring, inspection, testing, manufacturing formwork, concrete backfilling, and transportation are conducted. The other category is the assembly of modules. This category includes equipment assembly, pipeline assembly, pressure and leak testing, electrical wiring, corrosion protection, and insulation. The underlying tasks to these processes are, in addition to the before mentioned, e.g., alignment, bolting, welding, grinding, painting, and rinsing. The processes will be exemplarily elaborated on in more detail in Sec. 4.1.

For the rapid assembly of modular large-scale electrolysis plants, the pre- and site-assembly processes can be accelerated by efficient orchestration and partial automation [7]. Therefore, an efficient automated system for orchestrating assembly processes is required. This involves coordinating the work of personnel and machines as well as logistics. In order for such a system to trigger and orchestrate processes, the progress of the individual processes must be efficiently detected. As the complexity of the processes increases and the number of actors involved rises, so does the level of detail required for PD to realize efficient orchestration. This required level of detail cannot be fulfilled efficiently with manual methods. Therefore, an automated PD is needed for the pre-assembly and construction site of large-scale electrolysis plants. Besides the pre-assembly, the installation on the construction site represents a decisive cost factor. Hence, optimizing the processes on the construction site is accompanied by time and cost savings, which motivates the investigation of methods for automated PD on the construction site of large-scale hydrogen plants.

3. Related work

To increase production capacities, an automated assembly orchestration for the processes on the hydrogen plants construction site is needed. For such an automated orchestration system, a continuous and efficient assembly PD is necessary. Three steps are required for automated PD: data acquisition, data preparation, and data evaluation [3]. As a starting point, this work focuses only on the data acquisition during the assembly processes on the construction site. For this purpose, various methods from the state of the art are presented and discussed. Since the development of modular and large-scale electrolysis systems is a young research topic, methods from engineering disciplines with a large overlap are considered to cover all processes on the hydrogen plant construction site. There are the PD methods from civil engineering, which cover many processes especially in the category preparation of the construction site and construction of buildings. However, the detection of progress during piping work and the interconnection of process technology inside the containers have similarities with the interior construction of buildings. Furthermore, many publications address progress determination during manual assembly in shop floor environments and production lines. The goal is to detect small-step assembly activities that are similar. These assembly activities are also present in the assembly of hydrogen plants, for example, in the connection of pipelines or the wiring of cables.

3.1. Manual methods

Traditional methods of PD, such as daily site reports, require manual data collection using construction plans and schedules that must be prepared by construction personnel [8]. For this purpose, there are several methods to optimize these manual processes. Existing data, such as site reports and delivery bills, can be digitized for automatic data processing for PD [9]. Another way is to digitize the feedback from the construction personnel directly by entering the current construction progress into a digital system via mobile devices [8].

Besides these methods, there are more small-stepped, manual feedback methods in the field of Human-Robot Collaboration (HRC). In this field of application, process steps must be confirmed by the user in small steps by means of haptic, acoustic, or visual feedback, which is recorded by the system [10].

3.2. Image-based methods

However, manual methods are labor-intensive, time-consuming, costly, and error-prone. This motivates the fully automated methods for data acquisition on the construction field. For this, data can be recorded via optical systems and then processed automatically. The 3D reconstruction of the construction site to the digital model is a necessary part of the automated monitoring of the construction progress [3]. Furthermore, image data from the construction site can also be used for object detection and the tracking of object movements. Therefore, several techniques for image acquisition on the construction site are introduced in the following.

Measuring method: Established systems for the generation of a 3D point cloud are laser scanners or LiDAR systems. These Time-of-Flight (TOF) methods measure the distances of individual measurement points over the travel time of a light signal. Compared with other methods for data acquisition, laser systems are characterized by high measurement accuracy and efficiency. In addition, these systems do not depend on the lighting conditions. However, laser systems are expensive to purchase, and their operation is associated with high technical requirements, as well as a high expenditure of time [11]. Lately, this is changing with the emergence of low-cost mobile devices with LiDAR technology.

Another measuring technique are RGB cameras. In addition to using the captured images for object recognition, these RGB images can also be used to generate a 3D point cloud using photogrammetry [3]. Therefore, RGB-image data sets are highly relevant for PD. However, RGB image-based methods depend on illumination conditions, which can be poor on construction sites. Captured image data can be classified as sorted and unsorted image sets depending on the method of acquisition. Whereas sorted image-sets contain detailed information about the position and viewpoint, unsorted data has only a patchy documentation.

Depth images from stereoscopic or infrared cameras can also be used for 3D reconstruction of the environment [12]. Depth cameras are inexpensive to purchase, portable, and easy to operate. However, these systems are only suitable for close-range and indoor operation due to their limited range. Besides their use for depth imaging, infrared cameras can also be used to capture thermal images.

Besides static images, video-based methods are present in the state of research. They are used in HRC systems to make manual feedback by the worker obsolete through action recognition and tool detection systems [10].

Platform: Stationary cameras are one way of acquiring image data. Here, the fixed and, if necessary, known poses of the cameras facilitate downstream data processing. However, a fixed camera position over the construction period results in many occlusions due to changing structures [13]. In addition to stationary-mounted cameras, remote sensing imagery as recorded by high-flying aircraft or satellites can be used. However, the remote sensing images are subject to heavy occlusion by ceilings and floors, poor resolution, and depict textures only moderately.

To overcome the effects of occlusions for stationary cameras, a mobile device can be used during a walk-through by qualified personnel [14]. The recorded data is then wirelessly transmitted to a central computing unit, where it is automatically processed.

In the state of research, further methods and systems for automated data acquisition are suggested [15]. The previously addressed problems of stationary cameras are addressed by unmanned vehicles. The use of Unmanned Aerial Vehicles (UAV), Unmanned Ground Vehicles (UGV), and the cooperation of both is being investigated. Both systems, UGV and UAV, have distinct advantages and disadvantages based on their respective measurement positions. A ground-based mobile robotic platform has a higher payload than a UAV. Therefore, UGVs are usually equipped with more sensor technology than UAVs. LiDAR systems are often mounted on UGVs for recording

3D point clouds. Conversely, UAVs are usually equipped with lighter camera systems that record images and video. One advantage of UGVs is that they can operate more safely during ongoing construction operations. In addition, the operation of UGVs is associated with lower noise emissions than that of UAVs. However, ground-based measurement techniques are subject to stronger occlusions by objects on the construction site. Based on the advantages and disadvantages of both systems, their combination is proposed in [15]. Path planning is an essential issue for both UGVs and UAVs to be used in the later concept. The state-of-the-art offers several established methods that are considered suitable for this application [16]. Therefore, this issue will be considered as solved for the following concept.

3.3. Localization methods

The localization and tracking of movements of construction machinery, personnel, or materials can provide important insights into the overall progress of the construction site. Therefore, object and personnel tracking is an important data source that must be included in the data acquisition concept. Using system-specific markers, UWB, RFID, and GPS systems can track these movements [17]. UWB and RFID systems require additional infrastructure on the site for localization, whereas GPS does not. However, GPS is less accurate and often unavailable, especially indoors. In addition, image-based localization systems can also be used. Some of these systems also require markers, while others do not.

3.4. Data fusion

More information may be needed to make a reasoned evaluation of progress at a construction site than can be captured by a single data source [18]. For data fusion, all available information sources are classified and divided into four categories.

The first category is **volumetric** information providing information about the change of volumes on the construction site. Based on this volumetric change, the progress of the construction site can be detected. Object detection results from point clouds obtained either by 3D laser scanning or photogrammetric methods are included in this category. **Localizations** are classified in the second category, including all data sources that can be used to indicate the position of an object in a global coordinate system, a local coordinate system, or in a short-range system. These sources include GPS, UWB, RFID, and image-based localization systems. All other sources of information that can be derived from a construction project that are not directly related to individual objects and specific to construction projects are assigned to the third category of information sources from **project control**. These include, for example, schedules, payment reports, and reports on the documented degree of completion of the construction site. Finally, **general data** sources that do not provide site-specific information are grouped into one category. This includes information, e.g., about the weather, season, or time.

4. Concept of data acquisition for progress detection

An overview of the processes relevant to the hydrogen plants construction field was given in Sec. 2.2. In the following, the methodology for deriving requirements is presented exemplarily using a concise process. The methodology was applied to all identified processes to obtain the final requirement list.

4.1. Analysis of processes and derivation of requirements

The process used exemplarily to show the methodology is the corrosion protection of large assemblies and pipes on the construction site [9]. The underlying process steps are depicted in the process priority graph in Fig. 2. To derive requirements for PD, the processes are examined to determine which progress must be detected for orchestration: detection of the process start, the (intermediate) progress and the end. Thereby, requirements for PD are derived.

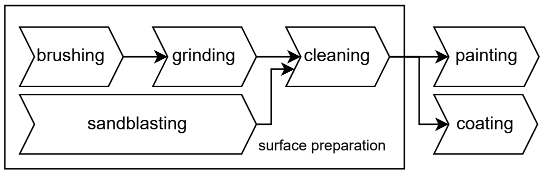

Fig. 2. Corrosion protection process priority graph for assemblies and pipes.

In the exemplary process, the detection of process start is not required. However, a continuous PD is required for the surface preparation to orchestrate its sub-processes. Here, corrosion protection is applied on surfaces that have already been prepared, while surface preparation is still being carried out on other sections. The progress is defined by the finished prepared surfaces, which must be detected based on their structure and color by the data acquisition over long distances and distributed over the construction site. The detection of the completion of the application of the final layer of corrosion protection is relevant for the orchestration because, with this, the corrosion protection activities are completed. After application, the drying or curing time of the corrosion protection starts. The complete application of corrosion protection can be recognized visually by the structure and color of the surface in the same way as the surface preparation.

Applying the methodology exemplified, all processes on the hydrogen plants construction field were examined, and the derived requirements for a data acquisition system were grouped. The list of requirements is provided in Table 1.

4.2. Overall concept

The hydrogen plant construction field is defined by processes with different orchestration needs, as confirmed by the versatile requirements derived. This motivates the combination of different technical solutions into an overall system. Various subsystems for data acquisition on the construction site are therefore proposed. A digital collection point for all acquired information and its evaluation in the form of a central computing unit is required [18, 13]. Due to the vastness of the construction site and the mobile operating subsystems, a wireless data transfer between the systems is necessary, which can be an existing infrastructure, such as mobile networks or temporary local infrastructure. In the following, a methodological technology selection for the exemplary process is conducted. Thereby, data acquisition methods for project control and general data sources, which are the digitization of already acquired information, are not considered. Subsequently, the selected technologies for all derived requirements are presented in Table 1.

The requirement derived from the exemplary process of corrosion protection is the detection of the color and structure of large surfaces. To capture the color and texture of a surface, an RGB image is required. Therefore, the measuring method is set as an RGB camera. The four potential platforms for the measuring device, as described in Sec. 3.2, are stationary [13], a handheld device [14], a UAV and a UGV [15, 16]. Detecting features on large and distributed objects on the construction site, stationary data acquisition is not efficiently applicable [14]. For the remaining three mobile platforms, the requirement-specific aspects of occlusions, security, operation in enclosed spaces, mobility, and effort were examined. A handheld device has benefits in avoiding occlusions, safety and in operation in enclosed spaces. But the effort is very high since skilled personnel is required all over the construction site [14]. An autonomous operating UGV decreases the personnel effort but is prone to occlusions and also has moderate mobility [15]. The UAV captivates with its high mobility on the construction site, which decreases the effort since several distributed processes can be monitored simultaneously. Furthermore, due to the airborne data acquisition, occlusions can be reduced. However, UAVs have no safe emergency shutdown during operation. In addition, they can only operate in enclosed spaces to a very limited extent. Due to the advantages, a UAV with an RGB camera is proposed as the technological solution to meet this requirement.

To meet the requirements given in Table 1, three platforms were selected for data acquisition on the hydrogen plants construction field. These are data acquisition with a mobile device, a UAV, and a UGV. The selected platforms for data acquisition and the required measurement equipment are presented below. The overall concept with the selected subsystems is visualized in Fig. 3.

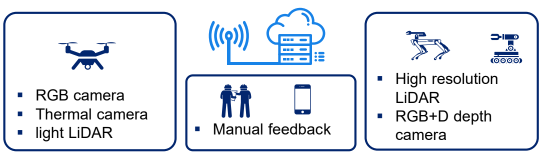

Fig. 3. Selected subsystems for data acquisition.

The use of a **mobile device** for direct digitization of feedback from skilled personnel [14] in the process is motivated by the requirement for efficient digitization of manual feedback. By linking the mobile device to the central processing unit, it is possible to directly process the relevant feedback.

Table 1. Requirement list for data acquisition for automated progress detection (exemplary process in italics).

Group	Requirement
Manual feedback	Digitization of manual feedback
Object detection and localization	Detection of objects of different sizes on the construction site (e.g. piles)
	Detecting position and orientation of objects on the construction field (e.g. 20 and 40 feet containers)
	detection of structures over long distances (e.g. pipelines, cables))
	large-area detection of geometries and volumes (e.g. concrete foundation, trenches, dikes)
	high resolution detection of geometries and volumes (e.g. reinforcements)
Manual assembly tasks	Detection of individual assembly tasks and the use of hand tools by personnel (e.g. screwing)
Movement detection	Detection of personnel movements
	Detection of material movements (e.g. sheet piling, steel assemblies from stock)
	Detection of movement and use of construction equipment of various sizes (from vibrators to pile-drilling equipment)
Operating status of construction equipment	Detection of the operating status of construction equipment (e.g. drilling depth on the drill rig mast)
Surface features	*Detection of color and structure of (large) surfaces*
	Detection of heat signatures (e.g. detect stress relief annealing after welding or construction machinery in operation)

To meet several requirements, a **UAV** as a platform for data acquisition was selected as a subsystem for data acquisition [15]. Various measurement tools were combined with the UAV. These requirements are derived from many processes on the hydrogen plants construction field so that the UAV can monitor multiple processes in sequence or simultaneously. UAVs have a high travel velocity on the construction field and enable data acquisition from many perspectives due to their third-axis positioning capability. In addition, UAVs only cause minor disruptions of the processes because UAVs operate outside the workspace. However, UAVs have a lower payload compared to UGVs and do not have a safe emergency shutdown during operation, as already discussed. The different measurement tools selected to meet the requirements are presented below.

First, 2D RGB images of processes on the construction site must be acquired using an autonomously operating UAV to meet many requirements from the group of object detection and localization, as well as from motion detection. Furthermore, this combination is recommended for the detection of the operating state of construction equipment, as well as for the detection of the color and texture of extensive surfaces.

A thermal imaging camera on an autonomously operating UAV is required for the detection of thermal signatures. Camera systems are available on the market that records both 2D RGB images and thermal image, so a single UAV can be used to meet several requirements.

Last, a lightweight LiDAR system on a UAV is selected for large-area detection of geometries and volumes. These systems are also available in combination with RGB camera systems. Furthermore, the measuring equipment on UAVs is usually modular and equipped with quick-release connections so that these can be replaced in a time- and thus also cost-efficient manner, and the UAV system can thus be converted to meet different requirements on the construction site.

UGVs are associated with higher investment costs than UAVs [15]. In addition, ground-based systems are more likely to affect or interfere with construction field processes than airborne systems. However, due to the higher payload and safe operation in close proximity to construction personnel, a UGV is selected as the platform for data collection to meet two requirements. This involves combining two different measurement techniques with a UGV, as listed below.

For high-resolution detection of geometries and volumes, a high-resolution LiDAR system is required, which cannot be airborne due to the required payload and stability of the image capturing. Therefore, this system will be deployed on an autonomously operating ground-based UGV.

Last, a UGV equipped with an RGB+D depth camera is recommended for detecting individual assembly activities and the use of hand tools by construction personnel.

5. Conclusion and outlook

This paper describes the specific assembly characteristics of large-scale hydrogen plants and presents a novel concept for data acquisition at their construction sites. The objective of data collection is to provide information for automatic PD, which is essential for an efficient assembly orchestration system. Moreover, the data acquisition concept enables PD with varying levels of detail, forming the basis for handling flexible process flows. Besides the modular concept for data acquisition, applicable technical solutions from the state of research are proposed. The modular concept, combined with these technical solutions, is the basis for further work and discussion as this research field advances. However, the proposed data acquisition framework needs to be applied to a real use case and refined for a more profound validation. Besides the more detailed evaluation and validation of the concept, an investigation of the data processing and evaluation needs to be conducted to implement a PD for the presented use case. A technical implementation of the concept is envisaged in a demonstrator as part of the HyPLANT100 project. To accomplish this, an investigation of the availability and technical maturity of the covered data acquisition methods is necessary.

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CRediT author statement

Büsch: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Project administration, Writing – Original & Draft & Review & Editing. **Koch,Schüppstuhl:** Resources, Funding acquisition, Supervision, Writing - Review & Editing.

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