From Tables to 3D-Models: Improving the Usability of Scientific Data Visualization

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***Abstract*—In research facilities, critical components such as reactors or other centrepieces are equipped with a large number of sensors to record safety, process, and research-relevant data in real time. The effective visualisation of this measurement data is crucial for fast acquisition, analysis, and decision-making by plant operators. This Work in Progress Paper investigates different methods of visualising complex sensor data using the example of a 2-in-1 reactor, starting from classical tabular approaches to color-coded 2D-heatmaps, and interactive 3D-models. One focus is on human perception and the cognitive processing of the large amounts of data from 171 temperature measuring points. While tabular visualisations offer maximum precision, they are often unsuitable for the rapid detection of patterns and anomalies. Graphical visualisations - especially color-coded maps and 3D-models - provide an intuitive representation, but can be challenging due to color perception problems, information overload, and limited scalability. The system implementation, featuring an interactive 3D-model of the reactor, is described in detail in order to improve usability, reduce the cognitive load on the user and increase situational awareness. In further steps, specific usability tests will be carried out to validate the effectiveness of the 3D-visualisation and to analyze its influence on the user.**

***Keywords*-research facilities; HMI-Systems; 3D-integration.**

I. Introduction

Research equipment often consists of a centerpiece, which is the primary focus of scientific investigations and serves to generate key measurement data. It is usually embedded within a complex environment of plant technologies, automation systems and a Human-Machine Interface (HMI). Such centerpieces can include detectors in accelerator systems, electric fields inside microscope probes, flow measurements in neutron targets [1], or temperature distributions in batteries, turbines, reactors, or other components.

The visualisation of this measurement data is crucial, particularly in research facilities, where fast comprehension and accurate interpretation are required. While traditional tabular visualisations provide precision, they often lack clarity when it comes to recognising spatial patterns or anomalies quickly. Alternative visualisation methods, such as 2D-heatmaps, and 3D-models, can support more intuitive data exploration. However, the choice of visualisation technique has a significant impact on usability and user performance.

In the field of Human-Computer Interaction (HCI) and visual analytics, previous work has investigated the cognitive effects of different visualisation forms. For instance Tory and Moller [2] emphasises that while 3D-representations may enhance spatial understanding, they can also introduce interaction complexity and perceptual challenges. Ware [3] highlights that, in many analytical tasks, well-designed 2D representations with multi-dimensional icons can be more effective than full 3D-renderings.

Despite these findings, 3D-visualisation can offer advantages in scenarios where data is inherently distributed across three dimensions, such as the temperature distribution in layered reactor systems. However, empirical validation of these approaches in research environments is still limited. This paper contributes to this gap by presenting the implementation of an interactive, browser-based 3D-visualisation for a 2-in-1 reactor.

The implementation addresses 171 temperature measurement points across three spatial planes, focusing on enhancing usability, reducing cognitive load, and supporting analytical tasks such as anomaly detection and system overview. Section II outlines the general visualisation requirements, followed by Section III, which compares different visualisation strategies. The implementation of the 3D-model is detailed in Section IV. Section V concludes with an outlook on planned usability evaluations and future applications in similar research systems.

II. Requirements

Different application scenarios also lead to different priorities in the requirements for the presentation of information. In applications where, for example, critical temperatures or temperature anomalies need to be recognised quickly, the quick and clear presentation of information for the user should take centre stage. At the same time, the system should offer interactive elements that allow the user to quickly show or hide details as required in order to focus attention on the relevant information. The ability to customise or filter the display according to individual requirements contributes to the flexibility of the system and ensures that the user has the most important data quickly available at all times [4].

For stable processes, on the other hand, the precise and accurate display of temperature values is paramount in order to make well-founded decisions. Here, a detailed, interactive display of temperature curves and the option of customised filtering or data analysis could support the user - for example, by selecting specific time periods or parameters. The ability to customise the display of information to the respective requirements promotes efficient and effective use of the system [5].

The balance between precision and quick recognisability can change quickly depending on the situation, so scalability between overview and detail levels is usually required. The user should be able to switch between a quick, clear view and a detailed, precise display, depending on the type of information required at the time. In addition, all individual requirements should be easily adjustable without compromising user-friendliness. However, all individual requirements should follow basic ergonomic aspects of human-centred design in order to create a task-oriented HMI-System that allows the user to work effectively and efficiently [6]. Simple interactivity and customisable filter options help to reduce the workload and adapt the HMI-System flexibly to different needs and working conditions.

III. Realisation

The following section deals with the temperature recording and visualisation of a reactor, as it can be found, for example, in the field of hydrogen storage in research facilities. This consists of six radius levels on which a total of 86 internal heating tubes are arranged at the same distance from each other. For temperature measurement, 17 multi-thermocouples are guided onto the inner tubes from the outside, which measure the contact point of the inner tube, as well as other measuring points between the outer wall of the reactor and the inner tube, shown in Figure 1.

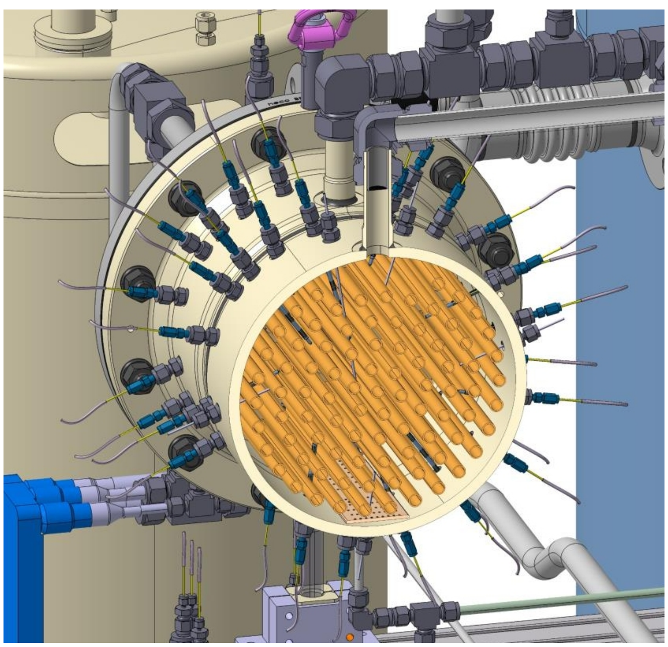

Fig. 1. Sectional view through the 2-in-1 reactor with a view onto the inner heating tubes and the multi-thermocouples.

This results in 17 measuring points that reflect the temperature of the inner tubes, and 40 measuring points of the temperature inside the reactor. This arrangement of thermocouples is placed three times along the length of the reactor, resulting in a total number of 171 temperature measuring points. The temperatures recorded in this way must be displayed to the system operator for various purposes, such as troubleshooting, monitoring against overheating and homogeneity. The various visualisation options are compared in the following subsections.

A. Tabular presentation

One of the most common methods of visualising temperature can be in tabular form. This enables a clear numerical representation of the temperature values. The advantages are the high accuracy and comparability of individual values, but it is no longer possible to assign them to the measuring position in the reactor without an additional drawing. The human ability to absorb information is limited, so tables with more than 5-9 entries (chunks) can cause difficulties [7]. Therefore, tables have the disadvantage that they are not very clear and it is difficult to recognise patterns or anomalies. Figure 2 shows the representation of the measured values of measuring plane-A from the component view of a thermocouple. The contact points on the heating tubes are shown in the left-hand column and the measuring points inside the reactor are shown in the following columns.

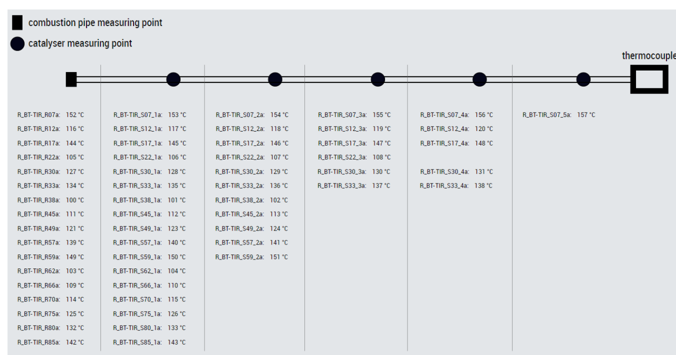

Fig. 2. Table based temperature monitoring of plane-A with 57 measuring values.

Despite the listed disadvantages of simplicity, this view can be very helpful in the application case of troubleshooting due to the direct assignment between the name of the measuring point and the current temperature value. A highlighting of limit value violations or other events can improve the interpretation of information.

B. 2D-presentation

If the table view of plane-A is transformed into a two-dimensional sectional view of the reactor, shown in Figure 3, the clarity and the possibility of recognising patterns or anomalies can be significantly improved.

In addition to the textual display of the temperature directly at the measuring point, the object can also be color-coded according to a defined color scale. The direct assignment of

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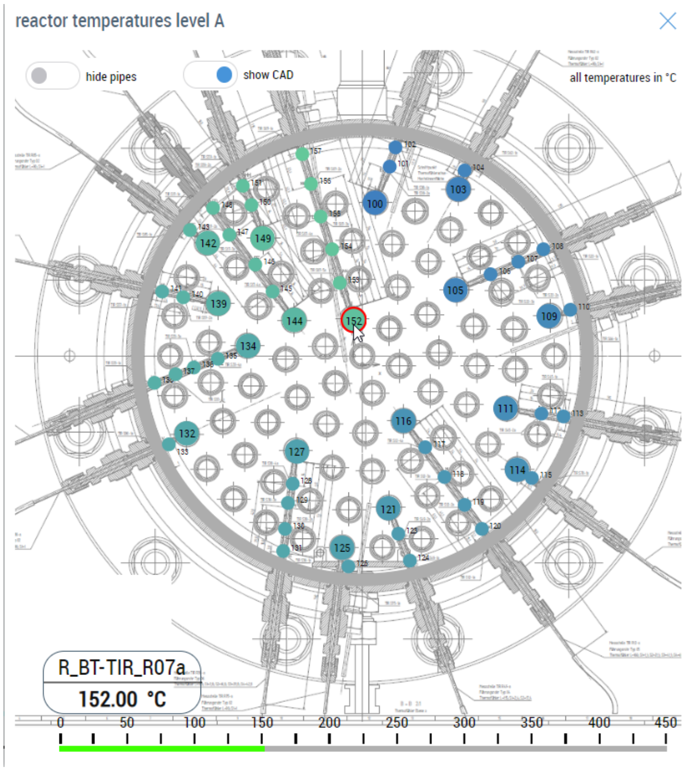

Fig. 3. 2D-based temperature monitoring of plane-A inside the construction drawing.

the temperature to the location inside the reactor, as well as the preattentive processing of colors, the ability of humans to recognise colors and color gradients very quickly [8], can be of great importance in the interpretation of local hotspots or cold areas. By adjusting the scale start and end values, the representation can be easily scaled to different temperature ranges. Nevertheless, color coding is only a quantitative classification of the measured value, as it is subject to errors due to different color perceptions and an indirect interpretation via the color scale. This disadvantage can be compensated by the additional textual representation, but the visual possibilities are much more limited by using the 2D-sectional view than in a tabular representation.

C. 3D-presentation

The two display types described refer to the measured values of one measuring plane. If the entire temperature curve within the reactor needs to be analysed, it is necessary to display all three planes simultaneously or to switch between the screens. This leads to a further loss of clarity due to the tripling of measuring points. The color-coded representation of temperatures in 2D-view can also be extended to the model in 3D-space. Figure 4 shows the simplified 3D-model of the reactor, in which the heating pipes are divided into three cylinder sections along their length and the measuring points within the reactor are represented by spherical objects.

The color of the object can then be converted into a temperature of the respective measuring point using the color scale, analogous to the 2D-representation. The 3D-display offers the option of moving the model, selecting different zoom levels and hiding individual objects in order to display the desired observation area. Clicking on individual objects inside the 3D-model opens a dialogue with the exact temperature of the object and additional properties. The 3D-visualisation of measured values, such as temperature profiles for example, offers an excellent overview, as it allows users to capture visual relationships intuitively. However, 3D-visualisation is not suitable for all types of measurement data or applications. In cases where the focus is on precise individual values, 2D-diagrams or tabular visualisations can often be more efficient. In addition, an overloaded 3D-visualisation can make it difficult to absorb information, especially when a large amount of data is displayed simultaneously.

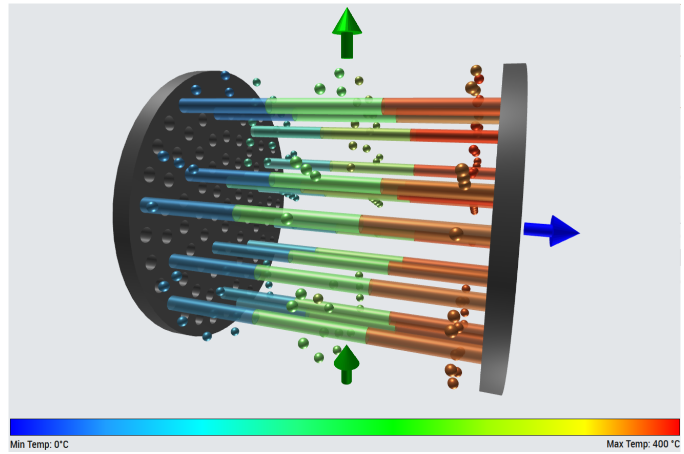

Fig. 4. 3D-based temperature monitoring of plane-A, B and C in the developed 3D-tool.

IV. IMPLEMENTATION OF 3D-INTEGRATION

For the integration of 3D-content in the TwinCAT HMI, a 3D-Framework Controls was designed by Beckhoff Automation GmbH & Co. KG [9], which uses the JavaScript library Three.js [10] to display 3D-graphics inside the browser. The camera position, lights and colors, as well as scaling and movements can be influenced. Various functions are available, such as controlling animations or dynamically changing the colors, size or position of objects, which can be controlled from external Programmable Logic Controller (PLC) variables.

In order to implement a new model, it must be prepared in 3 steps. The model to be displayed was either designed directly in a Computer-Aided Design (CAD)-programme or is available as a .step file format. The model must first be broken down into individual assemblies, whereby each individual part to be edited later in the HMI must represent a separate assembly. These assemblies must then be exported to stereo lithography (STL) files, which simplifies the model into a surface model with triangular shapes [11]. Secondly, the individual .stl objects must be assembled into an overall model in the 3D-tool Blender [12]. To do this, the coordinates from the original CAD-tool can be used, which are created during the separation into assemblies. All objects must be described with a unique name and objects for which the color is to be dynamically adjusted later need to be provided with a material property and a default color. The revised model must then be exported as .gltf format, a JSON-based 3D-format witch was chosen due to its good performance in web applications and its compatibility with the most commonly used browsers Firefox, Chrome and Microsoft Edge [13].

In the third and final step, a configuration file must be created and linked for the framework control, in which the 3D-model is embedded and all required dynamic functions are linked to PLC variables.

Figure 4 shows the representation of the processed reactor model from 177 assemblies in the HMI, in which the following functions were implemented:

- Display of the current temperature with a color-indicated temperature scale of 171 measuring points.
- Interaction with the model to open additional measuring point information.
- Whitening of passive components through opacity.
- Insert visual section planes to display the 3 planes of the measuring points.
- Opening defined views and scalings.
- Activating the auto-rotate function and influencing the rotation speed.

V. Conclusion and Future Work

The visualisation of measurement data in research facilities poses unique challenges: it requires both the rapid identification of critical states and the precise interpretation of complex data. This paper presents a modular 3D-visualisation approach integrated into an HMI for a 2-in-1 reactor, based on the Three.js framework. The implementation demonstrates the feasibility of mapping 171 temperature sensors onto a spatially accurate 3D-model, providing color-coded data overlays, interactive views, and real-time control via PLC variables.

While the current solution offers an intuitive and immersive experience, its effectiveness for specific analytical tasks remains to be evaluated. Previous research in visual analytics and HCI suggest that while 3D-representations support spatial understanding, they can be less effective than 2D methods for certain analytical tasks [3]. In future work, usability tests will be conducted with domain experts to assess the cognitive load, task efficiency, and user preference between tabular, 2D, and 3D-visualisations. These tests will also consider accessibility aspects, such as color vision deficiencies, which are not yet fully addressed in the current implementation.

Furthermore, the system will be extended to support other types of sensor data and centerpieces. An important part of future work is to derive task-specific guidelines for when 3D-visualisation is beneficial and when simplified, abstracted views may be more effective.

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