Visualizing Autonomous Warehouse Data Streams through User-Centered Design

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***Abstract*—In this paper, we develop and evaluate a dashboard design that visualises a stream of data from different entities involved in autonomous warehouses, as a subset of cyber-physical systems. The dashboard is designed and developed through User-Centered Design (UCD) methodologies based on two iterations of feedback sessions with the stakeholders. During these sessions, semi-structured expert opinion interviews are conducted. The paper discusses the different stages involved in building the proposed dashboard design, the design decisions, the technical aspects of the libraries used, and the results of the feedback sessions towards the end of the project. It also presents the implemented dashboard as a proof of development efforts and explains its different functionalities. The study concludes by evaluating the dashboard through the semi-structured interviews with the respective stakeholders and suggests features for further development.**

Keywords—data visualization; cyber-physical systems; user experience; user-centered design; supply chain; autonomous warehouse; intelligent agents; dashboard design.

I. INTRODUCTION

In simple terms, a Cyber-Physical System (CPS) is a system in which different computational and physical processes are being carried out together in order to perform several tasks [1]. These tasks could belong to a wide range of domains, including assisted living, traffic control and safety, advanced automotive systems, distributed robotics defense systems, manufacturing, and smart structures [2][3]. In this paper, we discuss a narrow application of CPS, namely, an automated warehouse.

Traditionally, a warehouse involves four major functions: (1) receiving, (2) storage, (3) order picking, and (4) shipping [3]. Today, there is an ever-increasing demand for a variety of products and shorter response times causing a tremendous emphasis on the ability to establish smooth and efficient logistics operations. These logistic operations are complex and hence produce a lot of data. This data has the potential to be used for further monitoring the complex operations by the stakeholders to understand the current state of the warehouse. Based on this, the stakeholders can analyse several Key Performance Indicators (KPI), including interoperability, knowledge reusability, performance, sustainability, safety, risk, and profitability [4]. Hence, for a smooth functioning and maintenance of these systems, there is a need to gracefully represent these complex data streams in an easy to understand manner.

This study is part of a project, which is called Secure Connected Trustable Things (SCOTT) and focuses on complex logistics use cases. The study explores a dashboard design to best represent the data streams in an automated warehouse to help the stakeholders to monitor the current state of the warehouse. The automated warehouse in question has three levels as follows: (1) Supply Chain level, (2) Warehouse level, (3) Intelligent Agent level [4].

The aim of the project is to address the research question: *What are the suitable visualization techniques that are required to build a dashboard which represents a stream of data from an autonomous warehouse, focusing on KPI such as performance, safety, and sustainability by employing user-centered design methodologies?*

To this end, this report leverages on expert opinion [5] and semi-structured interviews [6] at the onset of the study to understand the needs of stakeholders, gather feedback and suggest new features for further iterations. Section I introduces the concept of CPS and autonomous warehouse, defines the problem statement, the objective of the study, methodology used to achieve that and delimitations of certain procedures and technology used. Section II discusses the previous work done in the field of CPS and autonomous warehouses, different methods to build user friendly dashboards for retailers and smart warehouses. Section III discusses the design process, the initial decisions taken, defining the entities, and building three different dashboard views based of the level of the warehouse. Section IV discusses the metrics for the user study and interviews. Section V explains the results based on the interview feedback. Section VI discusses the results and breaks down similar feedback into three categories. The paper ends with concussion and suggestions for future work in Section VII.

A. Objective

The primary goal of the study is to design and develop a dashboard to answer the defined research question. This dashboard represents a stream of data that comes from the different entities involved in and around an autonomous warehouse which is a fully-automated CPS. These entities include (1) trucks, (2) warehouses, (3) retailers, (4) smart robots, and (5) conveyor belts.

B. Methodology

During the project, the identified stakeholders were interviewed on two stages of the design process. Semi-structured interviewing is a very flexible technique for

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small-scale research in which detailed structure is left to be worked out during the interview, and the person being interviewed has a fair degree of freedom in what to talk about, how much to say, and how to express it [7]. The feedback session was an informal user study with one stakeholder where a pen-paper prototype was evaluated. Based on the feedback, the final visual design was made which later got converted to a functional prototype. The development was further shaped by feedback from one-to-one semi-structured interviews. Towards the end of the final prototype, a final interview was conducted to get feedback relevant to the next iteration of the dashboard.

To develop this prototype, ReactJS[15], a component-based JavaScript framework was used for the base front-end of the application. It was primarily because of its rendering performance and the ability to break down the application into smaller independent components. D3js[16], the industry standard of data visualization javascript library was used to develop the dashboard prototype. A state machine, Redux, was also introduced to capture the state after every change in the data as an immutable object. This was done to avoid continuously calling the server to make the dashboard more performant. Nivo, a wrapper on top of D3js, was used to make the visualizations. Nivo was preferred because of the flexibility in the layout of the graphs it generates and the data structures are more adaptable unlike libraries like react-d3. ImmutableJS was used to create factories for the entities in the form of records. Fetch was used for the HTTP requests to the server. Postman is used for mocking the back-end API.

C. Delimitations

The project does not involve a real-time data streaming coming from automated warehouse since the research project prototype is still under development. Therefore, there are assumptions made for the structure and properties of the data streams that might change or evolve. Although a very strict data structure is followed and obeyed while building the visualization, there might be performance issues due to the machine learning algorithms. In terms of design, although the dashboard incorporates the UCD approach [7][10], the feedback session is limited to 5 people, considering stakeholders include user experience designers, system engineers and researchers who work on the same project. The dashboard currently incorporates 3 KPI: (1) safety; (2) sustainability; and (3) performance. The scope of the work does not include the identification of the relevant KPI and also does not include the further data integration with the existing or in development CPS. However, the interested reader can learn more about the earlier research conducted as part of the project to identify these KPI [4] and the minimalistic data model for monitoring purpose [8].

II. Background and Related Work

Research in the domain of CPS is driven by several recent factors: (1) the development of low-cost and increased-capability sensors of increasingly smaller form-factor, (2) the availability of low-cost, low-power, high-capacity, small form-factor computing devices, (3) the wireless communication revolution; abundant Internet bandwidth, (4) continuing improvements in energy capacity, alternative energy sources and energy harvesting [1].

As we mentioned before, automated warehouses, an example of CPS, have interactions between different moving parts (or entities) involved in keeping or retrieving different objects present in the warehouse or the interactions of the warehouse with the outside world. The complex nature of these interactions makes it difficult to see the overall activity in and around the warehouse.

In [4], the authors conduct several interviews with experts to identify the important KPIs and stakeholders as a first step. During this work, an example dashboard design is also presented. However, this preliminary study does not include a working prototype.

Furthermore, in [7], (1) safety, (2) sustainability, and (3) performance are chosen as important KPI to monitor through the dashboard.

Safety refers to the level of trust in the warehouse. A collision probability is one example metric used to monitor the safety level in the warehouse.

Performance is related to metrics such as time, goals accomplished by a particular robot or the overall goals of the warehouse.

Sustainability refers to the energy levels of the warehouse. This includes the energy and the battery consumed to perform actions within the warehouse, which is directly correlated to the efficiency of the robots and the warehouse.

Later, a minimalistic data model [8] is presented in the same study through a linked data technologies which promise both consistency and interoperability throughout the CPS in focus.

Other research projects have been working with management dashboards in scenarios specific to retailers and for one of them, the views are split into (1) Management layer, (2) Physical layer, and (3) Agent layer but these layers have not been evaluated by the respective stakeholders [8].

The automated warehouse's smartness is guaranteed by the intelligent agents. These agents are the representations of real components such as robots, smart shelf systems and so on. For this purpose, Soar, a general cognitive architecture, has been a studied as part of the project. It offers demonstrations of individual components, components working in combination, and real-world applications [9]. VISTA is a generic toolkit that allows stakeholders to visualize internal reasoning of these intelligent agents [10]. However, this toolkit is concentrated on the behaviour of the agents, in contrast to, the data streams from the agents.

III. Design Process

A. Initial Design Decisions

In terms of the first design process, the first step was identifying the entities and splitting them into the three levels. Every level was then split into cards and atomic design [11] approach is used to build smaller cards instead of making one big dashboard. Atomic design is a methodology of creating a design system based on creating small components (or atoms) like buttons, inputs, headings, and so on. Later, these components comb are combined to create larger components (or molecules) like forms, button groups and in our case, cards. This approach is chosen for the purpose of making the application as modular as possible.

To make the implementation as light as possible, a highlight boolean variable is included in every entity which enabled to fetch the required data instead of querying all the data. This way, the performance of the prototype is ensured.

The idea of not revealing the entire data set was given prime importance to enhance both experience and performance. Hence, a highlight boolean was introduced in all the entities and only entities set to true by the users were displayed at first and the entire data set was released once requested by clicking the button.

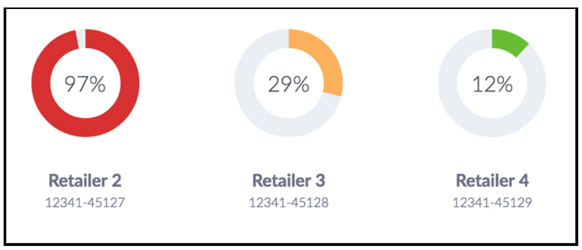

Figure 1. State of the retailers and warehouse on the supply chain level.

The dashboard consisted of a lot of data streams that signify an empty or a full state which could not be expressed only by numbers, hence three colors, based on color selection for highlighting tasks [12] were consistently used to signify negative (full), positive (empty) and in progress space (Figure 1).

As we mentioned before, the warehouse is divided into three levels (supply chain, warehouse, and intelligent agent) and the information for each level is represented by cards. The dashboard is designed in a way that each card owned a separate API request to make all cards independent of each other. Moreover, information text was provided for every card in the form of a tooltip so that the helpful information is only available when needed. These implementation decisions are selected to allow enough resources available for the performative visualizations [13].

B. Defining Entities and Their Records

The following entity records are defined to represent the entire system:

- **Warehouse and Retailers** represent the entire space and consist of a similar data structure composed of an ID (string), highlighted tag (bool), location (geo), the name of the space (string) and the capacity of the space (num). The IDs of these entities are needed for trucks to identify destination and source of their journeys.
- **Robots** of different kinds: (1) arms, (2) conveyor belts, and (3) other retrieval systems are an integral part of the intelligent agent level and warehouse level. Their data stream is comprised of an ID (string), activity, battery and performance indicators with their respective deviation. It also consists of the location ID and the object ID that signifies in which warehouse they are present and the object they are carrying. They could be highlighted based on battery or robot status. The prime value is the time to return to its base after completing its task.
- **Trucks** are entities that connect: (1) retailers-retailers; (2) retailers-warehouses, and (3) warehouse-warehouse, and hence consist of their location (geo) of start and end point. Trucks also have a sustainability index and activity, measured in hours.
- **Notes and stakeholders** card is shared across all the three levels and also have an ability to be highlighted to display the notes and stakeholder of choice on the home screen. Notes consist of an ID (string), the text field (string), the data of addition (string), author ID (string) and the highlight tag (bool) and type (string). Stakeholder consists of the ID (string), name (string), email (string), type (string), phone (num). The author ID of the notes is linked to the stakeholder ID to identify where the note is coming from.

C. Data Connections

All the entities are connected to each other and share data as per the linked data structure. Stakeholders and Notes are present in all the three levels of the data visualizations, but their ids are linked to their respective levels (Figure 2). For example, a stakeholder responsible for Retailer 1 has its ID linked to the ID of the retailer. At the supply chain level, the trucks are linked to the warehouse and the retailers as their locations (to and from) with the time left to complete the task as the primary variable.

At the warehouse level, the position of the robots is used to define the interior map layout of the warehouse. They carry boxes that have unique ids.

At the intelligent agent level, information related to the interoperability between robots is visualized through data about interaction and memory usage of the agents.

D. Level 1: Supply Chain level

The purpose of the Supply Chain level is to visualize data available outside the warehouse scope and how the objects in the warehouse interact with the outside environment (suppliers, retailers, and warehouse). The dashboard is divided into 5 cards: (1) Capacity, (2) Truck Journey, (3) Profitability vs. Risk Curve, (4) Notes, and (5) Stakeholders.

- **Capacity:** The capacity card details the available space in the current / adjoining warehouses along with the

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space available at the retailers. The data is represented by a dial visualization to give stronger emphasis to the color and the percentage value of availability. This section can be updated to check the average capacity of the warehouse or the retailer over the month, week or even year.

- **Ongoing truck journey** card details the connection journey between (1) warehouse-retailer; (2) retailer-retailer; (3) warehouse-warehouse; and depicts the current state of the journey as a progress bar. Since there is a lot more data available for the truck (Figure 3), it could be displayed on clicking the View more button next to every truck progress bar.

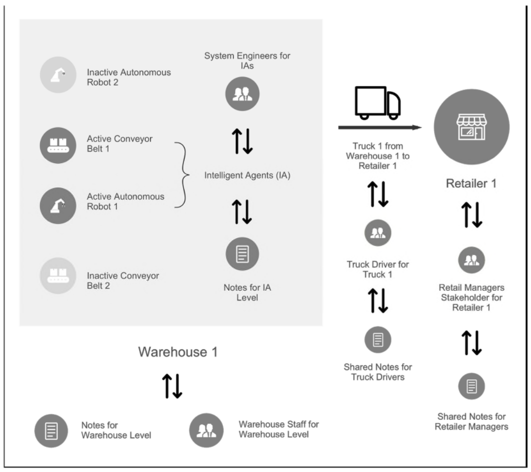

Figure 2. An overview of Warehouse 1 with different kinds of active robots (Autonomous Robot 1 and Conveyor Belt 1) being managed by system engineers.

- **Profitability vs. risk curve** is an X-Y plot with Profitability/Risk on the Y-axis and the time on the X-axis. The curve could be updated to accommodate daily, weekly monthly and yearly values. This curve represents the profits (in %) and related risk generated from the warehouse while dealing with different retailers.
- **Notes and stakeholders.** Stakeholders for the supply chain level are the truck drivers, warehouse managers, and retail managers and they have the option to add and share notes between each other.

E. Level 2: Warehouse level

The purpose of the Warehouse level is to visualize the movement and exchange of data inside the warehouse primarily by the robots. The dashboard is divided into (1) Real-time map of the warehouse, (2) Stacked-Performance Chart, (3) Robots, (4) Notes, and (5) Stakeholders.

- **Real-time map** of warehouse depicts the top view of the warehouse with robots being placed by the waypoints [7], X (Line - <num>) - Y (Y - <num>) coordinates as circles with the size of the circle representative of the battery of the robots and the intensity of the color signifying the activity state of the robot. To view more information on the robot like the danger zone, destination and the ID of the object being carried, any robot can be clicked to display that information (Figure 4).

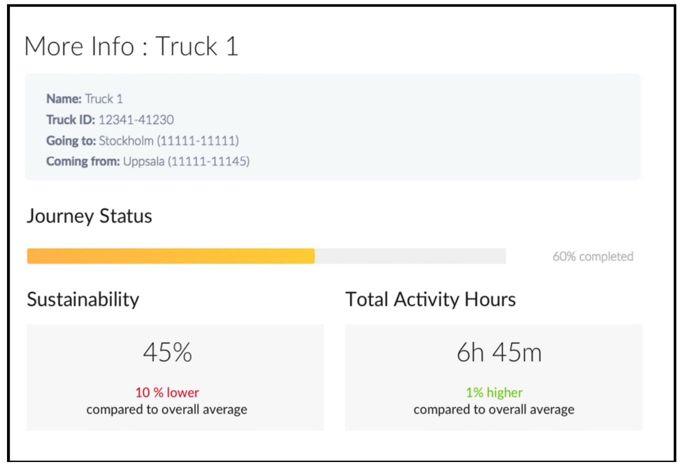

Figure 3. The modal with secondary information about the truck including the total activity hours and the Sustainability Index.

- **Stacked performance chart** gives the stakeholders an ability to select the robots from all the active robots in the warehouse and check their performance index varying from 0 - 100. The different types of robots are represented by different colors. This chart could be updated based on daily, weekly, monthly and yearly performance for further analysis (Figure 5).
- **Battery status of robots** card signifies the battery status of the robots as a primary value, which is also represented in a map state (Figure 4). Clicking on the 'view all' button reveals more information on the robot-like time left to return, the performance percent of that robot and how it is performing compared to the overall warehouse average.
- **Notes and stakeholders.** Stakeholders for the warehouse level are the warehouse managers and robot operators and they have the ability to share notes with everyone or one another.

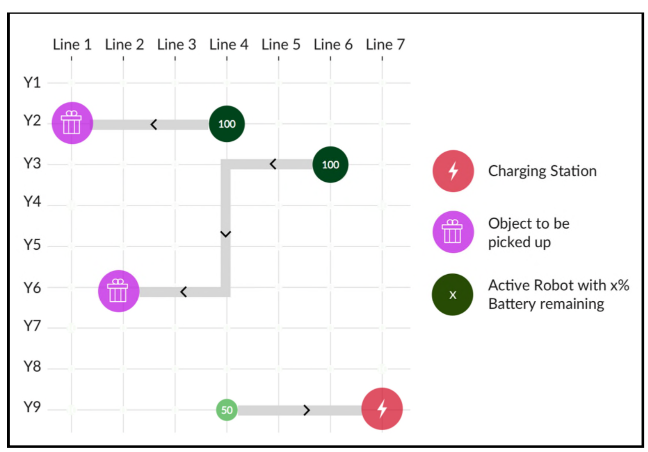

Figure 4. An overhead map of Warehouse

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F. Level 3: Intelligent Agent level

The purpose of the intelligent agent level is to visualize intelligence and interoperability related concerns of the robots. The dashboard is divided into (1) Interoperability Curve, (2) Activity Monitor, (3) Notes, and (4) Stakeholders cards.

- **Robot interoperability curve** is an updatable chord diagram that has all the axis as robots in the warehouse represented by different colors. This interdependence allows the stakeholders to monitor robots when they perform a particular task. This curve can be updated on a daily, weekly monthly and yearly basis (Figure 6).

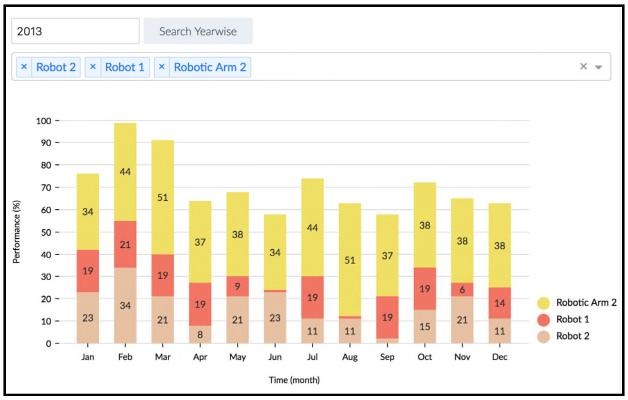

Figure 5. Stacking different robots in the warehouse with each other to compare the performance of their combination for the year 2013.

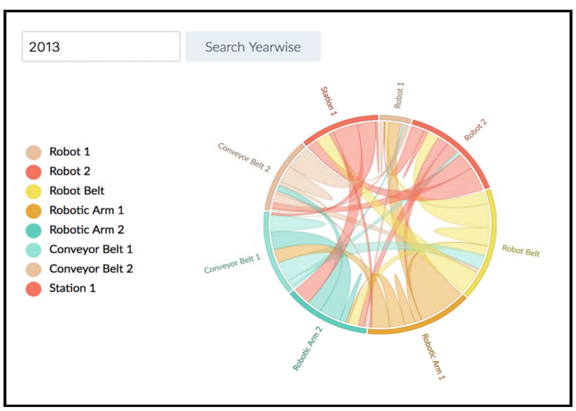

Figure 6. A chord diagram was used to visualize the interoperability between all the available robots present in Warehouse 1 for the year of 2013.

- **Activity monitor** details the connection points of the robots, with the prime value as the percentage of the job completed. When a user clicks the 'view all' button, more information about the performance of the robot is revealed such as, the start and end point, the objects being transported and the overall active hours. This information is deeply connected to the information from the real-time map and the battery status in the warehouse levels.
- **Notes and stakeholders**, the main stakeholders of this level are the system engineers, robot maintainers, and the warehouse managers. They have an ability to add and share notes between each other.

IV. USER STUDY

The final interview was conducted with 5 stakeholders who took part in the development of the automated warehouse project. These interviewees come from different domains including design, software development, systems engineering and robotics. The interview was conducted in a one-to-one semi-structured way. The length of every interview varied between 20 to 30 minutes with both the interviewer and interviewee discussing the use case of the dashboard relevant to their domain of knowledge. The interview was conducted in an uninterrupted open environment and the response was handwritten. The general structure of the interview included:

1) Introduction of the interviewer and the interviewee, the roles in the project and discussion about the first feedback iteration.
2) Primary discussion about SCOTT project and the prior experience with the dashboard and the data architecture.
3) A think-aloud session of using the dashboard exploring different levels and asking questions before switching levels with additional efforts to find the answers within the dashboard.
4) Questions the interviewee had with respect to the cards most relevant to the interviewees. What works for them and what does not?
5) Optional hands-on exercise: If any visualization is not clear, is there a better way to represent a data?

V. RESULTS

Based on the interview feedback, it was evident that defining KPI, in the beginning, proved out to be a crucial step to make the dashboard unified. During the hands-on exercise, four out of five stakeholders preferred using the chord interoperability diagram due to prior experience with a similar visualization while one stakeholder suggested using a tree-map visualization to represent the same data. Three stakeholders suggested giving preference to data susceptible to daily changes instead of data closer to the three KPI under consideration that does not update frequently. Four out of five stakeholders felt using size to represent the amount of battery left, on the warehouse map was confusing as compared to using colors to depict the same data. All the stakeholders preferred fetching only highlighted data on the dashboard instead of the entire data set on the first load because of the decrease in page load speed. Two stakeholders suggested using stakeholder hierarchy to customize the available data could be used to further simplify the visualization. For our use case, the warehouse managers could have access to all three levels of the dashboard while the systems engineers could only access the intelligent agent level.

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VI. DISCUSSION

A. Using three KPI as a starting point

Before the implementation of the visualization, two earlier studies [3][7] were conducted to identify KPI, stakeholders and the data model as the basis of deciding what kind of data would be presented on the dashboard, for whom and by what data which turned out to be extremely helpful to make both, data streams and, the dashboard uniform. At this stage, a minimal set of required data was selected, which was to be used only for monitoring purposes.

B. Expert opinion as an evaluation technique

Despite the exploratory nature of this study, we tried to validate the dashboard using a structured approach. Using expert opinion at the preliminary stage of the research proved out to be a fast and efficient way to build the prototype and identify the direction of future development. So, if these expert evaluations are not performed prior to formative evaluations, the formative evaluations will typically take longer and require more users, and yet reveal many of the same usability problems that could generally have been discovered by less expensive heuristic evaluations [14]. Thus, expert evaluations can reduce the cost of formative studies.

C. Cognitive bias in visualizations used

In terms of the visualizations used, there was a strong bias towards the visualizations used by the stakeholders for a prior similar data set, which greatly reduced the learning curve for the dashboard. The bias was expressed in the final feedback from the stakeholders when the data visualizations were fully functional. This feedback was not expressed in the earlier feedback session. This is a classic case of cognitive bias, which is observed when similar design patterns (or, in our case, data visualizations) are used frequently [15].

VII. CONCLUSION AND FUTURE WORK

Future work will be to extend the above dashboard to incorporate real-time data streams from a working warehouse. We will continue to work on the dashboard and customize the dashboard to further to improve the user experience in the light of the feedback we received after the interviews. Furthermore, we plan to employ user-centered methodologies in the form of research tools like eye-tracking and heat-maps, to capture participant behaviour while performing certain tasks within the dashboard to draw clear conclusions.

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