Visualising Autonomous Warehouse Data Streams Through User-Centered Design

RAGHU NAYYAR
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Raghu Nayyar
raghun@kth.se

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Supervisor : Dr. Mario Romero
Examiner : Dr. Tino Weinkauf

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Abstract

This thesis aims to develop and evaluate a dashboard design that visualizes a stream of data from the different entities involved in autonomous warehouses, a subset of cyber-physical systems. I created this dashboard through User-Centered Design (UCD) methodologies based on two feedback iterations with the stakeholders employing semi-structured expert opinion interviews. This thesis also discusses the different stages involved in building this dashboard design, the design decisions, the technical aspects of the libraries used, and the feedback session towards the end of the project. It also presents the implemented dashboard as a proof of development efforts and explains its different functionalities. The project concludes with evaluating the dashboard through a semi-structured interview with the respective stakeholders and suggests features for further development.

Visualisering Av Data Strömmar Från Autonoma Lager Genom Användarcentrerad Design

Abstract

Denna studie ämnar att utveckla och utvärdera en design för ett dashboard som visualiserar data strömmar från olika enheter som kan hittas i autonoma lager. Detta dashboard har utvecklats genom att använda metoder inom användarcentrerad design, som baserades på två iterationer med intressenter som är experter inom området, där semistrukturerade intervjuer gjordes. Denna studie diskuterar också de olika steg som är involverade i att bygga designen av detta dashboard, de olika beslut som togs i designprocessen, de tekniska aspekterna av de bibliotek som används och resultatet från de sessioner som hölls för att få feedback i slutet av projektet. Studien presenterar också det dashboard som utvecklades samt förklarar dess funkionalitet. Slutsatser dras från de semistrukturerade intervjuerna med respektive intressent och föreslår framtida funktioner som skulle vara möjliga att implementera.
Visualising Autonomous Warehouse Data Streams Through User-Centered Design

Raghu Nayyar
KTH - Royal Institute of Technology
Stockholm, Sweden
raghun@kth.se

ABSTRACT
This thesis aims to develop and evaluate a dashboard design that visualizes a stream of data from the different entities involved in autonomous warehouses, a subset of cyber-physical systems. I created this dashboard through User-Centered Design (UCD) methodologies based on two feedback iterations with the stakeholders employing semi-structured expert opinion interviews. This thesis also discusses the different stages involved in building this dashboard design, the design decisions, the technical aspects of the libraries used, and the feedback session towards the end of the project. It also presents the implemented dashboard as a proof of development efforts and explains its different functionalities. The project concludes with evaluating the dashboard through a semi-structured interview with the respective stakeholders and suggests features for further development.

Author Keywords
Data visualization, information visualization, cyber-physical systems, user experience, user centred design, expert opinion interviews, prototyping, data structures, supply chain, autonomous warehouse, intelligent agents, dashboard design.

1. INTRODUCTION
In simple terms, a cyber-physical system (CPS) is defined as different computational and physical processes being carried out together to perform several tasks [1]. These tasks 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 process, we discuss a narrow application of CPSs, automated warehouses. A standard warehouse involves four major functions: (1) receiving; (2) storage; (3) order picking; and (4) shipping [3]. There is an ever increasing demand of a variety of products and shorter response times causing a tremendous emphasis on the ability to establish smooth and efficient logistic operations. These logistic operations are complex and hence emit a lot of data. This data could be used to further optimize these complex operations by the researchers or by the managers to understand the current state of the warehouse or by engineers to maintain the robots carrying out operations within the warehouse. Based of this, these stakeholders can analyze several Key Performance Indicators (KPIs), 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.

This thesis explores a dashboard design to best represent these data streams to help the stakeholders involved in the different levels of an autonomous warehouse: (1) Supply Chain Level; (2) Warehouse Level; and (3) Intelligent Agent Level [4]. The aim of the project is to address the Research Question:

What are the viable visualizations required to build a dashboard that represents a stream of data from intelligent autonomous warehouses in Cyber-Physical Systems (CPSs), focusing on performance, safety and sustainability as Key Performance Indicators (KPIs) employing User-Centred Design methodologies?

To this end, this report leverages on expert opinion [12] and semi-structured interviews [5] at the onset of the study to understand the needs of stakeholders, gather feedback and suggest new features for further iterations. Semi-structured interviewing is a very flexible technique for small-scale research in which detailed structure is left to be worked out during the interview, and the
The primary goal of the study is to design, develop and evaluate a dashboard that represents a stream of data that comes from the different entities involved in and around a fully-functional cyber-physical system, namely an autonomous warehouse. These entities include: (1) trucks; (2) warehouses; (3) retailers; (4) smart robots; and (5) conveyor belts.

1.2 Methodology
During the thesis project, the identified stakeholders were interviewed on two stages of the design process. The feedback session was an informal user study with one stakeholder where a pen-paper prototype was evaluated. Based on the feedback, final visual design was made which later got converted to a functional prototype.

To develop this prototype, ReactJS [20], 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. D3.js [23], the industry standard of data visualization javascript library was used to develop the dashboard prototype. A state machine, Redux [21], 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 [24], 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 [25]. ImmutableJS [22] was used to create factories for the entities in the form of records. Fetch [27] was used for the HTTP requests to the server. Postman [29] is used for mocking the back-end API.

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.

1.3 Delimitations
The project doesn’t involve a back-end so there are assumptions made for the data streams that might change or evolve as a back-end is written. Although, a very strict data structure is followed and obeyed while building the visualization, there might be performance issues due to the machine learning mathematics going on in the back-end. In terms of design, although the dashboard incorporates UCD approach [7, 10], the feedback session is limited to 5 people, considering stakeholders include user experience designers, system engineers and researchers who work in the same domain. The dashboard currently incorporates 3 KPIs: (1) safety; (2) sustainability; and (3) performance. The scope of the thesis work does not include the identification of the relevant KPIs and also does not include the further data integration with the existing or in development CPSs.

2. 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].
Automated Warehouses, a small subset of CPSs, has 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.

These entities must be networked for data collection, aggregation, and response. This data is collected and structured in the form of linked data models. The term “Linked Data” refers to a set of best practices for publishing and connecting structured data on the web and is the basis of storage and linking data across the world wide web [8, 9, 14].

In previous study [10], (1) safety; (2) sustainability; and (3) performance were decided as metrics to design the dashboard. Safety refers to the level of trust in the warehouse. Collision 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 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. These KPIs were used to visualise the above data points (Figure 2) in the form of a dashboard (Figure 4) but the process didn’t follow a design process and was not evaluated by the respective stakeholders due to lack of resources [4].

More research projects have been working with management dashboards in a scenarios specific to

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**Figure 3:** An overview of Warehouse 1 with different kinds of active robots (Autonomous Robot 1 and Conveyor Belt 1) being managed by system engineers. The entire warehouse is maintained by the warehouse staff. The Truck 1 connects the warehouse to Retailer 1 which is managed by the retail managers. The double arrow represents that the exchange of data between these managers (stakeholders) with their entities (entity data) and with each other (notes)
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 [29].

Figure 4: Early stage dashboard design for the Warehouse level, where Autonomous Robot 1 is in focus [4].

VISTA is a generic toolkit that allows stakeholders to visualize internal reasoning and knowledge sharing in intelligent agents [30].

In terms of knowledge sharing between different agents, Soar, a general cognitive architecture, has been a topic of research since the past 30 years. It offers demonstrations of individual components, components working in combination, and real-world applications [14].

3. DESIGN PROCESS

3.1 Initial Design Decisions

In terms of the first design process, the first step was identifying the entities and splitting them for the three different levels: (1) Warehouse level; (2) Supply Chain level; and (3) Intelligent Agent Level. Every level was then split into cards and an atomic design [28] approach is used to build smaller cards instead of making a complete dashboard. Atomic Design is a methodology of creating a design system based on creating small components (or atoms) like buttons, inputs, headings, etc. first and then combining them to create larger components (or molecules) like forms, button groups etc and in this case, cards. This is done to make the application as modular (Figure 1) as possible. A highlight boolean is included in every entity which gives the user the ability to fetch the required data instead of querying all the data. It is assumed that this improves both the experience and performance.

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.

The dashboard consisted of a lot of data streams that signify an empty or a full state which couldn’t be expressed only by numbers, hence 3 colours were consistently used to signify negative (full), positive (empty) and in progress space (Figure 6). Every level was divided into cards, with every card with its own API requests making all cards independent of each other. This was done to easily manage the state of the application. Help text was provided for every card in the form of a tooltip so that help is available when needed but not all the time, giving more breathing space for the visualizations themselves [15].

The help text was consistently kept for all the sections.

3.2 Defining Entities and their records
Due to lack of a back-end, considerable time was spent working on deciding the data structures of the entities involved in the 3 levels. In this project, for the sake of performance, immutable record factories were used to define the structures at the JavaScript level. Records [21] ignore everything that comes from the API calls but are not defined in the JS structures and gives the flexibility to use dot notations to read the keys instead of the traditional .get() method.

The entire API schema is documented in Table 1 and following are the entity records defined to make the entire dashboard:

3.2.1 Warehouse and Retailers: Warehouse and Retailers, which represent the entire space, consist of a similar data structure formed of an id (string), highlighted tag (bool), location (geo), name of the space (string) and the capacity of the space (num). The ids of both these entities are needed for trucks to identify destination and source of their journeys.

3.2.2 Robots: Autonomous 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 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.

3.2.3 Trucks: Trucks are entities which connect: (1) retailers-retailers; (2) retailers-warehouses; and (3) warehouse-warehouse; and hence consist of their location (geo) of start and end point. It also consists of the sustainability index and over activity as measured in hours.

3.2.4 Notes and Stakeholders: Notes and Stakeholder data 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 consist 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 is the note coming from. levels and also have an ability to be highlighted to display the notes and stakeholder of choice on the home screen.

3.3 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 3). 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 defines the map layout interior to the warehouse. They carry the id of the objects they are carrying, the warehouse they are a part of and the stakeholders responsible for each of them.

At the intelligent agent level, there is information on the interoperability between these robots and more detailed account of how the robots perform with each other.

3.4 Level 1: Supply Chain Level
The purpose of the Supply Chain level is to visualise 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.

3.4.1 Capacity: The capacity card details the available space in the current / adjoining warehouses along with the space available at the retailers. The data is represented by a dial visualization to give stronger emphasis to the colour 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. (Figure 6)

3.4.2 Ongoing Truck Journey: The 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 (Appendix, Table 1), it could be displayed on clicking the View more button next to every progress bar. (Figure 8)

3.4.3 Profitability Vs Risk Curve: Profitability Vs Risk curve is a XY Plot with Profitability / Risk on the Y 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.

3.4.4 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.

3.5 Level 2: Warehouse Level
The purpose of the Warehouse level is to visualise 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.

3.5.1 Real-time map: The 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 colour 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...
3.5.2 Stacked Performance Chart: The 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 signified with different colours. This chart could be updated based on daily, weekly, monthly and yearly performance for further analysis (Figure 7).

3.5.4 Battery status of Robots: This card signifies the battery status of the robots as a primary value, which also represented in a map state in Figure 5. Clicking on the view all button reveals more information on the robot like time left to return and the performance percent of that robot and how it is performing compared to the overall warehouse average.

3.5.5 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.

3.6 Level 3: Intelligent Agent Level

The purpose of the Intelligent Agent (IA) level is to visualise 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.

3.6.1 Robot Interoperability Curve: Interoperability curve is a updatable chord diagram that has all the axis as robots in the warehouse represented by different colours. This interdependence allow the stakeholders to monitor robots when they perform a particular task. This curve can be updated on a daily, weekly monthly and yearly levels (Figure 9).

3.6.2 Activity Monitor: The activity monitor details the connection points of the robots, with the prime value as the percentage of the job completed. Clicking on the view all button reveals more information about the performance of the robot, 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.

3.6.5 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.

4. USER STUDY

4.1 Final Interview Structure
The final interview was conducted with 5 stakeholders (Section 1.3), all of which came from different domains including design, linked data, back-end engineering, systems engineering and robotics. Interview was conducted in a one-to-one semi-structured expert opinion method. 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 (Secure Connected Trustable Things group) and the prior experience with the dashboard and the linked 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 them. What works for them and what doesn’t?
5. Optional hands-on Exercise: If any visualization is not clear, is there a better way to represent a data.

4.2 Final Interview Feedback
Based on overlapping feedback from the interviews, a set of features were decided which were to be worked in the next iteration of the dashboard:

4.2.1 General Feedback
Some feedback affected the entire application user experience as a whole instead of just a particular level. It included:
- Integrating visualizations with websockets to update dashboard.
- Incorporating levels to the stakeholders to split the cards into sub cards based on the relevance and knowledge sharing between two or more stakeholders.
- Incorporating search for notes or stakeholders instead of displaying all the information when clicking on the view all button.
- Prioritising the information related to task in hand especially in the daily view instead of information like performance index which might not update as frequently.

5.2 Level-Specific Feedback
Feedback specific to the three different levels is listed as below:

5.2.1 Supply Chain Level:
- Integrating truck journey and capacity cards to a geolocation based map with the journey being visually represented between the warehouses and the retailers marked as starting and end points.
- Including production unit from where objects are coming from to the warehouse as a new entity. These units could help balance the amount of objects being filled in multiple warehouses.

5.2.2 Level 2: Warehouse Level
- Testing the size of bubble vs colour of bubble to represent moving robots on the warehouse level map. According to the interview feedback, light green colour might not be best to represent low battery status of the robots.
- Using general X-Y coordinates instead of Line <Number> to Y - <Number> for the coordinate system in the warehouse map.
- Incorporating danger zones on the map itself instead of clicking the robot to see it.

5.2.3 Level 3: Intelligent Agent Level:
- Testing a treemap visualization for the Intelligent Agent interoperability chord visualization for the same data set.
- Segregating robot data into conveyor belt, robotic arms and robots individually considering the robotic arm (or multiple robotic arms) could be fixed on a robot.

6. RESULTS
Based on the interview feedback, it was evident that defining KPIs, 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 treemap visualization to represent the same data.

Three stakeholders suggested giving preference to data susceptible to daily changes instead of data closer to the three KPIs under consideration that doesn’t 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.

7. DISCUSSION

7.1 Using three KPIs as a starting point
Before the implementation of the visualization, we discussed using three KPIs as the basis of deciding what kind of data would be presented on the dashboard 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. However, this data is subjective to changes once the back-end is developed, and is left for future research.

7.2 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 [32]. Thus, expert evaluations can reduce the cost of formative studies. Apart from this, conducting formal controlled experiments at an exploratory phase might even be considered inappropriate, especially, when the data is susceptible to changes [30].

7.3 Using task scenarios for future usability tests
In order to deeply understand where the stakeholders might get stuck with the dashboard interface, defining task (or activity) scenarios based on stakeholder goals could be defined. These task scenarios need to provide context so that the stakeholders could engage with the dashboard to provide both qualitative and quantitative feedback. Based on this feedback, further iterations of the dashboard could be developed.

7.4 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 similar a data set previously 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 with researchers using similar design patterns (or, in our case, data visualizations) frequently [33].

8. FUTURE WORK

Future work will be to extend the above dashboard to incorporate data based on more KPIs. We plan to customize the dashboard based on the hierarchy of the stakeholder to further simplify the user experience. Furthermore, we plan to employ user-centered methodologies in the form of research tools like eye-tracking and heat-maps, to capture participant behavior while performing certain tasks within the dashboard to draw clear conclusions. Apart from this, we also plan to incorporate the overlapping feedback from the final interview round for next version of the dashboard.

9. ACKNOWLEDGEMENTS

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10. REFERENCES


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## 9. APPENDIX

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**Table 1: Linked Data Structure for all the entities.**

**Video Links:**

2. Base Design: [https://youtu.be/1xbfZ3phxY](https://youtu.be/1xbfZ3phxY)
3. Supply Chain Level: [https://youtu.be/teXMqf8vQnc](https://youtu.be/teXMqf8vQnc)
4. Warehouse Level: [https://youtu.be/3o_bVNJjGTU](https://youtu.be/3o_bVNJjGTU)
5. Intelligent Agent Level: [https://youtu.be/B5UxBfImvzw](https://youtu.be/B5UxBfImvzw)