Towards Effective Industrial Robot Fleet Visualization for Remote Service Applications

Veronika Domova and Goranka Zoric

Conference article

Cite this conference article as:

Domova, V., Zoric, G. Towards Effective Industrial Robot Fleet Visualization for Remote Service Applications, In Sumitra M. Reddy, Wojciech Cellary, and Mariagrazia Fugini (eds) 2017 IEEE 26th International Conference on Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE), Institute of Electrical and Electronics Engineers (IEEE); 2017, pp. 185-190.
ISBN: 978-1-5386-1759-5

DOI: <https://doi.org/10.1109/WETICE.2017.40>

Copyright: Institute of Electrical and Electronics Engineers (IEEE)

The self-archived postprint version of this conference article is available at Linköping University Institutional Repository (DiVA):
<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-152708>

Towards Effective Industrial Robot Fleet Visualization for Remote Service Applications

Veronika Domova
ABB Corporate Research
Västerås, Sweden
Email: veronika.domova@se.abb.com

Goranka Zoric
ABB Corporate Research
Västerås, Sweden
Email: goranka.zoric@se.abb.com

Abstract—In recent years, advances in sensors, Internet and communication technologies opened many promising opportunities for remote services of industrial robots. With remote service applications, potential problems in robot systems can be detected before they happen, and prevented pro-actively avoiding costly production shut-downs. However, to be able to effectively perform remote service operations, remote support engineers need to analyse vast amounts of information. For a remote support engineer to be able to manage such amount of data, effective data visualization is crucial. Based on field studies and collected needs of support engineers working with industrial robots, we have designed and developed a prototype, i.e. one possible solution of an effective industrial fleet visualization, applied on the overheated robots use case. The initial validation of the prototype showed the benefits of such visual data presentation, as well as future directions.

I. INTRODUCTION

In recent years, due to exceptional technology-push and changing operative framework conditions in industrial practice Industry 4.0 trend is rapidly developing [1]. As Industrial Internet of Things [2] is growing, machinery in industrial processes are getting instrumented with sensing, identification, processing, communication, analytic and networking capabilities allowing industrial objects to be monitored and/or controlled remotely across existing network infrastructure.

With this shift, however, comes the need to provide additional support to those persons who were previously solving issues onsite, but now need to do that same type of work via remote from their office locations, relying on sensor data transmitted over a remote connection. Remote support engineers, i.e. remote experts, fall into this category. Typically, they have worked for many years on diagnosing (i.e. identifying problems with equipment) and troubleshooting (i.e. fixing problems with equipment) customers' issues onsite. Their role has now shifted to the one whereby they need to engage in this same activity over distance by connecting to customers' fleets via Internet. When working this way, diagnosing and fixing issues takes a relatively short time-frame leading to improved efficiency, accuracy and economic benefits. On the other hand, with this new way of working comes the challenge of how to support this kind of work practice, thus a new set of tools is needed such as tools that support big data visual analysis and collaborative work, opening opportunities for remote service applications.

Remote service applications should be designed to enable remote support engineers to remotely interact with the industrial fleet and to utilize tools that enable smart, fast, manual or automatic data mining, analysis and analytics. Typically, available data consists of various fleet real-time and static data aggregated from various sources, such as embedded sensors and databases, creating vast amounts of data, i.e. Big Data, that remote support engineers should analyze in order to provide effective remote service operation. Furthermore, the principles of modern economy require from companies to maximize the utilization of machinery with a minimal amount of people involved. As such industrial processes and machinery are being monitored by fewer personnel who also often have other more challenging responsibilities. As a result, remote support engineers get to monitor thousands of fleet items. Consequently, effective visualization and focus on user experience is a crucial part for such big data applications [3].

Despite the technological advanced of the latest years, human involvement (such as interaction, judgment and logical thinking) is necessary when working with Big Data [4]. That is why visualization challenges represent one of the leading research questions in the era of Big Data [5], [6]. The two primary problems associated with Big Data Visualizations are wide datasets, i.e. datasets with large amount of features, and long datasets, i.e. growing amount of data records to be stored. These are very relevant to industrial Big Data visualizations (see, for example, works presented in [16], [17]) which are normally dealing with extensive datasets representing large fleets with a vast amount of supplying parameters for each fleet asset.

In this work we contribute to the field of industrial big data visualization by proposing one possible solution for effective industrial fleet visualization which allows remote support engineers to interactively explore fleet data. Based on feedback from service engineers working with industrial robots, we have designed and developed an interactive prototype for visualization of industrial robots, focusing on the overheated robots use case. The prototype is validated, and initial feedback showed the benefits of such visual data presentation, such as condensing large amount of robot data and making it easily and intuitively accessible in daily routines.

The remaining of the paper is organized as following. In section II we cover related work. Section III gives an overview

of industrial robot systems, their problems and remote service opportunities in the field. Section IV reveals a remote support engineer's requirements in remote service systems. Section V gives an overview of the data a remote support engineer is dealing with. Section VI gives a detailed overview of the proposed solution. Section VIII contains evaluation details. Section IX summarizes the work and gives a direction for future work.

II. RELATED WORK

To our knowledge, there is a body of work which gives an overview of remote diagnostics in industry [7], [8]. Jonsson et al. identify advantages and disadvantages of remote diagnostics for remote experts and for local workers [9], [10]. In [11] the authors propose and discuss key performance indicators developed for a set of proposed fleet monitoring solutions.

However, the prior work has barely explored how this support could manifest itself with respect to a concrete user interface (UI) solution. Several works [12], [13] describe remote condition monitoring systems giving minor details regarding their user interfaces. The interfaces presented mostly employ such visualization means as tables, nested lists, data charts. While doing a good job in providing access to the available data of a particular asset, they are not effective in giving an overview of the entire fleet and in spotting alarming items. Using these solutions, in order to identify alarming assets, remote support engineers would need to go through a long list of assets explicitly clicking on each of them, drilling into its details and looking for problems.

The work presented in [14] introduces a prototype aimed at supporting remote engineers within the maritime domain performing troubleshooting activities via remote connections. The work addresses needs of remote engineers by proposing tools such as a self-service dashboard, an interactive map, drag-and-drop techniques. However, for the fleet representation the table approach is used which does not eliminate the problems mentioned earlier.

J. Lee et al. in [15] describe a case study to emphasize the application of Cyber-Physical systems for health monitoring of industrial robots. They developed a predictive and preventive health monitoring system for a fleet of 30 industrial robots. Estimated statuses of the robots are presented to users in a web-based user interface as enriched infographics. The work does not address the problem of overviewing the entire fleet or highlighting the alarming items.

In this context, we discovered that existing work addressed the issue of remote services from a narrow perspective, usually being focused on technology and processes rather than on user needs and usability. The contribution of this paper is one possible solution for effective industrial fleet visualization which targets how remote engineers within the robotics domain can be effectively supported during proactive monitoring (i.e. noting, understanding and fixing robot problems).

III. INDUSTRIAL ROBOT SYSTEMS

Across a wide variety of modern industries, robots are widely used in production systems in order to improve ef-

iciency, productivity, quality and safety of manufacturing processes. Modern robots are considered complex distributed systems. Having articulated design, they are consisting of a number of integrated hardware and software modules (e.g. sensors, actuators, motors, controllers) cooperating together to achieve specific tasks [18]. Robot controllers are based on dual-core architectures meaning that motion control and data communications are processed on separate CPUs. Embedded sensors let robots "see and feel" enabling them to work safely and human-friendly in the environment. Having both actuators and sensors opens a wide variety of possible applications for robots to be monitored and controlled over a distance.

There are many potential faults that need to be monitored and addressed in industrial robot systems, e.g. connectivity issues, mechanical and electrical faults. For decades, monitoring and maintenance of the robots was taking place directly on site. With the embedded sensors and wireless connectivity, many of them can nowadays be monitored, analyzed and addressed remotely, see for example the systems described in [19], [20] or products available on the market such as ABB MyRobot system¹.

In addition to real-time data, there are possibilities to predict whether a robot will have problems in nearby future using prognostics and health management methodologies[15], [21]. Knowing potential candidates for breakage helps a remote support engineer to address and avoid unplanned downtimes and overwhelm uncertainties in robot systems by performing preventive maintenance, i.e. foreseeing and addressing a problem before it escalates. With the prediction capability, robots can be managed cost-effectively with just-in-time maintenance, which eventually optimizes robot up time.

From the remote support engineer prospective, four major statuses of a robot can be outlined:

- 1) **The robot is alarming:** there is an urgent problem which requires an instant action from the remote support engineer.
- 2) **The robot is predicted to be alarming in a nearby future:** at the moment the robot is working well but might have a problem in nearby future. The remote support engineer has to look into the details of such a robot to estimate possible reasons for the problem to appear.
- 3) **The robot was alarming, but not at the moment:** the robot was experiencing a problem lately but is working well at the moment. Sometimes a problem can be gone even without any action taken. This however does not mean that the situation should be ignored. The remote support engineer has to ensure that the problem was actually noticed by someone and addressed accordingly.
- 4) **The robot is working well:** the robot is not experiencing any problems. Such robots are generally out of interest for a remote support engineer.

Whenever the remote support engineer discovers a robot with a problem, he/she can either contact the customer asking

¹<http://www.abb.com/cawp/seitp202/bd66b068219f8937c1257d6b002ed760.aspx>

to inspect the robot, or act pro-actively by investigating the problem remotely and if needed sending to the field a technician to fix it. The remote investigation is done by looking at real-time data trends of the robot, comparing the trends of neighboring robots, etc.

In this work, we reduced the scope to the problem of overheated robots (i.e. overheating of the motherboard of the robot controller) which appears due to failures of electronics, environmental issues, such as dusty or cold environments, faulty fans, etc. Overheating can lead to misbehavior of the robot, its complete shut-down or even to a fire. However, it is quite a rare event. For example, out of several thousand robots 2-3 can be overheated.

IV. USER NEEDS

In the initial stage of this work, we had access to support engineers, customers and service managers, and possibility to interview them which enabled us to gain valuable knowledge on workflows being utilized in industry to monitor and address robot problems remotely, as well as on tools used nowadays for remote condition monitoring of the robots. As a result, we gathered user needs for visualization of robot data, and needed interaction to facilitate remote support engineers' workflows.

In summary, it is a must that the following workflows on data could be performed in a simple and intuitive way:

- 1) Overview a whole fleet of robots
- 2) Instantly spot overheated robots (alarming)
- 3) Drill down into an overheated robot details to investigate the problem (i.e. see the temperature and other related data)

Additionally, the following user needs were identified:

- **To see trends in temperature developments in time** for the whole fleet. This feature can not only shed light on the reasons why a certain robot is overheated, but also reveal correlations and tendencies in temperatures of groups of robots.
- **To have access to data of co-located robots.** Having this information can help a remote support engineer to understand whether the problem is caused by environmental issues or is specific for only the current robot.
- **To have displayed geographical location of the plant which has alarming robot(s).** It is necessary to know location information in a case when the problem can not be solved remotely, and a remote support engineer needs to send a technician on site to investigate/fix the issue.
- **To have access to customer information** since it is often needed to contact customers to request/communicate additional information or to notify them about a problem.

In summary, there is a large amount of robot data that should be accessible in a simple and intuitive way. From a remote support engineer prospective, all this data can be crucial to diagnose a (potential) problem, and to troubleshoot it.

V. DATA DESCRIPTION

In general, the nature of the data is hierarchical (see Figure 1). A customer has one or several plants located somewhere

Fig. 1. The hierarchical structure of the data.

in the world. A plant has robots used in production. For the purpose of human safety, a robot is often placed in a cell - physical space which is separated from the rest of the plant e.g. by a fence. Several robots can be co-located in one cell.

During the project, we had access to real data of 2281 robots including real-time measurements from sensors, runtime events, robot configuration parameters, technical descriptions, customers' details, etc. Missing information, for example customer-specific sensitive data, prediction data, etc, we populated with autogenerated data.

To minimize the data load during the prototyping process, we have extracted the temperatures of the robots during only last 24 hours. The retrieved temperature data was further processed to calculate the minimum and maximum temperature during the given period for each robot. Having calculated the minimum/maximum temperature values and knowing the latest temperature value, potential trends in temperature of each particular robot can be estimated, i.e. if the temperature was increasing, decreasing, staying still or was interchanging during the given period.

Grouping the data according to the hierarchy allowed us to get an understanding of the boundaries of the data. In the end, we had 532 customers. Out of the 2281 robots, 10 robots belonging to 8 customers were overheated, 3 robots of 3 customers had recently been overheated but were not so at that moment, 6 robots of 3 customers were about to be overheated in nearby future. The size of the customers' fleet varied from 1 to 256 robots. Amount of plants a customer had varied from 1 to 10. Each plant could have one or multiple co-location areas, maximum 256 robots were co-located in the same area. The temperatures varied from 0 to 100 °C.

VI. PROPOSED FLEET VISUALIZATION APPROACH

The proposed fleet visualization (see Figure 2) is based on grouping a fleet by customers. There are two reasons for doing so, first is to optimize the usage of a space on a screen for visualizing large amounts of data, and second is because of the hierarchical structure of the data as described earlier. Based on gathered user needs, we have created the following visualization rules:

- The more attention customer's robots require, the closer to the center of the user interface the customer is depicted, and in more details is shown.

Fig. 2. The developed user interface (sensitive data obfuscated).

- Customers whose all robots are working well are shown in a smaller manner with least details, and placed in peripheral areas of the user interface.
- Customers with alarming robots are shown in the center of the UI in an enlarged and detailed form.
- Customers with robots that were/might be overheated are shown in a medium size and can be enlarged on demand by mouse interaction.
- Customers with alarming robots stand out from customers placed in the periphery similarly to the fish-eye lens effect.

Based on these rules, we have designed and developed the UI for fleet visualization of overheated robots.

A. Layout

The layout of the proposed user interface consists of two areas: the central area containing the robot fleet visualization, the bottom area depicts the visualization of all the robots' temperature fluctuations during last 24 hours. The two areas are correlated: whenever the user interacts with an item in the central part, the temperature visualization instantly responds by showing only the temperatures relevant to the selection. Accordingly, when the user highlights a temperature value in the temperature visualization, the central area highlights the robot (in case it is overheated) or the customer to which the robot belongs to (in case the robot is not overheated).

B. Fleet visualization

A customer is visualized as a circle with the look and the content depending on the customer's fleet alarm status (see Figure 3). The customers with alarms are placed in the center of the visualization with geographical locations of the plants mapped to a map. Other customers are placed floating around

Fig. 3. Customers visualization based on their fleet status. a) A customer with overheated robots. The snowflake icon notifies that the temperatures can get low at the environment. b) A customer with robots to be overheated in future. c) A customer whose robots were overheated during last 24 hours but returned to normal temperature. d) A customer with no overheated robots.

them. The visualization is interactive, i.e. the user can freely move the customers around the screen.

1) *Customers with overheated robots:* Such customers are the top priority of the remote support engineers as an immediate action should be taken to address the issue. This is why we visualize such customers in a largest manner (see Figure 3 (a)), also they are placed in the center of the user interface. We depict them as large circles filled with light-red background. The name of the customer is written above the circle together with a number of alarming robots out of all the robots belonging to this customer. In the circles, the icons of the plants which have overheated robots are depicted. The geographical locations of such plants are showed on the map with dashed lines. Similarly, the plants have their name above the icon and a number of alarming robots out of all

the robots located at this plant. Inside the plants, robots are visualized as rectangles. Only overheated robots and the robots co-located with them are shown. The overheated robots are depicted as red rectangles with the temperature value inside. Even though this functionality remained unimplemented, the developed concept assumes that the user is able to click on a robot in order to drill down and see more information about it. The remaining not overheated robots from the same co-location are depicted as one gray rectangle with a number of such robots in braces. This is done to achieve a more flexible solution and save UI space as some plants may have hundreds of robots installed in the same physical area. The plants might have additional icons describing the environment in the plant, for example an icon of a water drop tells the user that there is a high humidity at this plant, a snowflake (see Figure 3 (a)) tells that temperatures in the plant environment can be low.

2) *Customers with robots that were/might be overheated:* Such customers have secondary priority for remote support engineers, as even though the state of their robots is of the engineers' interest, it does not require them to take an immediate action. We depict such customers as medium sized circles filled with brown/yellow colors accordingly (see Figure 3 (b), (c)). The circles are located closer to the center than those of customers with no overheated robots. The number inside the circles shows amount of robots of interest out of the total number of the customer's robots. On mouse hover such customers' view changes to the enlarged mode which is equivalent to the view of the customers with overheated robots.

3) *Customers with no overheated robots:* Such customers have a lowest priority for the remote support engineers. As such, we visualize them in a most calm manner: a small circle filled with a light-gray background and containing a total number of the customer's robots inside (see Figure 3 (d)). On mouse over, the user can see the name of the customer and the geographical locations of its sites on the map.

C. Temperature visualization

The temperature visualization is organized as following. It has a scale from 0 to 100 °C (see Figure 4 (a)). At the levels of 80 and 20 °C there are markers identifying the borders of normal temperatures: according to our interviews with the domain experts, everything that is above 80 °C can be considered overheated, everything that is below 20 °C can also be worth of attention especially if temperature drastically falls or increases to/from these low values. The visualization depicts the spread of temperatures of each robot during last 24 hours.

The temperature of each robot can be shown either as a dot if the temperature has not changed during the day or as a line spreading from minimum till maximum temperature value observed during the observation period. In the case there is a clear trend, e.g. the temperature was only going up or down during the day, the line will have an arrow at the top or at the bottom respectively (see Figure 4 (b)). If the temperature was jumping up and down during the day, the line will have arrows on both ends (see Figure 4 (c)).

Fig. 4. Temperature data visualization. a) Steady temperatures that have not changed during the observation period. b) Temperatures were going steadily up during the observational period. c) Temperatures that were interchanging (going up or down) during the observation period.)

To visually distinguish the temperatures of the robots that are/were/might be overheated, they are shown as correspondingly colored dots with a halo of the same color. The temperatures are arranged so that the trends are placed in the center to attract more attention of the user, whereas the steady not overheated temperatures are spread around.

VII. IMPLEMENTATION

The developed prototype is a web solution implemented using modern web technologies, such as JavaScript, HTML, CSS. In order to speed up the development process, we used a JavaScript framework for data visualizations D3.js². The prototype is running in a modern browser.

For prototyping purposes, to avoid possible issues of retrieving real-time data we saved the data of the selected robots and their temperature measurements during a 24 hour period into a common file and used it in the prototype as a static datasource.

The visualization is implemented using the so called force layout [22] where every item of the visualization is treated as a particle with a mass and forces defining the interaction and position related to other particles. Using this layout allowed us to achieve even spread of the data on the screen, avoid collisions and enable animated interactions between the components on the screen. The fish-eye lens effect is achieved by visually enlarging alarming customers visualizations. The content of an enlarged customer circle is fitted inside using the so called pack layout [23].

VIII. EVALUATION

In scope of the project, we had several preliminary evaluation sessions with remote support engineers of industrial robots and managers. In general, the developed solution was received positively. The users perceived the proposed solution as a starting point to begin a remote support engineer's workflows, also as a suitable platform for monitoring other robot problems. The users liked that the visualization condenses large amounts of data. They welcomed the idea of showing the specifics of sites with icons and requested additional functionality to be able to add such comments themselves. The ability to see temperature trends going up or down was received very well and was found to be useful for the everyday work practices.

²<https://d3js.org/>

One of the major comments received was related to the not overheated robots. According to the users, the remote support engineers are not interested in looking at such robots, as such they could be completely removed from the user interface. Doing so would free up more space on the screen and allow showing alarming assets in more detail. Another comment was related to prioritizing, i.e. which alarming robots should be handled first. More research in the topic is needed to investigate how to visually emphasize the important cases that should be handled first and by which criteria this should be decided. Another point of discussion was related to the fact that the overheated robots use case is just one of the possible robot faults. The interviewees were wondering how the visualization could be extended for monitoring other potential problems of robots. Finally, the interviewees were discussing the problem of finding similar cases to an occurred issue cases. As it is now, when an issue occurs, they are manually searching through historical databases using keywords specific to the issue. Ideally, the system should automatically match and show similar cases to simplify the engineer's work. A future research is needed to investigate how an effective user interface could facilitate this scenario.

IX. SUMMARY AND FUTURE WORK

We have presented a fleet visualisation prototype aimed at supporting remote engineers within robotics domain as they do remote condition monitoring, specifically focusing on overheated robots use case. The developed solution effectively manages large amounts of data and enables remote support engineers to interactively view data, performing their daily workflows. During our preliminary evaluation, we have received positive feedback from the test users.

Even though in this work we targeted the use case of monitoring overheated robots, we believe that the developed fleet visualization with minor changes could be adjusted for remote monitoring of other robot failures, and in general could be a good starting point for any industrial fleet visualizations. The future work will be directed towards applying the proposed fleet visualisation to other use cases, as well as industrial domains, and validating with the aim to generate some general fleet visualisation guidelines and solutions.

X. ACKNOWLEDGMENTS

We would like to thank all the participants in our studies and interviews for the dedicated time and valuable input during interviews and evaluation sessions. We would like to thank our colleagues from ABB in Germany for collaboration. Especially Benedikt Schmidt, Mohamed-Zied Ouertani, Boris Fiedler, for providing the access to real data and in general for their guidance and feedback during the project.

REFERENCES

- [1] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," *Business & Information Systems Engineering*, vol. 6, no. 4, p. 239, 2014.
- [2] S. Jeschke, C. Brecher, H. Song, and D. B. Rawat, "Industrial internet of things," *Cham, Switzerland: Springer*, 2017.
- [3] D. Fisher, R. DeLine, M. Czerwinski, and S. Drucker, "Interactions with big data analytics," *interactions*, vol. 19, no. 3, pp. 50–59, 2012.
- [4] E. Olshannikova, A. Ometov, Y. Koucheryavy, and T. Olsson, "Visualizing big data with augmented and virtual reality: challenges and research agenda," *Journal of Big Data*, vol. 2, no. 1, p. 22, 2015.
- [5] A. Cuzzocrea, I.-Y. Song, and K. C. Davis, "Analytics over large-scale multidimensional data: the big data revolution!" in *Proceedings of the ACM 14th international workshop on Data Warehousing and OLAP*. ACM, 2011, pp. 101–104.
- [6] K. Grolinger, M. Hayes, W. A. Higashino, A. L'Heureux, D. S. Allison, and M. A. Capretz, "Challenges for mapreduce in big data," in *Services (SERVICES), 2014 IEEE World Congress on*. IEEE, 2014, pp. 182–189.
- [7] S. You, M. Krage, and L. Jalics, "Overview of remote diagnosis and maintenance for automotive systems," 2005.
- [8] J. Kuschel and F. Ljungberg, "Decentralized remote diagnostics: A study of diagnostics in the marine industry," in *People and Computers XVIII Design for Life*. Springer London, 2005, pp. 211–226.
- [9] K. Jonsson and J. Holmström, "Ubiquitous computing and the double immutability of remote diagnostics technology: An exploration into six cases of remote diagnostics technology use," *Designing Ubiquitous Information Environments: Socio-Technical Issues and Challenges*, pp. 153–167, 2005.
- [10] K. Jonsson, U. H. Westergren, and J. Holmström, "Technologies for value creation: an exploration of remote diagnostics systems in the manufacturing industry," *Information Systems Journal*, vol. 18, no. 3, pp. 227–245, 2008.
- [11] S. Turrin and M.-Z. Ouertani, "Industrial fleet services: Introduction and application case," in *Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)*. Springer, 2016, pp. 621–628.
- [12] U. Topp, P. Müller, J. Konnertz, and A. Pick, "Web based service for embedded devices," in *Net. ObjectDays: International Conference on Object-Oriented and Internet-Based Technologies, Concepts, and Applications for a Networked World*. Springer, 2002, pp. 141–153.
- [13] J. M. Rybak, "Remote condition monitoring using open-system wireless technologies," *Sound and Vibration*, vol. 40, no. 2, p. 16, 2006.
- [14] G. Zoric, M. Ralph, P. Björndal, V. Domova, E. Vartiainen, and A. A. Muñoz, "Supporting maritime remote experts working over distance," in *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. ACM, 2016, p. 124.
- [15] J. Lee, B. Bagheri, and H.-A. Kao, "Cyber-integrated big data analytics agent for industry 4.0 applications," *de Agenten im Umfeld von Industrie*, vol. 4.
- [16] T. J. Overbye and J. D. Weber, "Visualization of power system data," in *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*. IEEE, 2000, pp. 7–pp.
- [17] F. Yang, S. L. Shah, D. Xiao, and T. Chen, "Improved correlation analysis and visualization of industrial alarm data," *ISA transactions*, vol. 51, no. 4, pp. 499–506, 2012.
- [18] N. Mohamed, J. Al-Jaroodi, and I. Jawhar, "Middleware for robotics: A survey," in *Robotics, Automation and Mechatronics, 2008 IEEE Conference on*. Ieee, 2008, pp. 736–742.
- [19] P. Brizzi, D. Conzon, H. Khaleel, R. Tomasi, C. Pastrone, A. Spirito, M. Knechtel, F. Pramudianto, and P. Cultrona, "Bringing the internet of things along the manufacturing line: A case study in controlling industrial robot and monitoring energy consumption remotely," in *Emerging Technologies & Factory Automation (ETFA), 2013 IEEE 18th Conference on*. IEEE, 2013, pp. 1–8.
- [20] D. Wang, Y. Chen, M.-I. Fang, and Y. He, "A study of robot remote monitoring system," in *Intelligent Control and Automation, 2002. Proceedings of the 4th World Congress on*, vol. 2. IEEE, 2002, pp. 1291–1295.
- [21] E. R. Lapira, "Fault detection in a network of similar machines using clustering approach," Ph.D. dissertation, University of Cincinnati, 2012.
- [22] T. M. Fruchterman and E. M. Reingold, "Graph drawing by force-directed placement," *Software: Practice and experience*, vol. 21, no. 11, pp. 1129–1164, 1991.
- [23] W. Wang, H. Wang, G. Dai, and H. Wang, "Visualization of large hierarchical data by circle packing," in *Proceedings of the SIGCHI conference on Human Factors in computing systems*. ACM, 2006, pp. 517–520.