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Trends for Low-Cost and Open-Source IoT Solutions Development for Industry 4.0

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Abstract

The aim of the paper is to review the trends on low-cost open-source Internet of Thing (IoT) in the Framework of Industry 4.0. We hypothesize that open source IoTs benefits small and medium sized (SME) manufacturing companies to help them tackle economical and technical barriers for technology adoption at factory floors. This research reviews the state of the art of open-source hardware and software and identifies the challenges of open-source IoT by compiling scientific literature and relevant online resources. The methodology is twofold: (i) we use a grey literature review including online information, and (ii) we complement the analysis by a structured keyword search using IEEE scientific repository. The study finds that open source is and will be an essential part of developing Industry 4.0 solutions and its integral constituent, Industrial Internet of Things systems (IIoT). However, there are challenges to overcome, such as interoperability and reliability.

Keywords: Manufacturing; IoT; Industry 4.0; Open source; Data collection

1. Introduction

The Industry 4.0 strategy emphasizes the communication, connectivity and visibility throughout the entire supply chain [1]. A wide range of industries can benefit by the vertical and horizontal integration among the value chain by coupling information and data flows from physical and virtual assets [2]. Industrial and consumer IoT solutions are becoming viable both economically and technologically, and in certain case they are implementable in highly automated lines. At the same time the general advancement in science and technology development has brought the prices down for the sensing, processing and sharing technologies. Thereby, IoT technologies are now widely adopted in many commercial and industrial products. In future industrial environments, the diversity and distributed nature of data will be prevalent [3]. Smart devices and IoT will provide the data and AI will be used to make informed decisions based on it [3]. These technologies intertwine to create more value and are essential parts in computerization of manufacturing to achieve the goals of Industry 4.0. Ultimately, The IoT ecosystems itself merge many different research fields as ubiquitous and pervasive computing, sensing and communication technologies, operating systems, mobile computing, big data management and embedded systems [4].

However, there are great challenges among small and medium sized enterprises (SMEs), with manual manufacturing and production steps, small lot sizes and large variety of machinery having highly heterogenous communication protocols. These companies do not, in many cases, possess financial capabilities to obtain commercial IoT platforms, do not tackle with big data, or lack skilled persons to operate and maintain these systems. The emerging data collection, analytics and distribution systems are very often tailored for the use of large enterprises capable of utilising multiple features, but also able to afford these. For example, commercial data collection systems such as

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Supervisory Control and Data Acquisition (SCADA) solutions are usually closed and often very expensive to smaller companies [5]. A lack of standardization and the use of closed solutions creates vendor locks and generates costs for upgrade and maintenance [5], [6]. Problems with interoperability with the existing systems can also arise [5]. In addition, as the IoT and its applications are growing there is a need for new intelligent devices to facilitate a large variety of applications and networking technologies [7].

To tackle these problems, it was suggested that platforms and devices with open-source hardware and software could be the solution [7]. Open-source model is a decentralized development model that facilitates open collaboration [6]. For the problem of large variety that stems from the lack of standardization and the great number of uses cases, replicability can be achieved with open-source platforms by doing minor changes. Thus, proven solutions can be used in multiple contexts and software or hardware can be reused in different systems which reduces the need for development and testing [6]. In general, open-source systems are more flexible and allow to use components from different manufacturers and suppliers [5]. The development of IoT can be compared to the development of the Web, because it requires a common access to its functions for shared accessibility similarly as the Web [11].

Interoperability is one of the biggest concerns in IoT. According to Farnell Global IoT Survey improved interoperability was risen as one of the biggest factors to accelerate the benefits of IoT [8]. Similarly, in GAO survey 30 out of 74 respondents stated that interoperability is the most significant challenge to adopting IoT technologies [9]. Consequently, the development of open standards could have a big impact on making open-source platforms more popular. This would especially benefit the open-source platforms that are based on the idea of openness and the use of open standards that everyone can share and adapt. This kind of development could also force the commercial platforms towards openness. On the other hand, this could even further open doors for open-source platforms as those could be more flexibly used with commercial platforms. Evidently, the decision to go towards interoperability is a trade-off between (1) the profitability of the business case, (2) their strategic position and (3) privacy and security considerations, while fulfilling legal requirements [10].

The vision is that open-source technologies will revolutionize the world in many areas including Industry 4.0, machine learning, IoT, Big Data analytics and cloud computing. Currently, open source is already playing a crucial role in creating IoT platforms and prototypes utilizing development boards. Similarly, many of the most used machine learning engines are open source, thus developers can test, re-build and learn from each other. [11] Further, it was concluded that AI will continue to contribute to the advancement of industrial informatics in the future [3], which strengthens the role of open source in industry 4.0 in the future.

New technologies are widely developed and used among open-source communities and are gradually becoming available for everyone. For example, GitHub is a popular platform for these kind of open-source projects [12]. Many open-source libraries and online guides are so easy to use that developers can use these tools without being experts on areas like artificial intelligence and machine learning. Similar development can be seen in the IoT world. Further, experts and researchers also benefit from these open-source online communities. The outcome is that new technologies spread fast and new research results are often tested efficiently. However, the lack of instructions and documentation sometimes becomes a problem as the development is fast and unfinished systems are used. In addition, when relying on open source, the licensing terms for using and contributing open-source material vary depending on the project and have to be taken into account [6].

We hypothesize that this kind of development would not be possible without affordable hardware to be used by the builders. New interesting hardware on the market usually brings more possibilities for developers and simultaneously new developments on the software side creates more demand on hardware. This creates a symbiotic relationship that accelerates the development on both fronts. This paper clarifies the current situation and presents information that can help predicting the future of open source in IoT. The paper tries to answer to the following two questions:

1. What are the challenges faced that hinder the mainstream adoption of open-source hardware and software in the context of Industry 4.0 and SME's?
2. What are the trends related to open source in IoT systems and the state of open-source hardware and software in the context of Industry 4.0 and SME's?

2. Methodology

This paper presents a review of the current tools and applications as well as new possibilities and challenges in the context of open-source IoT. The entailed methodology follows a two-step approach: (i) a grey literature review including online information, complemented by (ii) a structured keyword search using IEEE scientific repository. Scientific literature mostly relates to IoT open-source tools, but also grey literature was used as a source for information. The rationale behind including grey literature is to include public online information that may be produced by academia, business communities, industry or government, which is not necessarily peer reviewed [13]. In the context of this research, grey literature becomes especially relevant as IoT technological developments often advance more rapidly than academic research (i.e., technology advances fast and new things are not presented in scientific literature yet). Also, many new topic related developments are presented only in online communities and not in scientific papers. Further, the number of keyword related IEEE Xplore search results for each year are used to justify the alleged increase of importance of open source in IoT, and to compare the different technologies and their importance.

3. State of the art review

The exploitation of open source in the IoT tools could be in the software or the hardware side, or in both. Open-source software solutions in IoT can utilize complete tools or just open-source libraries. These tools vary from simple dashboards to complete platforms accompanied with cloud storages and data analysis tools. The libraries include tools for machine vision, sensor libraries and so forth.

3.1. Hardware

In this paper the hardware used with open-source IoT solutions are divided to two types:

1) *Simple platforms with low computational power:* These are mainly used to create simple sensors and are based on microcontrollers.

2) *More powerful platforms with high computational power:* These can be used as open-source system servers or as sensors with edge processing capabilities as image recognition, voice recognitions and AI.

The line between these two is quite vague on some cases and seems to be getting more obscure as the computational power of microcontrollers that are generally used in the category 1 products is increasing. Also new platforms arise that could be placed somewhere between these groups. Further, the development of AI algorithms that consume ultralow energy are leading to new opportunities [3]. Not only in the sense of saving energy in data centers but also possibly for low-energy edge computing sensors.

There are two platforms that rise above others when talking about open-source projects; Arduino and Raspberry Pi. Arduinos are the most widely used and best-known microcontroller boards and their popularity is easy to understand. The entry barrier is very low. The programming environment is easy to start with and the language is easy to understand. Raspberry Pi's are the most used single-board computers today as their cheap prices and ease-of-use have earned these devices their undisputed reputation. After these two pioneers many other companies have brought their contenders on the market. Espressif systems ESP2866 and ESP32 based boards with more processing power and Wi-Fi/Bluetooth capabilities have been the biggest thing after the emergence of Arduinos. For new IoT projects there are lots of development boards that have built in long-range wireless connections such as LoRa and 3G [14][15].

The same has happened with Raspberry Pi. Nowadays many of the contenders are specifically designed to be used for machine learning and to make AI more accessible. For example, Jetson Nano, a single-board computer from Nvidia is significantly more powerful than the newest Raspberry Pi 4 and is targeted towards AI [16]. Also, there are add-ons to improve the performance of Raspberry Pi's for machine vision and neural network related applications [17].These boards are great platforms for development projects and maybe even for industrial use. The industrial use is still a disputed subject, and many experts see them as toys that are not robust enough and lack reliability. Nevertheless, this is poised to change in the future as companies are bringing out new boards that are specifically designed for industrial environments. Additionally, some companies offer structures to make Raspberry Pi's more robust to endure industrial environments [18],[19],[20]. Moreover, Raspberry Pi's are increasingly being promoted for direct industrial use to even replace PLC's [20]. The Raspberry Foundation has even brought a board called Compute module 3+ on the market, which is specially designed for industrial applications [21].

Arduino Portenta family devices are designed for demanding industrial applications like AI edge processing and robotics. The first member, Arduino Portenta H7 can run Arduino code, Python and JavaScript. It can run processes created with TensorFlow Lite and is suitable for many tasks like, computer vision, PLC's, robot control and many more. [22] The open-source modules are said to have an advantage against the majority of currently sold solutions that are closed, as they can be used for any operation purposes [23]. The small size, low-price, good processing power and great support for real time applications are the factors for ESP32's expected to play a major role in the design of future IoT systems and embedded projects [23].

3.2. Software

To create an open-source ecosystem for IoT, a combination of many open-source technologies is required. Each part is implementing different functions of the architecture: from data sensing to applications for end users. [24] The importance of software cannot be neglected. Most of the commercial IoT solutions lack interoperability and standardization [25]. As a solution, Atmosphere, a non-vendor locked open-source framework for measurements was developed [26]. The idea of the system is to exploit state of the art data management technologies and to efficiently support development for a variety of relevant IoT applications. Atmosphere integrates APIs implementing Representational State Transfer (REST) services to provide a platform-independent HTTP interface. MongoDB open-source database is used for data storage. According to the tests made by the creators of Atmosphere their framework is easy to deploy and use. [26]. Another tool, Grafana [27] is an open-source analytics and monitoring solution which can be used to create dashboards and visualization for heterogenous data sets.

A more comprehensive survey of various open-source platforms was done to compare the different levels of technical requirements, such as device management, data management, communication, intelligent data processing, security and privacy protection. Also, the requirements of application development and deployment were investigated [24].

The latest hype surrounding IoT is on Fog and Edge computing. The idea on both is to move a big part of the processing closer to sensors which requires more processing power from the devices. For example, image recognition seems to be one of the most researched and promising areas where single board computers are used. Most commercialized image recognition and AI products can be seen as black boxes and are unaffordable for small and medium-size companies. Image processing solutions are often very expensive to purchase as those are usually custom-made solutions [28]. TensorFlow is an open-source framework for efficient numerical calculations. OpenCV is a library especially for computer vision algorithms. Keras is a high-level neural networks API, written in Python and capable of running on top of frameworks such as TensorFlow. There are lots of research projects utilizing these tools with single board computers. Projects vary from counting fish in the fisheries to apples in the orchards [29], [30], [31].

3.3. Regulations and licensing

Certain factors should be taken into consideration when using open-source hardware and software commercially. Licensing is one of them. For example, Arduino libraries are under LGPL [32]. This means that if the libraries are modified then the modified code is released. OpenCV is released under BSD license and hence can be used for commercial applications [33]. TensorFlow is licensed under Apache License 2.0 and thus allows users to use the software for any purpose, to distribute it, to modify it, and to distribute modified versions of the software [34], [35]. Keras can also be freely used without much limitation as it is licensed under the MIT License [36], [37]. There are also lots of open-source IoT platforms that can be used commercially, for example Thinger.io modules in GitHub are under the MIT license [38].

Another issue is the acceptance of electronic devices. All electronic devices should be tested for electromagnetic combability (EMC) which means the ability to operate reliable in its natural working environment. Also, devices should not interfere its environment by emitting unwanted electromagnetic radiation. In EU the electromagnetic compatibility is regulated by EMC-directives 2004/108/EY and for vehicles 2004/104/EC. For example, Raspberry Pi's are compliant with EMC directive as well as RoHS directive for hazardous substances in electrical equipment [39]. Also, ESP32 modules comply with FCC certification mark which certifies that the electromagnetic interference from the device is under limits approved.

The regulations are complex, for instance when using certified modules to design a device it doesn't mean that the device is certified [40]. The problems can easily arise, for example if the module is used with antennas that are not listed on the certification. Regardless the design manners the regulations and directives must always be obeyed.

Another option to simplify the electrical design is to use pre-made modules. For example, using pre-made RF modules can also save space, money and time [40]. Also, the modules are usually EMC tested and certified. Even though the whole system have to be checked for compliance when using a tested RF module, time and money can still be saved as the device passes the test on the first try [40]. The same arguments could be used with pre-made microcontroller modules as ESP32 WROOM and modules as Raspberry Pi Compute Module 3+ or similar.

4. Trends in the field

The trends related to the topic were investigated by doing keyword searches in IEEE Xplore. This information is used to support the idea of open source being relevant in the development of IoT. Firstly, the number of publications with a keyword "open source + IoT" has been increasing every year. This trend in Figure 1 shows that the topic is being researched more and more and indicates the relevancy of open-source technologies in IoT. The trends were taken till 2019 as the latest publications may not have been accurately reported.

The number of publications affiliated with the four most used hardware platforms in open-source projects are used to show their relevancy in Figure 2. The plateaued curves for Arduino and Raspberry in the recent years may indicate that the use of these platforms in publications may have reached its peak. Yet, there is no sign of decreasing numbers of publications on these topics per year.

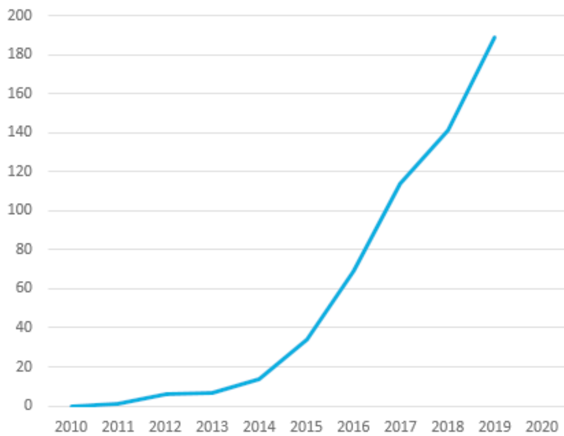

Figure 1. Trends in open source in IoT developments

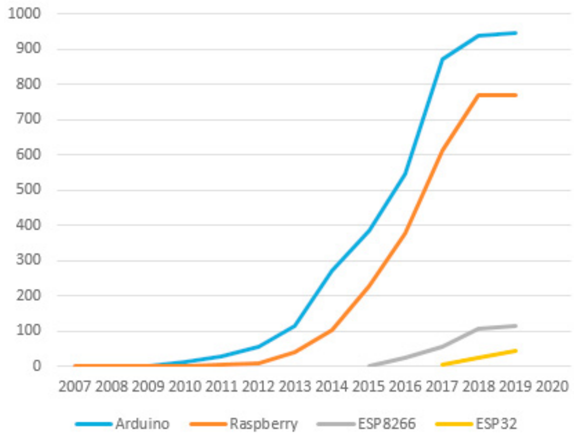

Figure 2. Search results for low cost hardware platforms

The three long range wireless technologies that were used as keywords in IEEE Xplore searches are mentioned in increasing number of papers each year as it can be seen in Figure 3. This shows that they are relevant as the use of IoT increases. Also, comparison between the number of the publications can be used to make a good guess which is the most relevant wireless technology for IoT today.

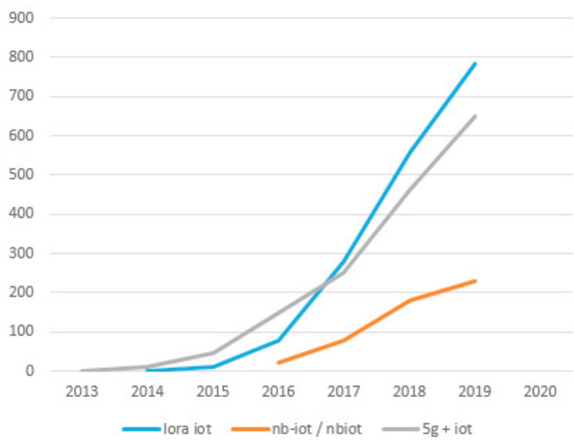

Figure 3. Search results for wireless technologies

5. Findings and Discussion

5.1. Observations on Challenges

As stated, there are still some obstacles to be overcome to make the open source come to reality in a big scale in IoT. For example, when using development boards or other physical platforms also the regulations need to be considered. Especially the problems may occur when making changes to a hardware that has been accepted to comply all the regulations and the acceptance must be done again. The licenses that are usually applied in open-source software and hardware do not generally hinder the commercial and industrial use. Notwithstanding that there are some restrictions not to break the open-source nature in the created products.
The ease of use is an important factor when deploying new systems. In this paper it was stated that current developments are bringing the tools available for anyone. Although, the expertise needed to utilize these tools and technologies is not explored in this paper. Similar developments have been seen on many areas, for example in the installation and use of open-source Linux operating system.

A reliable system that requires less maintenance and assured uptime from the vendor can work in favor of commercial systems over its open-source counterparts. On the other hand, this opens possibilities for consulting companies to deploy open-source tools-based systems and even take the responsibilities and offer full support.

For SME's the usual barriers for adopting open source are the lack of resources, expertise on the area and missing information on how to get started. Which platforms to use? What are the reasons to select a specific platform? How to connect platforms? What is the architecture of IoT system?

Also, the authors have noticed that many people still see open-source tools as unreliable and not suitable for professional use. Especially Arduino and Raspberry Pi platforms are seen as toys and their possibilities are overlooked. Companies have more trust on technology that has been used for years and proven to be reliable. On the other hand, their beliefs are with good reason and especially on mission critical use it is better to go with well proven technology.

Interoperability is one of the biggest concerns in IoT and open-source tools as well as open standards are a possible solution. This topic was more extensively reviewed in another paper by the authors.

5.2. Observations on Trends

The increasing trend observed in the previous section is evidence of its relevancy in the future. Further, several publications also see open source as a viable solution to fix the problems that are affiliated with commercial systems. Also, the increasing sales figures of Raspberry Pi's are supporting the idea. Open-source software and hardware have good potential in bringing new technologies to the market. Open source is already vastly used in product development, but it is gradually crawling into industrial use and to commercial products. There are already lots of popular open-source products like Android, Linux and Odoo that are largely used in their own areas. For IoT, similar developments require high level of reliability, performance, security and ease of use from the available tools.

The use of open source is being promoted in Europe and seen as an asset for companies. Even the German government has stated that "*Open-source software guarantees transparency, while open interfaces ensure interoperability and standardisation"* [41] which indicates that the use of open source is getting wide support.

Further, the FOSS4SMEs project which is co-funded by the Erasmus+ program of the EU promotes the use of open-source software by improving the skills of European SME's to use free and open-source software to improve their digital performances and competitiveness. Their report states that smaller companies are more likely to adopt digital technologies and almost 90% of the companies reported that digital technologies have generated positive outcomes. In turn many SMEs struggle to stay alive and competitive and unlike large companies, SME's often feel that they only have ability to focus on their immediate business. This means that these companies don't have much resources to put on long-term development, which clearly affects the digitalization of SME's and hence also their adoption of IoT solutions among other areas. Also there have been case studies where several organizations as French Gendarmerie, the Estonian government, and CERN moved away from proprietary software to open source where their costs were saved from 20% to 95%. [41]

5.3. Common Observations

The trends of open-source hardware platforms show that the companies are putting more emphasis on creating hardware for industrial use. Also, the development of open-source software tools indicate that they are becoming more comprehensive and capable of competing against commercial software. In addition, the support from EU and other actors towards open source could assist their uprise in the context of IoT.

On the other hand, the cloud services are becoming the center of gravity in IoT projects and this risks the IoT to be controlled by leading cloud providers. This gives an advantage to the big players as Google, Microsoft and Amazon. Further the continuity is one of the important aspects when choosing a service, and it plays even more on the side of big companies. The big players may still "open" some parts of their platforms to attract and guide developers, so it might become difficult for them to "switch" from those established and resourceful path. On the other hand, open source could be still a considerable option especially when the company is strict about where its data is stored. In addition, despite the use of commercial platforms at least the hardware still could be based on open source and possibly even open-source software and commercial systems could be used alongside, assuming the interfaces are open.

6. Conclusions and future research

The current available open-source tools are versatile and developing fast, which strengthens the idea of the use of open source in IoT and Industry 4.0 solutions. The trends clearly show that IoT platforms will not necessarily come towards harmonization and standardization. However, the licensing models, interoperability issues, and quality of the tools will not necessarily hinder their use in a professional environment including manufacturing SMEs. However, there are still obstacles for the use of open-source tools to overcome before becoming seriously taken. For example, the ease-of-use, customer support, guarantees, regulatory compliance and certifications. Further, this paper points out a need for means/an approach to evaluate the IoT tools, systems and requirements for the solution.

These means are needed to be able to answer to what is needed for open source to become a serious option for industry. Often the same hardware and libraries used by hobbyist are utilized by start-ups and existing companies for prototyping. There also seems to be an emerging trend for using these low-priced platforms even inside commercial devices. The potential of open source should be taken seriously, as this kind of knowledge for a company can give a valuable edge for their product development or production.

One important aspect to further study is the concept of modularity and flexibility in IoT systems. For example, we envision developments related to open-source middleware that connects data collection system (e.g. sensors) and data storage such cloud services. The idea is to create a platform that uses modules that can be installed to make it interoperable with different systems. The similar idea lies behind, software modules, and USB-drivers. Overall, the choice between open-source and commercial IoT tools depends on many factors, like the requirements and expertise inside the company. The reasons behind the answer seem complex and requires more deeper investigation.

CRediT author statement

Antti Martikkala: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing. Joe David: Writing - Review & Editing. Andrei Lobov: Supervision, Funding acquisition, Methodology, Writing - Review & Editing. Minna Lanz: Supervision. Iñigo Flores Ituarte: Supervision, Methodology, Writing - Review & Editing.

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