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IoT for Efficient Data Collection from Real World Resources

Dissertação para obtenção do Grau de Mestre em
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For my parents, sister and girlfriend

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At the end of a long and demanding course, I would like to thank all the people who in some way, contributed to the success of this stage of my life.

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Abstract

The Internet of Things is providing new ways of experiencing and reacting to the physical world through the ability of advanced electronic devices that collect data. At the same time, as new application scenarios are envisioned, with the assistance of information generated by sensors, new problems and obstacles will arise. This requires new development to meet business and technical requirements, such as interoperability between heterogeneous devices and confidence (such as validity, security and trust) over smart devices. With the increase of these complex requirements it becomes crucial to develop an infrastructure aimed at tackling such requirements mentioned. IoT middleware – a software layer that bridges the gap between devices and information systems. Thus, this work aims to study the mechanisms and methodology for data collection, devices interoperability and data filtering, closer to the data sources, in order to optimize the collection and pre-analysis of data that can then be used by various applications such as the ones in manufacturing industry.

Keywords: Data Acquisition, Data Filtering, Internet of Things, Middleware, Sensors, Interoperability

Resumo

A Internet das Coisas vem providenciar às pessoas uma nova forma de sentir e reagir aos aspetos do mundo físico, através da capacidade que os avançados dispositivos eletrónicos têm atualmente na recolha de informação. Paralelamente, novos cenários de aplicabilidade, nas mais diversas áreas, que advém do uso da informação recolhida pelos sensores, começaram a surgir e, diversos problemas e obstáculos prevalecem. Portanto, é necessário novos desenvolvimentos que satisfaçam os requisitos técnicos e de negócios, tais como a interoperabilidade entre dispositivos heterogéneos e a confiança (em aspetos como a validade, segurança e fiabilidade) que os dispositivos inteligentes asseguram. Com o aumento da complexidade deste conceito, surgiu uma infraestrutura que visa solucionar os importantes requisitos mencionados. IoT Middleware – uma camada de software que faz a ponte entre os dispositivos e a infraestrutura. Assim, esta dissertação pretende estudar os mecanismos e metodologias de recolha de dados, interoperabilidade de dispositivos e pré-filtragem de dados, perto da fonte de recolha, com o intuito de otimizar a sua recolha e pré-análise de dados que podem ser usadas em várias aplicações, como por exemplo, na indústria da manufatura.

Palavras-Chave: Recolha de dados, Filtragem de dados, Internet das Coisas, Middleware, Sensores, Interoperabilidade

Index

Index of Figures

Index of Tables

Table of Acronyms

Acronyms	**Definition**
AMQP	Advanced Messaging Queuing Protocol
API	Application Programming Interface
CO	Cooperating Objects
CoAP	Constrained Application Protocol
D2D	Device-to-Device
D2S	Device-to-Service
DCF	Data Collection Framework
DDS	Data Distribution Service
EPC	Electronic Product Code
GRIS	Group for Research on Interoperability of Systems
GSN	Global Sensor Networks
HTTP	Hypertext Transfer Protocol
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IT	Information Technology
JAR	Java Archive
M2M	Machine to Machine
MQTT	Message Queuing Telemetry Transport
NFC	Near Field Communication
PLM	Product Lifecycle Management
RDF	Resource Description Framework
REST	Representational State Transfer

Acronyms	**Definition**
RFID	Radio-Frequency Identification
ROS	Robotic Operating System
RW	Real World
S2S	Service-to-Service
SUT	System Under Test
TEDS	Transducer Electronic Data Sheet
TDT	Tag Data Translation
TTCN	Testing and Test Control Notation
XMPP	Extensible Messaging and Presence Protocol

1. Introduction

In recent years, we have witnessed a huge expansion in the utilisation of devices conceived to collect data for a variety of applications. With the ease of communication and transfer of information that the internet has provided in the last decade, the concept of IoT has emerged. It is based on information collected from the real world (RW), through sensors, and make it accessible anywhere and as much diversity of use as the diversity of data collection devices currently on the market (Minerva et al. 2015). The IoT's cover a wide range of areas, as depicted in Figure 1, which shows not only the need for advancement of core technologies but all the development of new business models, management strategies as well as new ways to protect information and increase privacy.

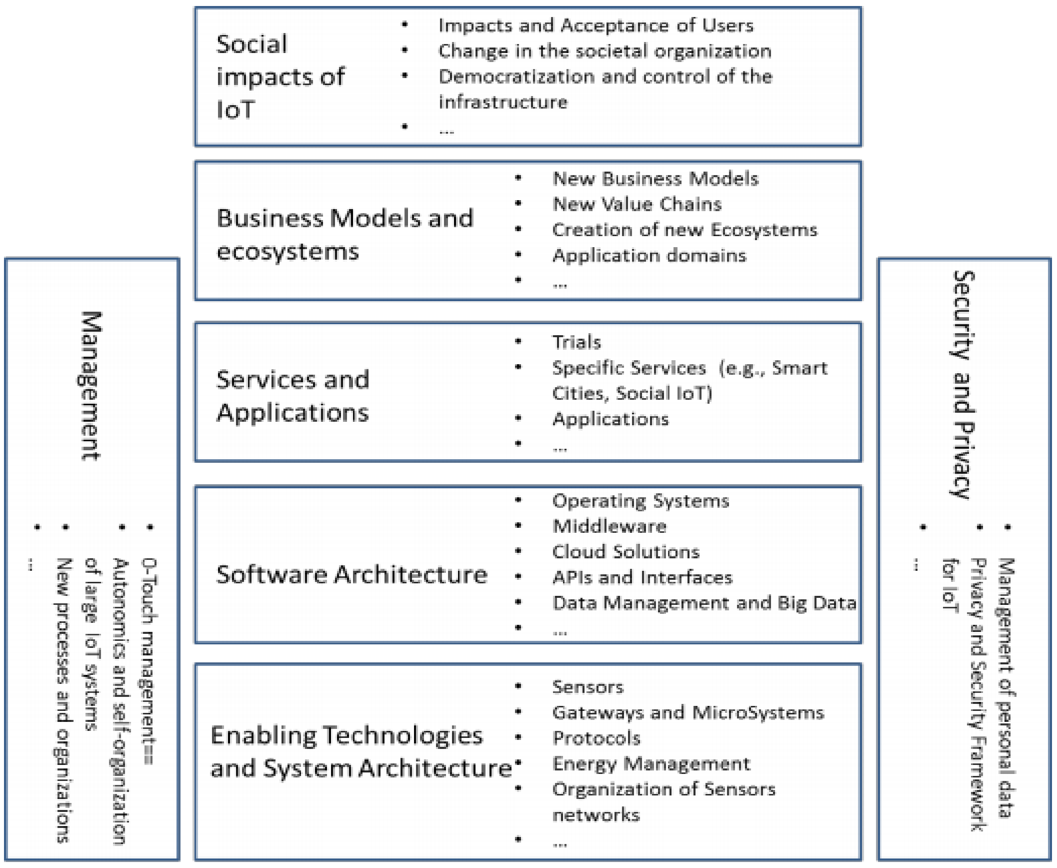

Social impacts of IoT
Impacts and Acceptance of Users
Change in the societal organization
Democratization and control of the infrastructure
...
Business Models and ecosystems
New Business Models
New Value Chains
Creation of new Ecosystems
Application domains
...
Services and Applications
Trials
Specific Services (e.g., Smart Cities, Social IoT)
Applications
...
Software Architecture
Operating Systems
Middleware
Cloud Solutions
APIs and Interfaces
Data Management and Big Data
...
Enabling Technologies and System Architecture
Sensors
Gateways and MicroSystems
Protocols
Energy Management
Organization of Sensors networks
...
Management
0-Touch management==
Autonomics and self-organization of large IoT systems
New processes and organizations
...
Security and Privacy
Management of personal data
Privacy and Security Framework for IoT
...

Figure 1 Technological and social aspects related to IoT (Minerva et al. 2015)

It is estimated that in 2020 there will be around 21 billion devices connected to each other, of which 7 billion do not relate to the consumer market but to the use of devices in industrial sector (Gartner 2015). This technological advance derives mainly from the constant search for maximum efficiency that many companies are looking for with the purpose of increasing its self-management in both data monitoring and in its management and control. In this perspective, companies are looking for solutions in three major areas (Sheng et al. 2015):

- Network Management - focus on quality and reliability of the hardware, such as routers and servers;
- System Management - focus on quality and reliability of software, such as data interpretation and operating systems programs;
- Application Management -concern aesthetic and reliable aspects, both in safety and operability.

In order to correlate these three areas and hence reduce the difficulties of integration and management, one of the solutions that can be adopted is the middleware technology – a software layer between two systems that make it easy for the two to communicate (Winter & Rosenblum 2001). Figure 2 shows two different approaches for data collection and/or integration of heterogonous devices. The middleware based approach provides an abstraction layer between the devices (data producers) and other higher level services and/or applications (data consumers), like data analytics, data broadcasting, event detection and other business applications. This abstraction layer provides added value for high application development by removing the need for understanding different types of standards and protocols followed by wide range of devices. Simultaneously, it can lower the burden on the backend services by implementing generic data filtering, security checking, data validation etc. at the point of data collection. This can enrich the reliability over the data collected from different sources.

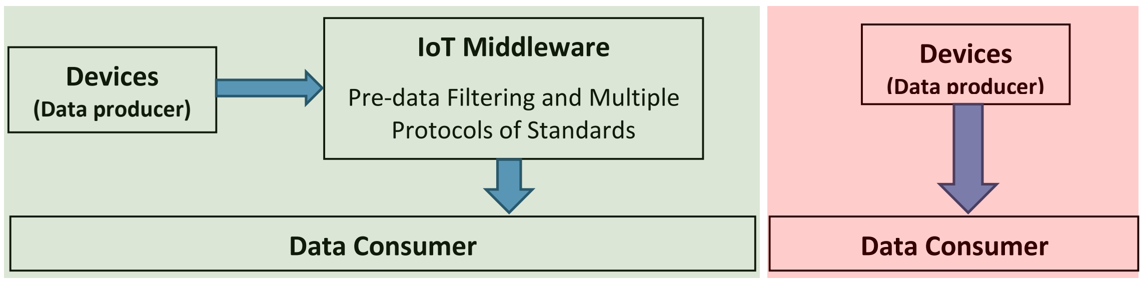


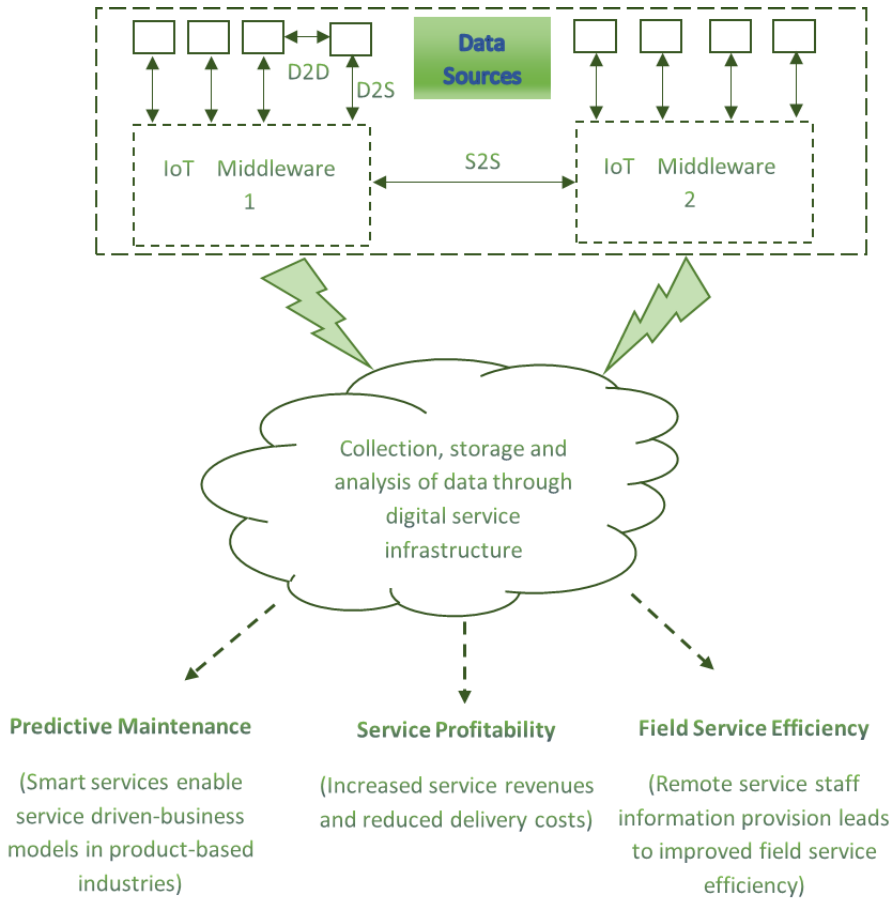
Figure 2 Middleware based Vs Direct approach of data collection through source devices

Essentially, this work aims to contribute to improve the methodology for data collection from different devices by considering improvement across data access uniformity, communication resources optimization and central management of connected devices. This project aims to provide a solution for the integration of IoT devices with the cloud based platforms with less effort for high end data processing and data analytics. The scope of this project also includes Within the scope of this work it is expected it to provide solution that can provide added value to improve production lines, increase interoperability and self-management in the manufacturing industry through affordable technology to small and medium enterprises.

1.1. Motivation Scenario – IoT

In an interconnected Industry 4.0[1], ideas are much more valuable if they are embedded in an equally innovative periphery of devices or related solutions. New impulses can come from a multitude of sources outside the own organization, and they have to be proactively integrated into an open innovation process. These 'outside-in' and 'inside-out' processes are enabled by digital technologies, such as community platforms or collaborative PLM tools, connecting knowledge resources. Collaborative engineering activities, for example with the customer, are also greatly facilitated by the use of appropriate digital platforms and the availability of sophisticated virtual product models (Bechtold et al. 2014). It can be clearly noted that collection, storage and analysis of data through digital a service infrastructure incorporating a wide range of data sources is an important feature. Figure 3 shows the high level view on value creation through smart services by resorting to the power of IoT devices.

[1] Industry 4.0 is a term applied to a group of rapid transformations in the design, manufacture, operation and service of manufacturing systems and products (Davies 2015).



Data Sources
D2D
D2S
IoT Middleware 1
S2S
IoT Middleware 2
Collection, storage and analysis of data through digital service infrastructure
Predictive Maintenance
(Smart services enable service driven-business models in product-based industries)
Service Profitability
(Increased service revenues and reduced delivery costs)
Field Service Efficiency
(Remote service staff information provision leads to improved field service efficiency)

Figure 3 Value Creation through data collection from different IoT devices

Recent developments in IoT technologies is enabling data generated by sensor networks to be used by business intelligence software to identify trends and patterns, and help companies to make better decisions and become more reactive to the surrounding environment (Santucci et al. 2012). Machine2Machine (M2M) technologies have the potential to be put to highly innovative and practical purposes (With 2013). Current research domain involves the process of connecting machines, equipment, software and “things” in our surroundings. “Things” will use a unique internet protocol address, which allows for the communication with each other without human intervention (Huang & Li 2010). At the same time, evolution of technology in the manufacturing sector has occurred faster than the ability of companies to keep up with it (Stöllinger et al. 2013). Thus, without having a real-time (or almost real-time) access to the shop-floor, what was expected at the end of the production line could be different from what is actually being produced. Besides the automated data collection and alignment to the manufacturing plans, the synchronization and maintenance of devices deployed at different stages of manufacturing line are often more complex (Microsoft 2009). This is partly because of the diversity in the devices being used by different manufacturing plants that often have multiple propitiatory protocols and of course also a large amount of data.

Summing up, the main motivation behind this research and development work is towards the ***realization of efficient IoT middleware*** (as clearly marked in Figure 3) for IoT devices integration for creation of value added enterprise services. The main target is to have a middleware solution that can deal with heterogeneous data sources and enable data filtering closer source. Another important requirement is also to develop a solution that is light-weight to be deployable in low-resource computing units such as raspberry-pi. The importance of having a light-weight yet robust IoT middleware is not only to provide one point of integration and interoperability but also to take advantage of data pre-processing at the source by implementing functionalities for data filtering, communication channel optimization and provide a management bridge between cyber and physical world.

1.2. Research question

The general theme for this thesis is "***Middleware based technology for data collection in IoT systems***", which is an important research domain in the wider scope of Internet of Things (IoT). The rational for the selected field of research has been explained in the previous section. In order to streamline the research work it is important to define a research question to be answered during the completion of thesis. Covering a wide number of sectors that can be improved with the gradual introduction of IoT, it is important to define the problem to be addressed and to which this works intends to contribute as a solution in industrial technological advancement. The main research question formulated for this Master's thesis is:

RQ: "Is it possible to develop scalable and interoperable middleware for continuous data collection from real world resources?"

To ensure the research focus and targeted results, the major question can be detailed with following sub-questions:

Q1.1: "What is the efficient mechanism for protocol adaptation to allow seamless integration of different types of devices?"

Q1.2: "What are the suitable data filtering methodologies and algorithms that can be implemented in the IoT middleware to enhance data pre-processing at the source with least overhead over time?"

Q1.3: "What will be the impact of the middleware based methodology in the overall process of data collection from real world resources in real-time systems?"

During the progress of this thesis, it was expected to find answers to the above mentioned questions through necessary system implementation, validation and assessment.

1.3. Hypothesis

Based on the discussions in the previous sections that provides the motivation and formulated research questions, one can estimate that:

"If we can develop IoT middleware, which can enable seamless integration of IoT devices with unified implementation to detect and filter faulty data collected from the source then efficiency of data collection from real world resources can be improved in the IoT paradigm."

The above statement is therefore the adopted as the hypothesis that will be challenged, implemented, tested and validated during the period that will lead to the completion of the thesis.

1.4. Work Methodology

This section focuses mainly on research-based strategy in which the dissertation and scientific methodology that was built upon. In order to lead my thesis with the maximum rigor that it requires, it was decided to base my scientific method of investigation in the classical methodology (Camarinha-matos & Terminology 2016) whose phases are shown in Figure 4 and explained in its follow-up :

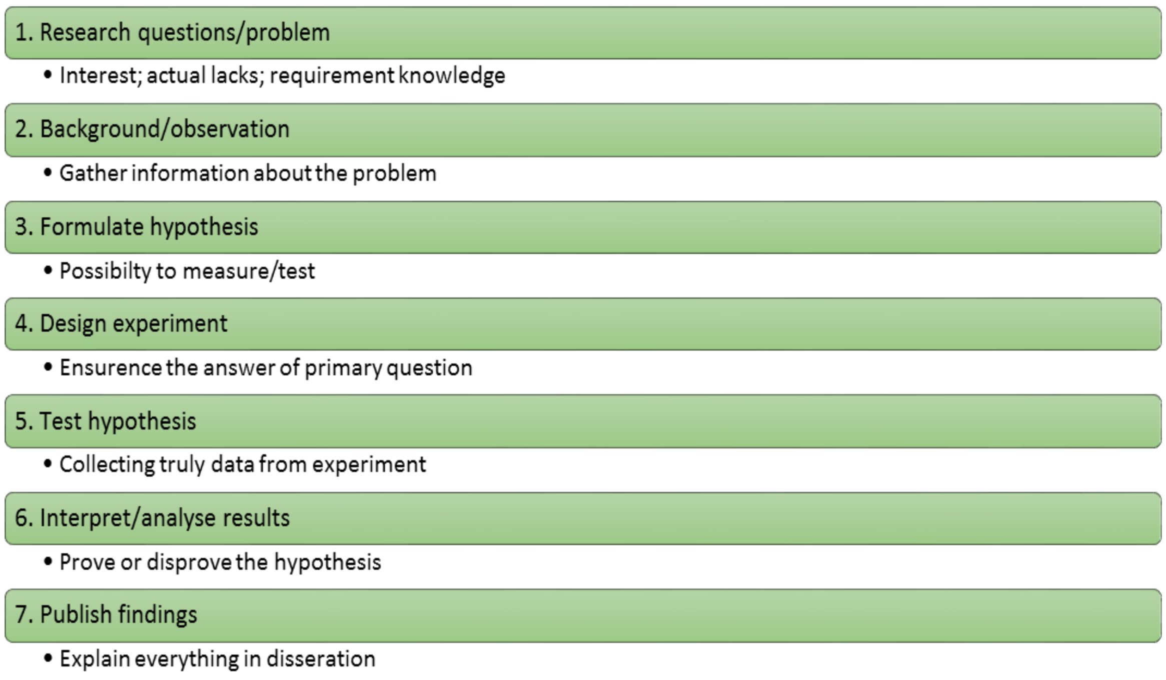

1. Research questions/problem
   - Interest; actual lacks; requirement knowledge
2. Background/observation
   - Gather information about the problem
3. Formulate hypothesis
   - Possibilty to measure/test
4. Design experiment
   - Ensurence the answer of primary question
5. Test hypothesis
   - Collecting truly data from experiment
6. Interpret/analyse results
   - Prove or disprove the hypothesis
7. Publish findings
   - Explain everything in disseration

Figure 4 Classical phases of scientific research (based on (Camarinha-matos & Terminology 2016))

1. Research Question / Problem – As in any scientific papers, the first step is the most important since it serves as the foundation for a specific problem or a possible solution, thus initiating all the research. It is important to realize that the main question could be the result of some minor questions interconnected.

2. Background / Motivation – This step requires a lot of investigation to allow the researcher to understand what type of similar work and projects have been done, as well as which solutions could be developed for a dissertation.

3. Formulate hypothesis – Already having found the problem and knowing what work has been done, it is beneficial to predict an outcome to facilitate the course of the investigation

4. Design Experiment – This is the most practical stage of the investigation as it begins with the trial phase of the work and some kind of implementation.

5. Test hypothesis / Collect data – At first a test set must be defined according to the characteristics of the problem formulated in step 3 and the implementation done in step 4. All the simulations results must be registered for the next step.

6. Interpret / Analyze results – At this point the results are analysed and the veracity of the hypothesis is proved. If there were not positive results it is advisable to return to step 1. On the other hand, when the results are achieved, it is possible to obtain some ideas for further research.
7. Publish findings – The last phase of the suggested methodology is as important as the first one, for the results of the investigation will be useful in future research and contribute to the scientific community. Or, ultimately, it might become of use for the industry.

1.5. Dissertation Outline

After the initial study that led to the question to be answered, this paper then evolves into the following chapters:

Chapter 2 – State-Of-Art: This chapter presents the related work elements studied. The first section explores the main definition concepts and considerations to have in data acquisition context whilst the other two sections introduce the IoT scenarios deployed as well as the existing middleware systems.

Chapter 3 – Hub Architecture: This chapter explains the hub on a high level overview and marks the beginning of design experiment.

Chapter 4 – Proof of Concept Implementation: This chapter is also a stage of the design experiment. It includes a detailed report about the practical component and an explanation on what and why was considerate.

Chapter 5 – Testing and Hypothesis Validation: This chapter discloses the tests used to validate the formulated hypothesis and the respective analysis to verify if the initial objectives were achieved. It refers to the fifth and sixth stage of the work methodology. The chapter ends with the development integration and validation with other research activities.

Chapter 6 – Conclusion and Future Work: The final chapter has an analogy between what was studied and what was implemented, and what could be improved in future.

2. State-Of-Art

This chapter presents all the research undertaken and the basis for the implementation of the formulated hypothesis. The following sections cover, in particular:

- 2.1. Overview - Definition of the most important concepts related to IoT paradigm.
- 2.2. IoT Deployment Scenarios – Different types of deployment approaches followed by the realization of IoT ecosystem.
- 2.3. Middleware Solutions for IoT – A survey of existing research work in designing middleware systems for the IoT.

2.1. Overview

The problem that this thesis proposes to investigate is part of a vast subject, covering several technical concepts. Therefore, it is important to provide an explicit definition and build the background on which the research will be based. In order to formulate the foundation for this thesis. The following sub-sections provide the state of the art on different aspects of IoT that were taken into account for development and research in the scope of this dissertation.

2.1.1. Internet of Things

According to (IERC 2010), IoT is "A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network."

It is a concept and a paradigm that considers pervasive presence around us in the environment of a variety of things/objects/devices, which through wireless and wired connections and unique addressing schemes are able to interact with each other and cooperate with other things/objects/devices to create new applications/services and reach common goals (Atzori et al. 2010).

According to (Bradley et al. 2013) the five main factors increasing the values associated to the IoT are:

- Increasing the return on research and **innovation** investments, reducing time to market, creating new business models and opportunities;
- Increasing the **lifetime of customer** and adding more customers;
- Improve **utility services** such as supply chain and logistics, to a new and more efficient level;
- Improve **business process** with the expense on goods reduced;
- Increasing the **employee productivity** and efficiency.

The IoT awareness affects a large number of areas and interested parties. The associated values at manufacture industry, the main target of this thesis, benefits in areas like machine auto-diagnosis and assets control through sensors installed in machines allowing a faster response to detected problems and remote monitoring of elements such as temperature, raw materials and humidity, adjusting them automatically. The IoT potential is analysed in (Joseph Bradley, Joel Barbier 2013) with examples of critical improvements such as reduction of materials, energy and costs of automated tools, which is less expensive to manufacture and implement. The potential of IoT extends also to the automated management, detection and self-healing of the machinery, available resources, product quality and other services. Lastly, increased sales from real-time market assessments and reactions, location-based selling and improve coordination with other products and services (two-sided markets).

2.1.2. Middleware for Data Acquisition

In order to develop a data collection system from RW resources, there are generic features that have been identified:

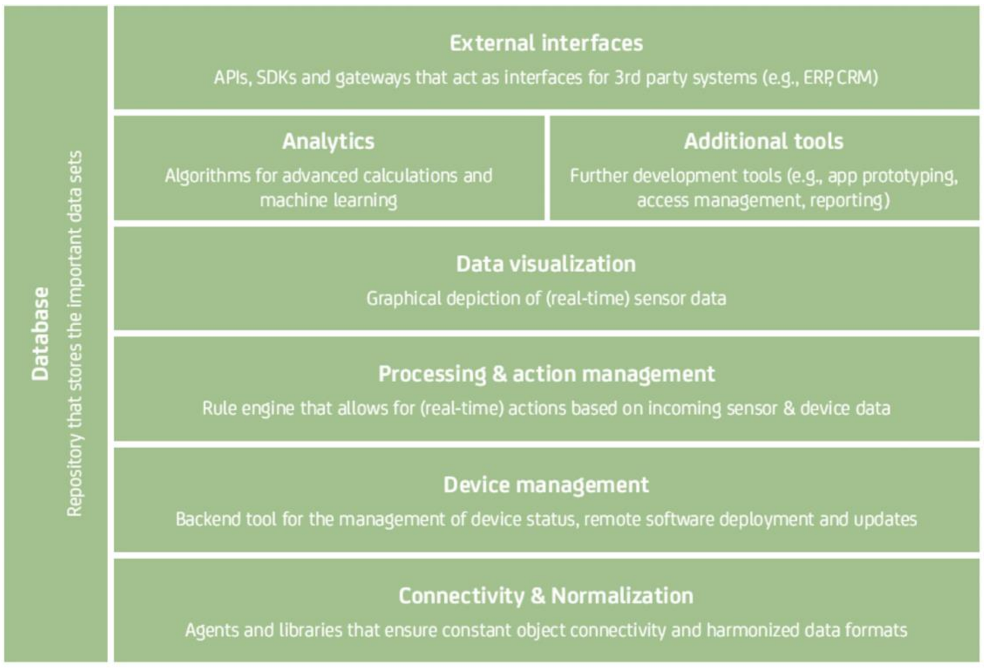
- Provide an infrastructure to capture data from IoT sources.
- Provide an infrastructure that is modular and independent of the devices geographic location and functionality.
- Techniques of filtering data to control the flux of data coming into the platform.
- Security of communication channels (where authenticated data should flow).
- Support to different communication protocols should be available;

In IoT context, the objective of having a middleware platform is to present a unified model to interact with devices as it provides an abstract layer interposed between the IT infrastructure and the applications (Chaqfeh & Mohamed 2012). Therefore, the problems concerning with interaction of devices are described in Table 1, according with (Fersi 2015):

Table 1 Five main functionalities handled by an IoT middleware

Interoperation	Share information through diverse domains of applications using diverse communication interfaces. Divided in: Network, Syntactic and Semantic.
Context Detection	Characterize the situation of an entity (person, place or object) relevant to the interaction between a user and an application, including the user and applications themselves.
Device discovery and management	Enables any device in the IoT network to detect all its neighbouring devices and make its presence known to each neighbour in the network.
Security and privacy	Data confidentiality - refers to protecting the data from any kind of unauthorised disclosure; Data integrity - refers to protecting data from being lost, destroyed, corrupted or modified; Data availability - refers to the ability to guarantee that the collected data can be used in dedicated time.
Managing Data Volume	Finding, fetching and transfer raw data in order to process and indexing it allowing a more efficient querying result.

To summarize, an IoT middleware is a true end-to-end platform that enables connectivity between "things" or devices constituted by eight architectural building blocks, as shown in Figure 5.



Database
Repository that stores the important data sets
External interfaces
APIs, SDKs and gateways that act as interfaces for 3rd party systems (e.g., ERP, CRM)
Analytics
Algorithms for advanced calculations and machine learning
Additional tools
Further development tools (e.g., app prototyping, access management, reporting)
Data visualization
Graphical depiction of (real-time) sensor data
Processing & action management
Rule engine that allows for (real-time) actions based on incoming sensor & device data
Device management
Backend tool for the management of device status, remote software deployment and updates
Connectivity & Normalization
Agents and libraries that ensure constant object connectivity and harmonized data formats

Figure 5 The eight components of an IoT Application Enablement Platform (Padraig Scully 2016)

2.1.3. Data Collection from Sensors – Context Acquisition

To understand the key considerations and challenges that data collection can bring, it is necessary to clarify the meaning of data sources. Sensors are hardware components that measure environmental information such as temperature, humidity, location, state of the machine, processing time and more that will be transformed into a digital signal. This information is accessed by software programs to help with some task (Microsoft 2016). In this way, an important consideration in a data collection system is the context-aware computing in IoT paradigm.

In the past, most of the proposed solutions collected data from a limited number of physical (hardware) and virtual (software) sensors. In these situations, collecting and analysing sensor data from all sources was made possible and feasible due to limited numbers. On the other hand, nowadays, with the progression in sensor hardware technology and cheap materials, sensors are expected to be attached to all the objects around us and connected to the internet, which means it is not feasible to process all the data collected by those sensors. Consequently, context-awareness will play a critical role in deciding what data needs to be processed, which implies that understanding sensor data is one of the main challenges that the IoT will face.

Context management has become an essential functionality in software systems. Data move from phase to phase, from the place where it is generated to where it is consumed, creating a data life cycle. Figure 6 consider the movement of context in context-aware systems.

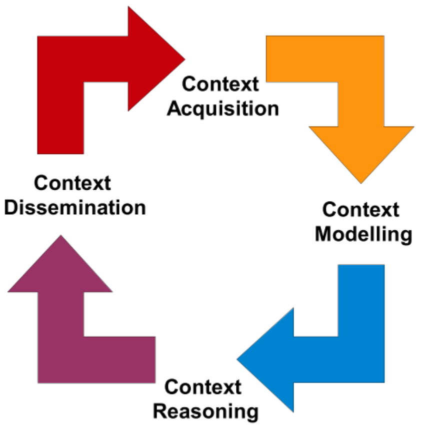


Figure 6 Four essential steps in context management systems and middleware solutions (Perera et al. 2014)

The definition of Context-Awareness is not strict due to its abstract nature. Different authors propose different definitions, notwithstanding, this thesis accepts the meaning proposed by Dey, due to the fact it is defined when it is applied in a system. Therefore, according with (Abowd et al. 1999): "A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task."

The focus that the concept context-aware will have in this thesis is related with context acquisition, since we are handling with pre-filtering data (Data Processing) and physical sensors (Data Source Support), as depicted in Figure 7.

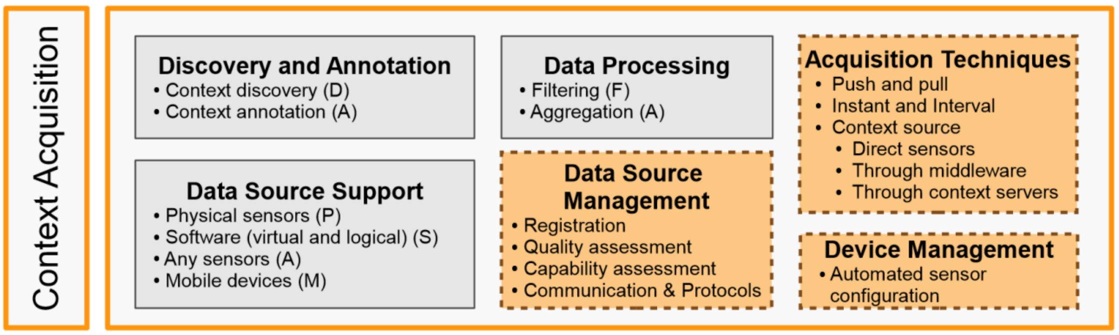


Figure 7 Conceptual Framework (features that need to be supported by ideal context-aware acquisition IoT middleware solution) (based on (Perera et al. 2014))

There are five techniques that need to be considered when we want to acquire context while developing context-aware middleware solutions:

Responsibility

According with (Pietschmann et al. 2008), there are two different methods:

- Pull - The software component which is responsible for acquiring sensor data from sensors make a request from the sensor hardware periodically or instantly to acquire data.
- Push - The physical or virtual sensor pushes data to the software component which is responsible to acquiring sensor data periodically or instantly.

Frequency

Making a parallelism with real world, the frequency technique is based on two different event types:

- Instant - The events do not span across certain amounts of time. Open a door, switch on a light are some types of instant events. In order to detect this type of event, sensor data needs to be acquired when the event occurs.
- Interval - These events span a certain period of time. For example, raining and seasons of the year are some interval events. In order to detect this type of event, sensor data needs to be acquired periodically.

Source

According with (Chen et al. 2004), acquiring information must have taken into account the source that can be categorized into three different categories:

- Directly from sensor hardware - Context is directly acquired from the sensor by communicating with the sensor hardware and related APIs. This method is typically used to retrieve data from sensors attached locally. Despite the growing use of devices that communicate wirelessly, in IoT paradigm, most devices and sensors today require some amount of driver support and can be connected via USB, COM, or serial ports.
- Through a middleware infrastructure - Sensor data is acquired by middleware solutions. The applications can retrieve sensor data from the middleware and not from the sensor hardware directly.

- Context servers - Context is acquired from several other context storages via different mechanisms such as web service calls. This mechanism is useful when the hosting device of the context-aware application has limited computing resources.

Sensor Types

There are different types of sensors that can be employed to acquire context and can be divided into three categories (Indulska & Sutton 2003):

- Software sensors – A web service is a perfect example of this type of sensor. The idea is to produce more meaningful information with the combination of physical sensors and virtual sensors.

- Virtual sensors – This type of sensors do not have a physical presence. They aggregate data from many sources and publish it as sensor data (e.g. calendar, contact number directory and chat applications).

- Physical sensors – Since IoT solutions needs to understand the physical world, this type of sensor is very important in data acquisition process due to the fact that is the only one that generate sensor data by themselves. For instance, measuring the temperature or humidity of a given space is made using temperature sensors or humidity, respectively. They are less meaningful, trivial, and vulnerable to small changes.

Acquisition Process

Finally, the acquisition process is a very important technique in the acquire context. In general, there are three different categories:

- Sense - The data is sensed through sensors (e.g. retrieve temperature from a sensor, retrieve appointments details from a calendar).

- Derive - The information is generated by performing computational operations on sensor data (e.g. calculate distance between two sensors using GPS coordinates).

- Manually provided - Users provide context information manually via predefined settings options such as preferences.

The main issue when we want to collect data is how to obtain it in a useful way. To do so, it is important to identify the key characteristics of data, knowing how to measure/collect them and what to do with the data collected. The overall objective of data collection is helping stakeholders of different levels to make decisions based on true indicators of real-time situations as depicted in Figure 8.

Data indicate that are a problem
This might have a problem

Figure 8 Difference between a good and a bad analysis of data collected

From the moment that data is sensed by devices such as a wireless sensor node, up to the moment that reach the backend system, there are many aspects that must be taken into consideration. In the future, IoT is expected to be an interconnection of networked embedded devices (Karnouskos et al. 2011) that will require to build systems with Cooperating Objects (CO). According to (Marrón et al. 2009), CO are computing devices with the ability to communicate, cooperate and organize themselves autonomously into networks to achieve a common task.

In conclusion, context is responsible for characterizing the situation of an entity, where an entity can be person, place, or object relevant to the interaction between a user and an application, including the user and applications themselves. IoT-middleware must be context aware for working into smart environments. Context awareness can be achieved by context detection and context processing. Context detection collects data and identifies the factors that have significant impacts on the response. Context processing extracts the context data, processes it and performs or takes decision based on that. A knowledge database is required for setting up a closed feedback path between these blocks to evaluate the effectiveness of context-aware systems and make some possible improvements.

However, this thesis proposes a middleware without persistent data storage. The knowledge of database is inexistent, so in this context, the data will go through, a pre-processing phase at the hub, before the main processing is made in the Cloud. Since, context-detection is a resource demanding task, the core implementation of this functionality is to be performed at the cloud (outside the scope of this thesis). But, preliminary context-detection can be implemented in the IoT-middleware that can be used for the data source identification, data type assertion and preliminary validation of the collected data based o on the sensor properties. These preliminary functionality of context-acquisition has been implemented in the scope of the thesis that can form a base for the development of context-aware applications.

2.1.4. IoT Protocols

Communication protocols are formal descriptions of digital message formats and defined rules that includes: packet size, transmission speed, handshaking and synchronization techniques, error correction types, address mapping, acknowledgment processes, flow control, packet sequence controls, routing and address formatting (Techopedia 2016b). They are implemented in hardware (communication protocols) and software (message protocols) and used to exchange messages between computing systems.

Messaging Protocols

In Internet of Things, the communication is made by three different computing systems:

- Device to Device – Example: DDS
- Device to Server – Examples: MQTT, REST/HTTP, XMPP, CoAP
- Server to Server – Example: AMQP

Each system has different types of protocols (with different message formats and defined rules) to interact. The examples given above are not restricted to the computing system which they belong, however, the protocols were grouped according the frequency of their utilization in the computing system. Considering that the concept of the middleware implemented in this thesis is based on the interaction between the device (sensors aggregated in a single device) and the cloud, this sub-section explains with more detail the software protocols of Device to Server system, resorting to examples which are summarized in Table 2. An example of the communication between the others computing a system is also included.

DDS - While interfacing with the IT infrastructure is supported, DDS's main purpose is to connect devices to other devices. As explained in (Esposito et al. 2008), architecture of DDS defines two layers: Data-Centric Publish-Subscribe (DCPS) and Data-Local Reconstruction Layer (DLRL). DCPS layer is responsible for delivering information to the end destinations (subscribers). DLRL represents, on the other hand, optional layer which serves as the bridge/interface to the DCPS functionalities (which is constituted by five entities to manage data flow: Publisher, Data Writer, Data Reader, Subscriber and Topic).

DDS can efficiently deliver millions of messages per second simultaneous to various receivers. Devices demand data very differently (faster) than the IT infrastructure demands data. "Real time" is often measured in microseconds. Devices need to communicate with many other devices in complex ways, so TCP’s simple and reliable point-to-point streams are far too restrictive. Instead, DDS offers detailed quality-of-service (QoS) control, multicast, configurable reliability, and pervasive redundancy. DDS offers powerful ways to filter and select exactly which data goes where, and “where” can be thousands of simultaneous destinations. DDS implements direct device-to-device “bus” communication with a relational data model.

MQTT – This protocol targets device data collection and communicating it to servers. As its name states, its main purpose is telemetry, or remote monitoring. Its goal is to collect data from many devices and transport that data to the IT infrastructure. It targets large networks of small devices that need to be monitored or controlled from the cloud. Since it has a clear, compelling single application, MQTT is simple, offering few control options. It also doesn’t need to be particularly fast. In this context, “real time” is typically measured in seconds. The protocol works on top of TCP, which provides a simple, reliable stream that don’t lose data.

MQTT consists of three key components: subscriber, publisher, and broker. An interested device can register as a *subscriber* for the specific content in order to be informed by the central point (*broker*) every time when a publisher disseminates information of interest (Locke 2010). In this architecture, the *publisher* stands for the meter/sensor sending data to MQTT broker. Secure communication between all parts is achieved by verifying the authorization of publishers and subscribers on the side of broker (Stanford-Clark & Truong 2013).
From the M2M communication point of view, the main disadvantage of MQTT is the fact that end devices may go to sleep state for a limited time period only (a lot of sensors/smart meters send the data once per few hours and therefore MQTT is not a suitable communication protocol for these power-constrained devices).

CoAP - In contrast to REST, CoAP is utilizing lightweight UDP as transport protocol, making it more suitable for the IoT domain because it is possible to build sufficiently basic error checking and verification for UDP to make sure that messages arrived without the significant communication overhead in case of TCP. However, CoAP was designed together with REST functionality; therefore, conversion between these two protocols has to be implemented in communication chain.

According with (Gligoric et al. 2012), CoAP can be divided into two sublayers:

- Messaging Sublayer - It detects duplications and based on that provides reliable communication even over the UDP transport protocol using the exponential backoff (multiplicative decrease of the rate of data transmission, in order to gradually establish an acceptable data rate); this is a necessary technique since UDP does not include error recovery mechanism;

- Request/Response Sublayer - It handles REST communication between individual nodes. This protocol utilizes four message types: confirmable, non-confirmable, reset, and acknowledgment. Reliability of CoAP is achieved by using confirmable and non-confirmable messages. Similarly, HTTP utilizes methods such as GET, PUT, POST, and DELETE to perform Create, Retrieve, Update, and Delete operations. A typical length of CoAP message can vary between 10 and 20 bytes (Colitti et al. 2011), this means that CoAP may be unsuitable for some domains of IoT.

REST/HTTP – This protocol follows the principal that every physical object and/or logical entity is a resource that has a particular state that can be "manipulated". A resource that is accessible via HTTP URI gives access to its data via GET and accepts inputs via PUT. REST aims on minimizing latency and network communication, while at the same time maximizing the independence and scalability of component implementations (Fielding & Taylor 2002). The effort needed to develop applications, especially in the IoT domain, can be greatly reduced since REST adopts a much lighter tool chain than other service oriented architectures, making this message protocol massively scalable, as explained in "M2M Communications: A Systems Approach" by D. Boswarthick, O.Elloumi and O. Hersent, Wiley, 2012. Data communication is generally initiated by the Device over HTTP GET/POST Request. Devices will be sleeping all the time unless during communication.

It is a good option for IoT device (data source) to IoT middleware to communicate in the local network. In order for IoT devices and IoT middleware to communicate via HTTP, we need to resolve some issues. The solemn problem that one need to work around is that HTTP is a challenge-response protocol. This means the device will either have to keep polling the server for new updates, or use long polling, or use websocket. The cost of communication has dipped significantly so the overheads attached to HTTP don't pose a significant constraint since Transport Layer Security [TLS] can be obtained through HTTPS. In the scope of this thesis, HTTP/REST has been identified as a very useful protocol for communication between the IoT middleware and data consumers but not a very suitable protocol for communication between devices and middleware.

XMPP - A protocol suited to connect devices to people, a special case of the D2S pattern. It was developed for instant messaging to connect people via text messages. XMPP uses the XML text format as its native type, making person-to-person communications natural. It connects clients and servers using the XML called *stanza* which divide the code into three components: message, presence and info/query (Jones 2009). Messages in *stanza* identify the source and destination address, types, and IDs of XMPP entities that provide PUSH method for retrieving data. The presence *stanza* notifies end users of the status updates. Finally, the iq *stanza* does the pairing between message senders and receivers. The possible disadvantage of XMPP is text-based communication using XML. This leads to higher network load (overhead). Ergo there is a possible solution to this problem: XML streams using EXI (Waher & Doi 2014).

In the IoT context, XMPP offers an easy way to address a device. This comes especially handy if that data is going between distant, mostly unrelated points, just like the person-to-person case. It's not designed to be fast. In fact, most implementations use polling, or checking for updates only on demand. "Real time" to XMPP is on human scales, measured in seconds. Its strengths in addressing security, and scalability make it ideal for consumer-oriented IoT applications.

AMQP - A queuing system designed to connect servers to each other. Communications from the publishers to exchanges and from queues to subscribers use TCP, which provides strictly reliable point-to-point connection. AMQP is realized by two key components (Fernandes et al. 2013):

- Exchanges: They are used for routing messages to appropriate queues. Routing (between exchanges and queues) is based on predefined rules/requirements;
- Message Queues: They are stored in message queues before sending to end destination (receiver).

Following that, two types of messages are defined in AMQP, bare messages (at the sender's side, includes properties, application properties and application data) and annotated messages (at the receiver side, includes header, delivery and message annotations, footer and the bare message information).

AMQP is mostly used in business messaging because it focuses in tracking all messages and ensuring each is delivered as intended, regardless of failures or reboots. It usually defines "devices" as mobile handsets communicating with back-office data centers. In the IoT context, AMQP is most appropriate for the control plane or server-based analysis functions.

To sum up, is presented in Table 2, a comparison between the four messaging protocols used in device-server communication.

Table 2 IoT D2S Protocol Landscape (Duffy 2013)

PROTOCOL	CoAP	XMPP	REST/HTTP	MQTT
TRANSPORT	UDP	TCP	TCP	TCP
MESSAGING	Request/ Response	Publish/Subscribe Request/Response	Request/ Response	Publish/Subscribe Request/Response
2G,3G,4G SUITABILITY (1000S NODES)	Excellent	Excellent	Excellent	Excellent
LLN SUITABILITY (1000S NODES)	Fair	Fair	Fair	Fair
COMPUTE RESOURCES	10Ks RAM/Flash	10Ks RAM/Flash	10Ks RAM/Flash	10Ks RAM/Flash

Communication Protocols

Wireless communication protocols can be classified according to the following 6 standards:

Satellite – This type of communications enables cell phone communication from a phone to the next antenna. In Internet of Things language, this form of communication is mostly referred to as “M2M” (Machine-to-Machine) because it allows devices such as a phone to send and receive data through the cell network. Satellite is useful for communication that utilize low data volumes, mainly industrial purposes.

WiFi - Is a wireless local area network (WLAN) that utilizes the IEEE 802.11 standard through 2.4GhZ UHF and 5GhZ ISM frequencies. Provides Internet access to devices that are within the range. In IoT systems is widely used for this advantages in security and integrity, flexibility, IP-based communication and scalability massive deployments.

Bluetooth - The technology is extremely useful when transferring information between two or more devices that are near each other in low-bandwidth situations. Bluetooth protocols simplify the discovery and setup of services between devices, they can advertise all of the services they provide, making their use easier, because it enables greater automations such as security, network address and permission configuration.

Radio Frequency communications are probably the easiest form of communications between devices. Protocols like **ZigBee** or **ZWave** use a low-power RF radio embedded or retrofitted into electronic devices and systems. In IoT systems this type of communication has significant advantages in low-power operation, high security and scalability.

RFID is the wireless use of electromagnetic fields to identify objects. Usually is installed an active reader, or reading tags that contain a stored information mostly authentication replies. It is also called an Active Reader Passive Tag (ARPT) system. An Active Reader Active Tag (ARAT) system uses active tags awoken with an interrogator signal from the active reader. The main advantage is the hundreds of applications which can be used.

NFC uses electromagnetic induction between two loop antennas located within each other near field, effectively forming an air-core transformer. There are two modes: Passive - The initiator device provides a carrier field and the target device answers by modulating the existing field. In this mode, the target device may draw its operating power from the initiator-provided electromagnetic field, thus making the target device a transponder; Active - Both initiator and target device communicate by alternately generating their own fields. A device deactivates its RF field while it is waiting for data. In this mode, both devices typically have power supplies. The main advantages are related with data security at multiple levels, the ability to connect the unconnected, easy network access and data sharing.

2.1.5. Data Pre-processing

Data pre-processing is often neglected but important step in the data collection process. If there is irrelevant and redundant information present or noisy and unreliable data then events and trends detection at application layer is made more difficult. This process also includes a technique that involves transforming raw data into an understandable format (the format can be defined by the hub or requesting data consumer). Real-world data is often incomplete, inconsistent, and/or lacking in certain behaviours or trends, and is likely to contain many errors (Techopedia 2016a).

In a real world data analytics situation, it is common to find several data pre-processing steps before using them in the application layer, mainly due to varying nature of the available data. The methodology for data pre-processing has been widely adapted in the domain of data mining, which can provide important background for data filtering in IoT scenario. In chapter 3 of (J.Han, J.Pei, M.Kamber 2012), is a detailed description of the steps that could be done prior to the main processing in order to have a better data quality which is defined in terms of accuracy, completeness, consistency, timeliness, believability and interpretability. The main steps and techniques are:

Data Cleaning – This method works to "clean" the data by filling in missing values, smoothing noisy data, identifying or removing outliers and resolving inconsistencies. Each step has its own methods:

Missing values – If it is noted that there are many tuples that have not recorded value for several attributes, then the missing values can be filled in for the attribute by various techniques:

- Ignore the tuple – This is usually done when the class label is missing. However, it is poor technique when the percentage of missing value per attribute varies considerably.
- Fill in the missing value manually – In general, this approach is time-consuming and may not be feasible given a large data set with many missing values.
- Use a global constant to fill in the missing values – It is a simple technique that replace all the missing attribute values by the same constant.
- Use the most probable value to fill in the missing value – This may be determined with inference-based tools using a Bayesian formalism or decision tree induction.

Noisy Data – It is a random error or variance in a measured variable and it is resolved with some data smoothing techniques:

- Binning methods – Smooth a sorted data value by consulting the values around it, performing a local smoothing.
- Clustering – Similar values are organized into groups or clusters
- Combined computer and human inspection – Outliers may be identified through a combination of computer and human inspection. Patterns whose surprise content is above a threshold are output to a list. A human can then sort through the patterns in the list to identify the actual garbage ones. This is faster than having to manually search through the entire database.

- Regression – Involves finding the best line to fit two variables, so that one variable can be used to predict the other. Using regression to find a mathematical equation to fit the data helps smooth out the noise.

Inconsistent Data – In some transactions of data inconsistencies might occur that could be corrected manually using external references. For example, known functional dependencies between attributes can be used to find values contradicting the functional constraints.

Data Integration – Involves combining data from multiple sources into a coherent data store as in data warehousing. This type of method requires an entity identification of each device, before the integration of data, in order to know the data source and henceforth determination of the nature of the data. Typically, databases have metadata (data about the data) that can be used to help avoid errors in this step.

Data Transformation - This method involves consolidate appropriate data for mining. It can involve four techniques:

- Normalization – The attribute data are scaled so as to fall within a small specified range.
- Smoothing – Remove noise from data by clustering, binning or regression.
- Aggregation – Aggregated operations are applied to the data in order to construct a data cube for analysis of the data at multiple granularities.
- Concept hierarchy generation – Low level data (raw) is replaced by higher level concepts through the use of concept hierarchies. Examples: transforming an integer that refers to someone's age into an attribute like young, middle-aged or senior; transforming the name of a street in a city or a country.

Data Reduction – It is used to make the data analysis less complex and feasible in terms of time. This method has been helpful in analysing reduced representation of the dataset without compromising the integrity of the original data and yet producing the quality knowledge. The main strategies of this pre-processing method are:

- Aggregation – Similar to the aggregation technique of data transformation
- Dimension reduction – Removed the amount of data if there are irrelevant, weakly relevant or redundant attributes.

- Data Compression – Encoding mechanisms are used to reduce the data set size.
- Numerosity reduction - Smaller data representations by histograms, sampling or other parametric models reducing the amount of data values.
- Concept hierarchy generation - Similar to the aggregation technique of data transformation

To sum-up, data pre-processing refers to the cleansing and transformation of the data in the early stage of data collection and before being pushed towards the data consumers and/or persistence storage. In an IoT scenario, it is a key functionality to guarantee the reliability of the data being collected. At the same time devices can generate huge amount of data to be processed, so applying techniques to process only key data, will allow the system to improve one's efficiency and performance. Those techniques are introduced by the definition of a set of rules, generally done by a user with administrative role.

2.2. IoT Deployment Scenarios

The growing popularity of the Internet and the availability of powerful computers and high-speed networks as low-cost commodity components are changing the way we do computing. This section describes the four possible deployment scenarios in IoT architecture for data collection and their different applications in different purposes and domains.

In presenting the deployment scenarios, different considerations are made in the way data sources and data consumers are integrated to form an IoT ecosystem. Firstly, is presented the peer-to-peer model, which considers building the network among different data sources and consumers with their own communication infrastructure. While, the others deployment models make use of external communication (and/or processing) infrastructure such as cloud to form the overall IoT ecosystem. Among these the first one is an architecture that lacks middleware and each of the data sources utilize their own communication resources and other higher level intelligence such as storage, processing, interoperability, etc. are all in the cloud. Subsequently, it is shown two types of architectures that use software abstraction layer - middleware - between devices and the cloud in different ways. In the first approach, the data collection system has several middleware that share various types of processing capacity, so that in the final process, the system achieves a particular purpose. In the second approach, corresponding to the architecture implemented in this thesis, each system has a middleware that has all the features that are required without being dependent on others.

2.2.1. Peer-to-Peer Devices

In general, in a P2P system every node acts as both a client and a server, providing part of the system resources, in a non-hierarchical scenario. This means that no master-slave relationship exists among the peers, and there is no central server responsible to store and administrate exists because there does not exist any peer machine with a global view of P2P system. However, with the advances in peer-to-peer technology began to appear slightly different architectures of traditional, as depicted in Figure 9. The complexity is not in the machine (simply client computers connected to the Internet) nor in the communication since all machines act autonomously to join or leave system freely (Kahanwal & Pal Singh 2012), so the main issue is in the architecture of the distributed control system, which can be structured or unstructured (Doulkeridis et al. 2007):

- Structured – A hash function is used in order to couple keys with objects. Then a distributed hash table (DHT) is used to route key-based queries efficiently to peers that hold the relevant objects. In this way object access is guaranteed within a bounded number of hops.
- Unstructured - Each peer maintains a limited number of connections (also called links) to other neighbouring peers in the network. Searching in an unstructured P2P environment usually leads to either flooding queries in the network using a time-to-live (TTL) or query forwarding based on constructed routing indices that give a direction for the search.

Hybrid Peer-to-Peer System

The major shortcoming of purely peer-to-peer systems is scalability issues and the poor performance during query processing. Therefore, except of purely decentralized architectures, also hybrid systems were proposed which can be divided into (Doulkeridis et al. 2007):

- Centralized indexing systems - there is a central server facilitating the interaction between peers and a centralized index is built at this specialized peer. The centralized index keeps information about the data stored at each peer, together with the peer identifier. Therefore, centralized indices are efficient during query processing; a single message is required to determine which peer stores relevant information. Notice that the actual sharing of information between peers is established by communication between the peers, without interaction with the central server. Despite the efficiency during query processing, centralized indices have a major drawback, namely they constitute a" single point of failure". Moreover, the centralized index may become a bottleneck for the system, especially in the case of a large P2P network.

- Decentralized indexing systems – Also known by Superpeers, this architecture tackle the scaling and the "single-point-of-failure" problems of centralized approaches, while exploiting the advantages of the completely distributed approach, where each peer builds and maintains an index over its own files. These systems are similar to purely decentralized systems (if only the Superpeers are considered), but some of the peers have a more important role, and are responsible to maintain the information available at their associated peers and facilitate the interaction between peers. Super-peer networks take advantage of the heterogeneity of peer capabilities (e.g., bandwidth, processing power) and peer application in a P2P network, once can have different roles by nature, similar to the case of file-sharing, where some machines are registered as dedicated servers to the system, while others are plain personal computers that mostly request information. Furthermore, in order to respect peers' autonomy, any approach should not rely on arbitrary data movement; hence each peer joining the network should autonomously store its own data. Therefore, super-peer architecture appears particularly suitable for applications that require efficient performance for advanced query operators; hence we model our distributed system as a super-peer network. The overall objective is for a set of cooperative computers to collectively provide enhanced processing facilities, aiming at overcoming the limitations of centralized settings, for example extremely high computational and storage load.

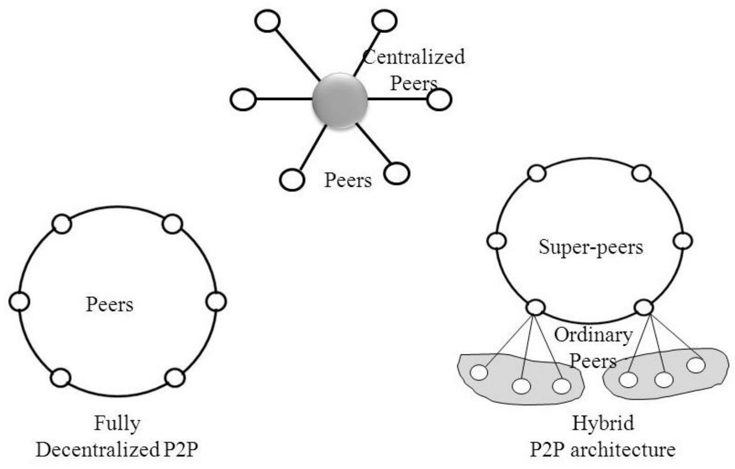


Figure 9 Three different approaches in an IoT Peer-to-Peer scenario (Hota 2013)

2.2.2. Devices to Service Providers

In this type of scenario, there is a direct interaction between the sensor nodes and application layer. Without using intermediary devices that regulate, transform or interpret the data before integration into the business processes. The main objective of this class of data collection system is, in general, focus data intelligence in a single infrastructure using “dumb” sensors, constituted only by a layer hardware responsible between the communication of devices and the provided services.

Making an analogy to the distributed computing systems, this scenario is similar to the idea of cloud computing in IoT systems which is explained carefully and detailed in (Buyya et al. 2011). The aim of this scenario is to concentrate computation and storage in large-scale data centres by transforming everything as a service, such as hardware virtualization (decouples applications from the underlying hardware) which mediate access between the physical resources and the software layer as highlighted in Figure 10. The biggest advantage is the independence that virtual resources have from each other and from the physical hardware (for instance, in case of failure or capacity constraints), creating an abstract architecture easy to access for the consumer.

Figure 10 Data flow between devices and Cloud (Brown 2014)

This data centre infrastructure can be shared by several customers without compromising the privacy and security of each one, providing a pool of computing resources to serve multiple consumers using a multi-tenant model as illustrated in Figure 11. The idea is to provide to the customers the capability of request, customize, pay and use services (which are available over the network and accessed through standard mechanisms by different platforms such as laptops and mobile phones), automatically, without requiring interaction with providers or any intervention of human operators (Mell et al. 2009). Although, the access of shared services is cost-effective, it causes performance degradation and performance unpredictability. To close this gap, it is possible to make this architecture auto scaling. In case of peak demand more virtual machines can be quickly provisioned (on two or more physical machines) or rapidly released when the work load decreases.

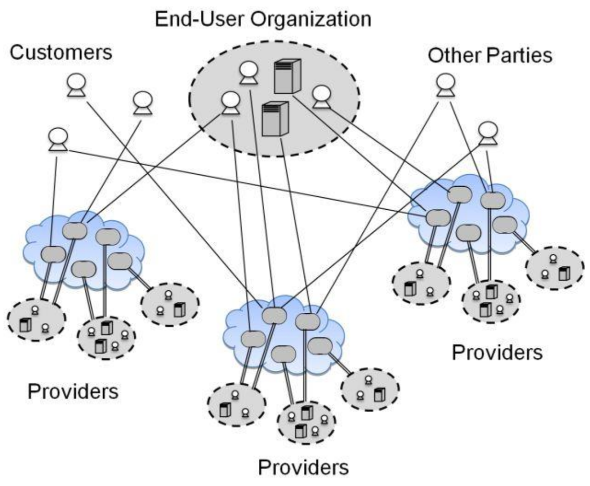


Figure 11 Interaction between the end-user and Cloud software services (TheOpenGroup 2013)

This system brings many advantages to IT companies, is based on the concept of utility computing where consumers pay-per-use computing services (Gong et al. 2010), allowing to deploy specialized virtual appliances in order to consider the great disparity between user needs in a multi-tenant environment, similar to what is being done for utilities such as Electricity, Gas, Water and Telecommunication. Furthermore, Cloud Computing brought cost savings for consumers (eliminating the total cost of the entire infrastructure by sharing the cost of electricity, hardware engineers, facilities management, system administration, fire protection, insurance, etc) (Buyya et al. 2011).

2.2.3. Devices to Middleware to Service Providers

In computer systems distributed in IoT, this scenario has emerged in parallel with the concept of Fog Computing. The aim of this architecture is to face the massive quantities of information at any time, in any place and with any device that is extremely dispersed and produced by and about people, things, and their interactions (Hajibaba & Gorgin 2014). In fact, big data, real time analytics and localization was the main reasons to businesses requiring a new approach to distribute all data and place it closer to the end-user, eliminate service latency, improve QoS and remove other possible obstacles connected with data transfer (Aazam & Huh 2015). Figure 12 shows an example of an IoT architecture divided by layers whose middleware corresponds to the gateway layer.

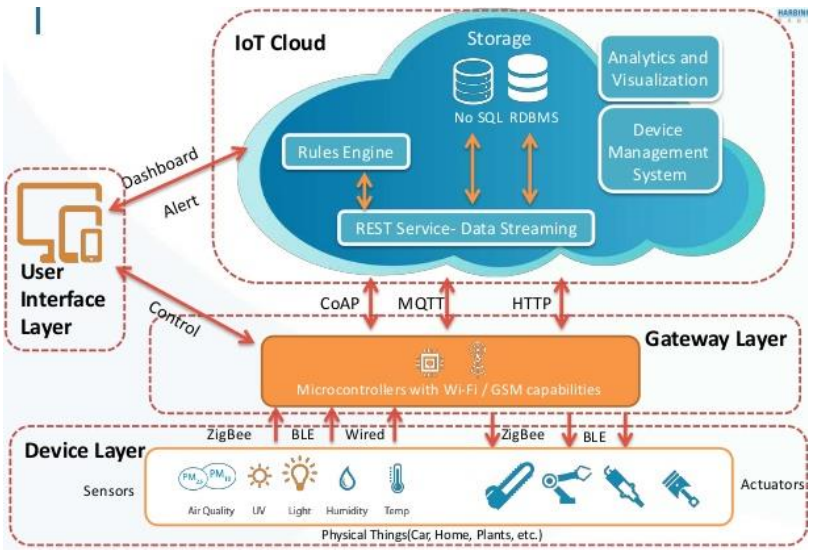


Figure 12 Example of an IoT Architecture with middleware (Harbinger Systems 2015)

The purpose of a middleware in a data collection system is not to remove some features of service providers, but to add more functionality to reduce the complexity of some of those services in order to reduce the amount of time, processing or storage in the Cloud. Middleware is software that provides services to software applications beyond those available from the

Cloud providing common programming abstraction and infrastructure for distributed applications. In generally, The Fog is located bellow the Cloud and his purpose is targets the services, compute, storage, workloads, applications and big data with widely and truly distributed systems (Aazam & Huh 2014).

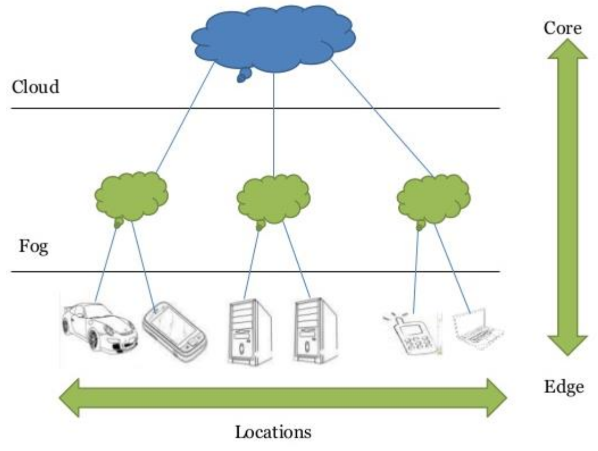


Figure 13 Fog between the edge and the cloud (Amaravadhi 2015)

As depicted in Figure 13, it is an additional layer which develops the concept of Cloud services bringing network resources near underlying networks (Hajibaba & Gorgin 2014; Aazam & Huh 2014). Services are hosted at the network edge or even end devices such as set-top-boxes or access points in order to enabling creation of refined, better and optimize applications or services. The creation of various edge points is turning data centre into a distributed Cloud platform for different types of users, bringing the computing from the core to the edge (Hajibaba & Gorgin 2014).

With the rise of interconnected devices and business scenarios around networked machines, the infrastructure to maintain all things connected is being more complex. The aim of this scenario is to have hierarchical organization from the core to the edges to support low latency and scalability. This “extra layer” has more proximity of the data to the consumer extending the Cloud services closer to mobile users (Bonomi et al. 2012). Another important characteristic is the dense geographical distribution which is the reason of existing a large number of nodes, that allows better support for location-based services as well as faster analysis of data in real-time (Buest 2013). Associated to the large number of nodes with a wide variety of environments appears the interoperability problem once the heterogeneity of devices at different levels require certain services and applications provided by this scenario. Besides that, middleware is used to be reliable and available, reducing application development and maintenance efforts and also to provide a distributed computing.

Centralized or Distributed Middleware

In contrast of Cloud's centralization, a middleware (layer located in the fog or local infrastructure) provides localization, once the server belongs to the same network as the end-users and have knowledge of each one becoming that information an advantage to customize the optimization (Zhu et al. 2013). This scenario supports better real-time interactions, actionable analytics, processing and filtering data by services implemented in the middleware, and then pushes to the Cloud. In this way, user data is isolated from the Cloud and from there administrators are able to tie-in analytics, security or other services directly into their cloud model (Kleyman 2013).

The main difference between a centralized and a distributed middleware is the services provided by them. In a decentralized system, the idea of having multiple middleware with different kinds of capabilities (data filtering, complex event processing, secure data validation and trust mechanism) is much more appreciate in terms of complexity and scalability. Moreover, the functionalities and heterogeneity of the devices connected in the system could be enormous, therefore, with this scenario it is possible to minimize the processing of a middleware once it will be used only for the devices that require that particular service. However, in a centralized IoT system that intends to have a specific purpose, a single middleware could be a better solution once their variety of applications could be work together without losing functionality.

Depending on the purpose that an IoT system has, different solutions could be better than others. Both of the sub-scenarios (single and distributed middleware) are being discussed in this sub-chapter have the same goal:

- Hide the heterogeneity of the shop floor resources;
- Provide an independence location of the resources;
- Help integrate legacy facilities;
- Aggregate common functionalities needed by many applications.

Although they have the same objective, their use depends mainly to:

- The use that devices give of the applications presents in the hub;
- The processing capacity where the hub is implemented;

- The complexity and scalability that we want to implement in the system, having in consideration further modifications.

In Figure 14 is illustrated both scenarios where in middleware 1 has data filtering capability, while middleware 2 has capability for complex event processing and middleware 3 has secure data validation and trust mechanism, and the functionalities are distributed among middleware to achieve an overall full functional system. On the other hand, a single middleware is independent from each other and every necessary functionality needs to be implemented in each of them.

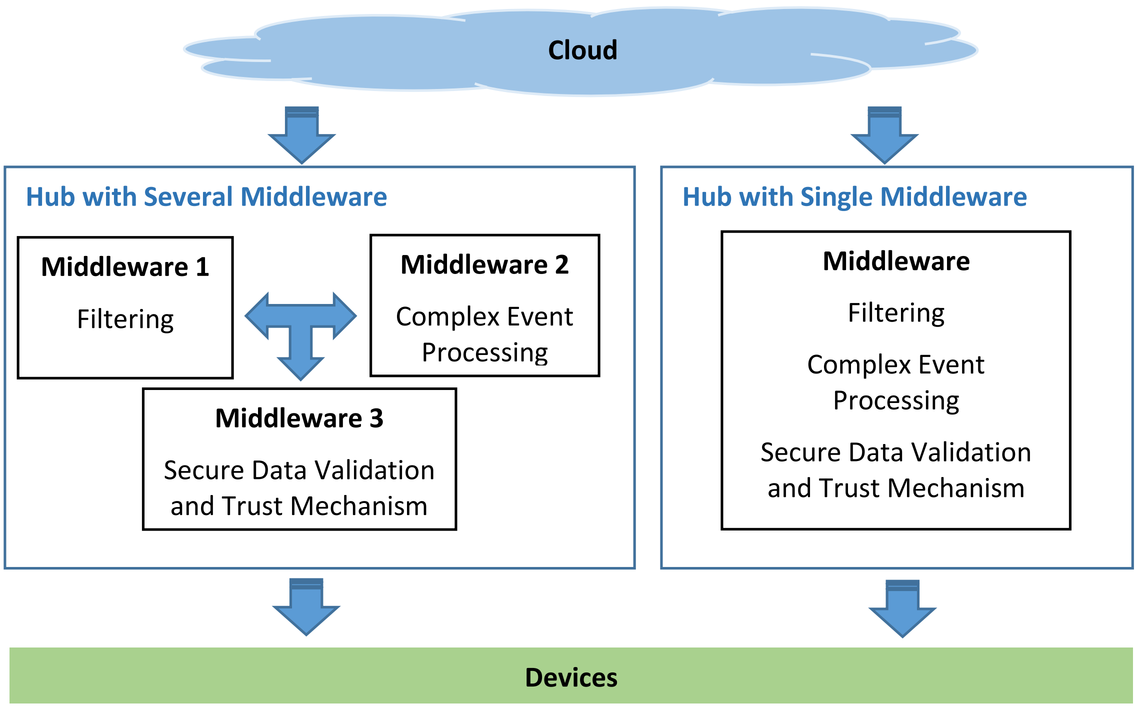

Cloud
Hub with Several Middleware
Middleware 1
Filtering
Middleware 2
Complex Event Processing
Middleware 3
Secure Data Validation and Trust Mechanism
Hub with Single Middleware
Middleware
Filtering
Complex Event Processing
Secure Data Validation and Trust Mechanism
Devices

Figure 14 IoT middleware for data collection - Single or Distributed

2.3. Middleware Solutions for Internet of Things

As the IoT encompass a wide area of applications, middleware layers also have different domains which might be covered and will be explained in the first sub-section. Subsequently, the current solutions in the context of IoT will be presented. Finally, an analysis on the major challenges in implementing middleware systems assessing their strengths and weaknesses is explained.

2.3.1. Domain

The middleware solutions can be categorized according to the involved domains into three major categories (Chaqfeh & Mohamed 2012):

Semantic Web and Web Services

The main goal of semantic web is to make information understandable by machines, or things, so that machines can perform intelligent tasks based on the meaning of information. This also enables interoperability across semantic layer between devices and information. Furthermore, semantic web solutions can provide context awareness applications where the search space for the automatic discovery and service composition is reduced (Gomez-Goiri & Lopez-de-Ipina 2010). In addition, the semantic information supports better understanding to users, improving their privacy decisions since they can compose numerous services.

RFID and Sensor Networks

A significant part of the IoT will be the sensor networks, since these devices can measure and detect different types of environmental information by monitoring the physical world. Intelligent context-aware networking is rapidly approaching the position of seamless networking systems, where development of tiny sensors and actuators can easily perform in social support services, including earthquake warnings, sensitive support to the emergency context and patient monitoring and in large factory environments, smart houses and offices and automotive networks. (Luckenbach et al. 2005).

Robotics

In general, the recent middleware systems does not lead to an evolution of a standardized middleware for pervasive computing or intelligent environments (Roalter et al. 2010). In fact, it is more challenging to provide such an interaction in the robotics domain, because moderate to high mobility devices are not often considered. In addition, a fixed infrastructure is usually assumed to construct an intelligent environment such as smart homes and cognitive offices.

2.3.2. Approach

A middleware platform for the IoT can have a multitude of functions, so a single solution that can adapt all environments will probably not exist. In this perspective, different solutions have emerged, such as:

Triple space-based

A triple space-based distributed middleware for the IoT is a semantic data, expressed by the three items (the subject, predicate and object) defined in the Resource Description Framework

(RDF). Who registers the serviced in the assumed space is the service provider, while the creation of an invocation and its advertisement is done by the consumer. Lastly, the service provider will recognize a new event and retrieve the input data from the consumer and perform the desired service (Gomez-Goiri & Lopez-de-Ipina 2010).

This particular approach aims to improve existing middleware triple space that already exists so as to make it suitable for the IoT in order to enable the embedded and mobile devices to perform this middleware. However, there are certain devices that cannot be part of the semantic network took Peer-to- Peer, since it does not have the ability to implement the proposals primitive, which could allow management services and complex queries. Importantly, in this latter context, both the utility of the proposed middleware and the resulting applications are limited. Even so, the triple space approach seems to perfectly fit the IoT environment, where several objects are connected to each other so as to share semantic knowledge and interact.

Test Computing Framework

The solution previously presented, is an extension of Test Computing Framework, which focuses on the interoperability of the semantic layer by following three steps. Firstly, semantic services are generated according to the various devices discovered by the middleware. Then, users are enabled to build tasks as service compositions using a semantic user interface. Lastly, the task (which is a workflow of services) is completed by executing the devices. This approach has the advantages of semantic web approaches such as meaningful information to users, context awareness to applications and interoperability.

UBIWARE

UBIWARE is conjectured to provide support services in collaboration with heterogeneous resources and semantic communication services. In (Katasonov et al. 2008), this solution will enabling different components to configure complex functionalities based on the agent technology and to automatically discover each other. The advantages of this solution undergo:

- Service discovery in a decentralized manner;
- Negotiation-based integration of services;
- Possibility to allow the mobility of services between different platforms;
- Utilization of suitable communication protocols.

Furthermore, interoperability is also possible using metadata and ontologies. The agent is responsible for making decisions, discovering the requests, requesting external help when needed and monitoring the state of the resource. An adapter or interface is used to connect the application with its software agent and may include semantic and adapter components, sensors and actuators, and data structures, as required.

The main issues that must be solved in UBIWARE are (Katasonov et al. 2008):

- The representation of mechanisms for the distributed resource histories;
- Design of the agent platform;
- Configurability and security;
- Techniques for information sharing among agents;
- Automatic discovery of other resources in a peer-to-peer fashion.

SOA approach

Service Oriented Architecture (SOA) as the approaches proposed in (Spiess et al. 2009), are the basis of promising middleware solution, in which each device provides its functionality as standard services, while the discovery and invocation of new features can run simultaneously. The advantages of vertical SOA-based integration undergo reduced the effort and cost required for the recognition of new business scenarios since no device drivers or third-party solutions are required. The proposed architecture supports open and standardized communication through different services for service management, device management, application interface, security, devices layer and platform abstraction.

SOA may offer a promising approach, since it is expected that millions of devices interconnect and cooperate in order to provide and consume services. This solution states that each device provides a co default set of services and which is capable of services from other devices in consumer demand.

Global Sensor Networks

Global Sensor Networks (GSN) is another solution. The architecture of GSN follows a container-based model, in which each container hosts and manages a number of virtual sensors simultaneously, that is able to communicate with each other in a peer-to-peer fashion. The identification and the discovery of virtual sensors are made through metadata (Aberer et al. 2006). On one hand the design of the GSN (Aberer et al. 2006) provides four main advantages: scalability, adaptively, light-weight implementation and simplicity. On the other hand, it also presents three major disadvantages:

- Transducer Electronic Data Sheet (TEDS) provides only the information necessary for the interaction with the sensor, not dealing with storage, resource management and security;
- The requirement of human intervention;
- It is assumed an IEEE 1451 compliant sensor, which provides a Transducer Electronic Data Sheet TEDS that is stored inside the sensor to provide a simple semantic description of its properties and measurements.

Fosstrak

This middleware solution is a project based on open source RFID platform (Fosstrak 2009), that is focused on the management of RFID related applications. In (Schmidt et al. 2009), the authors propose a general Tag Data Translation (TDT) system that extends the standard of EPCGlobal which only targets Electronic Product Code (EPC).

The objective of this system is to provide advanced data translation techniques by integrating a set of existing technologies for identifying items. The significant advantage of such a system is that it can offer a way to design a unified architecture of RFID middleware for the IoT encompassing existing useful standards. Nevertheless, integrating more standards is still required to conform to the system objective.

TinyREST

TinyREST focus on how sensor networks can be integrated with the Internet through a framework (Luckenbach et al. 2005). It is a sensor-enhanced middleware for Internet-based access to different types of sensors and actuators that may support different application domains. This approach has the advantage of conforming to the most widespread internet HTTP standard, in addition to enhancing human-device interaction.

This solution moves a step forward to the full integration into the smart environments test bed, by proving its concepts in home automation and facility management. However, further steps are required for the development of application scenarios to make use of the proposed Internet-integrated sensor network environment.

Robotic-based

The potential of a robotic-based middleware for distributed, heterogeneous, sensor-actuator-based, communicating intelligent environments and the IoT is enormous (Roalter et al. 2010). A successful application based on two existing middleware architectures from the robotic domain are: Play/Stage (Collett et al. 2005) and Robotic Operating System (ROS) (Quigley et al. 2009).

2.3.3. Synthesis

The technical challenges of designing middleware systems for the IoT include interoperability, scalability, abstraction, spontaneous interaction, unfixed infrastructure, multiplicity, security and privacy. Table 3 (Chaqfeh & Mohamed 2012) show the highlighting list of challenges considered.

Table 3 Challenges in middleware approaches for IoT

Domain		Semantic web and web services				Sensor Networks and			Robotics
Approach		Task Computing Framework	Triple space-based	UBIWARE	SOA Approach	GSN	Fosstrak	TinyREST	Robotic-based
Interoperability		●	●	●	●	●		●	●
Scalability				●	●	●	●	●	
Abstraction	I/O hardware devices		●	●	●			●	●
	H/S Interfaces			●	●				●
	Data Streams and Physicality	●	●	●	●	●	●	●	●
	Development Process			●	●	●	●		
Spontaneous Interaction			●	●	●	●	●	●	
Unfixed Infrastructure		●	●	●	●	●	●	●	
Multiplicity		●	●	●	●	●	●	●	
Security and Privacy			●		●	●			●

3. Hub Architecture

This chapter presents the concept of the middleware that has been developed in this dissertation. In the first section is presented an overview of the architecture. In the following sections is presented the details of the concepts that have played vital role in the implementation phase. Finally, application scenario is presented, which presents a vision for the application of the middleware solution utilizing different types of sensors that have been considered during the experimentation of the implemented solution.

3.1. Overview

In an industrial IoT scenario, there are many sensors and actuators that interact with the machinery. Each sensor and actuator is attached to a microcontroller that is responsible for acquiring the data or controlling a switch through a pre-defined instruction set. The microcontroller — along with the sensors, power unit and a radio antenna — is called a sensor node. It is a self-contained, deployable unit that captures the data generated by sensors.

In general, the sensor node does not have enough processing power, memory, and storage to deal with the data locally as the case of the microcontroller used in this thesis. So, it's necessary to communicate with devices capable to deal with that. In this dissertation the device chosen to implement the hub was a Raspberry Pi that acts as an aggregator of multiple raw datasets generated by the sensor nodes.

This IoT framework has the capability to deal with two major problems:

- To transform and normalize the data. The datasets generated by the sensor nodes will be in disparate formats. The gateway acquires heterogeneous datasets from multiple sensor nodes and converts them to a standard format that is understood by the next stage of the data processing pipeline.
- Protocol transformation. It supports multiple communication protocols for accepting the inbound data sent by the sensor nodes. It uses a REST service for the outbound communication, sending the data to a process running in the cloud.

The framework for IoT-based continuous data collection from supply network resources includes a methodology and set of tools capable of collecting and pre-processing data from different sources and push them towards the cloud service i.e. Data Collection Framework (DCF). All the data consumers then can uniformly access the data through the APIs provided by DCF, without having to understand the details of the data sources. The architecture developed took account the scalability, interoperability, adaptation and plug-and-play functionality between the sources and the hub. The *Figure 15* illustrates the IoT framework architecture.

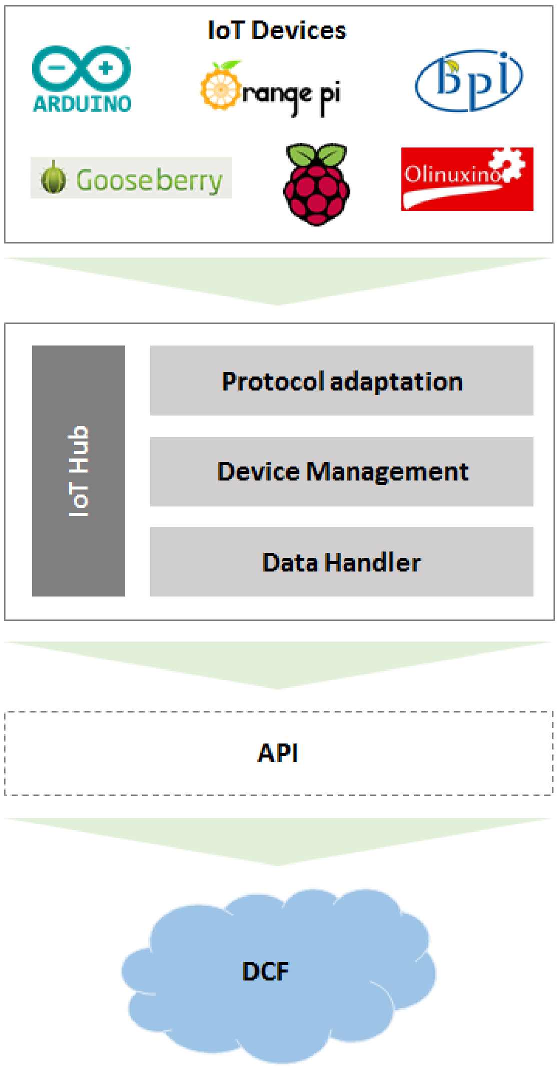


Figure 15 IoT Middleware Information Flow

In general, the three main components of IoT hub shown in Figure 15, have different purposes that could be briefly distinguished:

Protocol Adaptation - This component is responsible for providing seamless communication between IoT devices located at shop floor and other components of IoT hub. The main functionality to be provided by this component is to allow connectivity for various devices with different communication standards and request/response paradigm for devices integration into the IoT hub. Major functionalities provided by the communication component are:

- Provide an interface for communication with the IoT devices;
- Creation and management of necessary communication channels (together with device management component) and provide message routing when necessary;
- Provide implementation for communication protocol conversion between the external protocols and the internal communication protocol.

Device Management – This component contains core management functionality of the IoT hub and handles creation of necessary communication channels between devices and IoT hub and IoT hub and DCF. This component includes the functional sub-components to handle the registration/connection of devices and their identification. The respective details of the device like native communication protocol, device type, data type etc. are collected from the meta-data of the device from the details stored in the DCF. At the same time, other important objective of this component is to deal with the connectivity status of the devices. On the whole this component keeps all the information about the different IoT devices registered and connected to this IoT hub, providing information about the identifier of the device, properties/capabilities of the device, registration and connectivity status of the device, working status of the device and, authentication and authorization policies for device.

Data Handler - The IoT hub is the entry point of data from IoT resources. That means that this module will then consume a huge amount of data coming from external sources. It is mandatory to provide a module where data could be filtered, aggregated or merged allowing applications to consume only specific/value-added data or pre-processed ones. Data handling module will be responsible for providing such functionality. Data Handler Factory addresses the need for filtering real time data being collected from the heterogeneous sources, thus providing pre-processed data to DCF. Data handler pre-processes the data based on understanding the context of the device and data processing constraints defined by the end users. Note that this component will be designed in such a way that new implementations necessary for data handling can be easily integrated into the Data Handler Factory. However, it is important to emphasize that IoT hub intends to be a lightweight infrastructure with low processing capacity, so the chosen technique to pre-processed data should be effective.

To summarize, IoT Hub collects data from the shop floor IoT resources, pre-processed and provide it with the expected format to DCF. Outputs of IoT hub are data streams, which are defined as “a sequence of digitally encoded signals used to represent information in transmission.” - Federal Standard 1037C1. In the scope of IoT hub a data stream is a set of timestamped relations, i.e. each element of the data stream consists of a set of tuples. The order of the data stream derives from the ordering of the timestamps and the IoT hub provides support to manage and manipulate these timestamps.

This way it is always possible to trace the temporal history of data stream elements collected through IoT hub. It allows IoT hub to be the central observation tool for the physical world, in which network and processing delays are inherent properties of the observation process, which cannot be made transparent by abstraction. The data collected by IoT hub should be pre-processed in order to filter out unnecessary and faulty data and this process can be achieved by several techniques. Finally, this pre-processed data will be provided to the Data Collection Framework through the DCF API for further processing.

3.2. Concept

In order to understand the general operation of the IoT hub, this section defines the high level flow of configurations, data and commands during the device addition, as well as the registration and run-time phases for collection of data from devices. *Figure 16* presents the view of the methodology to address the real time data collection from real world resources via IoT Hub, with distinction between device registration and run time phases and control, data and configurations flow. Data flow is represented by the flow of data from producers to consumers; commands flow presents the actions that each of the components pass between each other at different phases to invoke specific functional implementations while configurations flow is the flow of configuration details for all the devices to be connected to the IoT hub.

The overall flow of Figure 16 is explained by the following steps. In order to add and register a device in the IoT Hub, a conjunction of manual and automated interactions occur (1. and 2.)

1. The IT company personnel firstly create a new instance of the resource (IoT device) that he wants to connect to platform. This step is performed at the DCF, where he provides

the details, including protocols, port, behaviour, data type etc. The instantiation of the device also includes providing contextual details like the location of the device and data handling constraints;

2. Following that registration activity, the DCF main component automatically provides the IoT Hub the necessary information for device identification, behavioural properties and data handling;

3. After registration, IoT Hub is ready for collecting data from the resource. Communication component provides necessary implementation for communication between device and IoT Hub. During run-time, devices are provided with communication channels based on their communication protocols;

   3.1. During the process of communication, the communication component works together with the device management to identify the communication protocol of the device, and creation of respective communication channels. At the same time this step is also used for the runtime authentication and authorization of the device;

4. With successful creation of the communication channel and security check, the data is forwarded towards a data handler for pre-processing of data (to filter faulty data);

   4.1. Data handler component interacts with the device management to retrieve the necessary rules and device properties to perform data filtering;

5. Pre-processed data is published to DCF message queue for further processing and persistent storage;

6. Data consumers can then query DCF to request data collected from the real world resources.

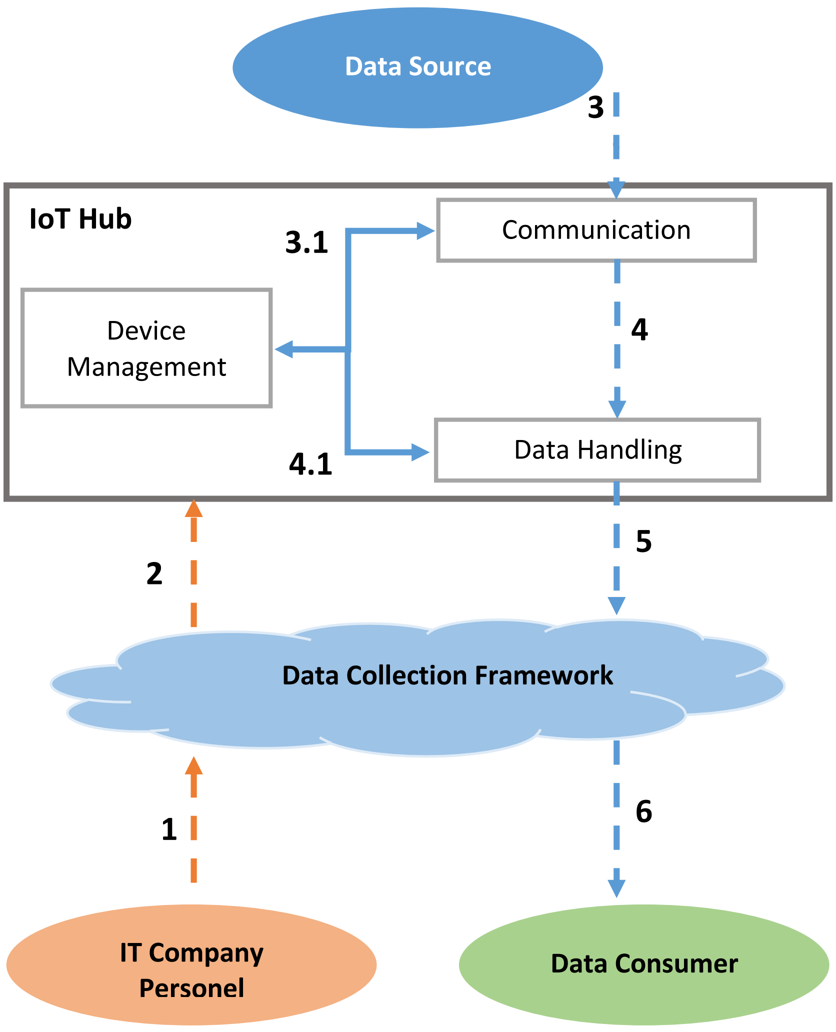


Figure 16 Methodology for addressing the real time data collection from real world resources

3.3. Application Scenario

The deployment of this middleware in an overall perspective is presented in Figure 17. It should be clear that IoT Hubs are going to be deployed in the private infrastructure of the industries, having direct connection to their IoT networks. This, means for the business scenario involving number of industries, the industries will have independent IoT Hubs deployed on their private premises. The integration between data collected by these independent hubs are performed by the cloud services.

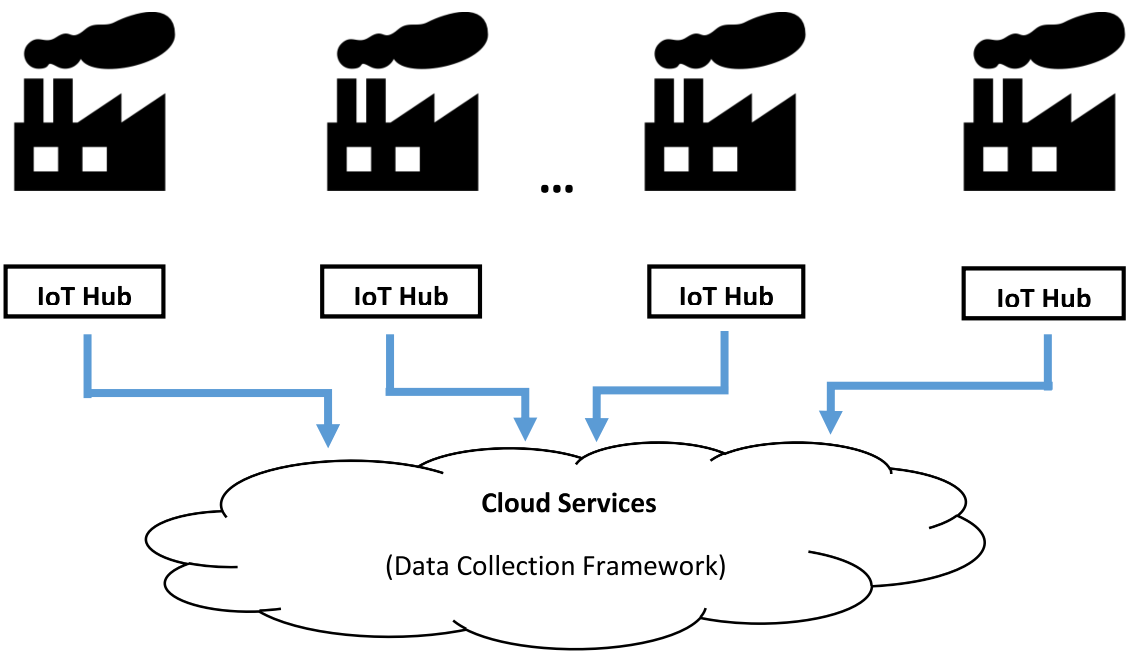


Figure 17 Middleware Model's Deployment

The fact that IoT Hub is configurable and extensible according to each company requirements, allows to easily add and configure new devices from each pilots' networks. These properties provide the IoT Hub with the desired scalability to handle the constant growing and diversity of company's IoT devices.

For the implementation of the IoT Hub it is necessary to understand the IoT devices and the data that needs to be collected from each Pilot. The next table summarizes the different contexts that data collection can reach, as well as purpose in an industrial environment consideration in Table 4.

Table 4 Examples of context data collection

Data	Objectives
Quantities	Drugstore inventory planning and monitoring
Position/Location	Product path within the facilities
Packaging	Route
Delivery Order, Time and Date	Measure stops duration in distribution
Component Batch	Waste and spare parts inventory management
State of the Machine	Measure stops duration in production
Speed	Production status
Worker Performance	Non conformities management
Workstation Downtime	Production planning
Energy Consumption	Monitoring the energy consumption of Test Area
Temperature and Humidity	Production line monitoring and control
Production Station	Product/material traceability
Processing Time	Delays
Origin of raw material	Product quality management
Product Details	Storage location and space optimization

3.3.1. Smart-Shopfloor Scenario

The functionalities of a smart system that is able to perform the management of the devices in an industry is countless, and each software specifications will depend on the specifications of the implementation site. This dissertation objective is to demonstrate the applicability of implementing an optimization process to the work quality of employees in a factory environment, and thus justify the choice of sensors used on the system that has been developed.

Nowadays the environment of a shop floor is quite different from the one 20 years ago. The progress of the machinery, especially on the efficiency and functionality, enabled the exponential increase of the production capacity, which in turn meant the clients demanding shorter deliver timelines. This increase of responsibility made a lot of companies to move the technical work nearer to the employee direct contact, instead of being restricted to an office space. The shop floor was no longer the machinery space but also become the office space. Another huge contributor to this change was the unfolding of the product complexity, and consequently the production lines that started to include different phases, as design, software, and hardware, among others. This new business/production model required the constant interaction between each group/element responsible for its share of the end product and gathering all parties within a single space translated in an increase of the productivity through enhanced communication among team members which in turn affected the output. As a result, the control in the shop floor environment increased considerably through the detailed management of activities and the flow of materials inside the plant, including employees, materials, machines, and production time.

On another hand, to keep up with the technology efficiency it is necessary to ensure a proportional efficiency in the workforce, offering them better work conditions. As the physical boundaries are being bridged, a complex and competitive world focuses on innovation and creativity is being developed. A smart shop floor now is one that ensures the optimal and effective utilization of physical infrastructure and IT resources.

To build a smart shop floor is necessary to have an intelligent space that optimizes efficiency, safety, comfort, system control and by collecting and analysing sensor data. In order to interconnect different devices with different achievements, a smart shop floor will require software with the ability to connect with everything – a middleware. It helps shop floor managers to visualize information and make fast and precise decisions, through a management system, increasing the employee’s productivity and decreasing the energy consumption and operating costs.

For an illustrative example, let us consider three aspects that are directly related with the work conditions in a shop floor, which are room temperature, luminosity and safety. For that purpose, the sensors that can be chosen are:

- Temperature: this sensor is useful to guarantee the general comfort, in maintaining the temperature and air circulation, in case it is connected to electrical windows or A/C;

- Photoresistor: this sensor will prevent the loss of visual capabilities caused by poor illumination, it is also useful to turn on and off the lights, depending on the luminosity levels;

- Ultrasonic: considering that in a plant we have people and machines working side by side, it is of utmost importance to guarantee the safety of all elements. Thus, this sensor is responsible to measure the distances with the purpose of alerting the workers in case they enter a restricted area for machinery only.

Now based on these sensors, we can build different conditions that be used for detecting and providing immediate actions in the shop floor. Table shows the function that each sensor may represent to ameliorate the three aspects mentioned.

Table 5 Analysis of selected sensors

Sensors	Controlling action
Temperature	Temperature LOW or HIGH Threshold then AC ON or OFF
Photoresistor	Light Intensity LOW or HIGH Threshold then Bulb Auto
Ultrasonic	Distance LOW Threshold then Alarm/Buzzer ON
Temperature and Photoresistor	Temperature LOW or HIGH Threshold **AND** Light Intensity LOW or HIGH Threshold then Fire Alarm ON/OFF
Temperature and Photoresistor and Ultrasonic	Temperature LOW or HIGH Threshold **AND** Light Intensity LOW or HIGH Threshold **AND** Distance LOW Threshold signal that the room is overcrowded and not safe for working

It is important that the table above presents only the simple test cases that can be detected by utilizing few sets of sensors mentioned before. The simple use-case has been considered not only for understandability but also to be aligned with the experimentation set-up for testing in the lab environment (reported in details in section 5). The main purpose of these simple scenarios is to demonstrate that he system implemented and the sensors used can be utilized (alone and integrated) in a shop floor environment to detect some interesting situations. But, it is important to note that the IoT middleware solution that has been developed in the scope of this dissertation can support other types of sensors, thus providing the possibility for realization of more complex scenarios.

4. Proof of Concept Implementation

In this chapter is presented the practical implementation of the middleware. The development is based on the architecture explained in chapter 3. Before going into the details of the implementation, the first section presents the requirements and functionalities of the system. The following section presents the technology that has been used for the implementation the proof of concept, explaining their purpose and choice. Subsequently, the characteristics of the hub are explained in different modules.

4.1. Requirements and Functionalities

In this section, firstly we present the generic requirements that the IoT system should fulfil, which have guided the overall architecture development and implementation of the middleware solution discussed in this dissertation. It also presents the functionalities that have been implemented along with some assumptions that have been made to realize the solution. This is an important section for understanding the overall IoT system requirements and corresponding functionalities that have been addressed in the proof-of-concept implementation.

Requirements

- **The architecture of the system should be interoperable:** The main idea of having a middleware is, mainly, to facilitate the data acquisition from a huge diversity of devices which can have a large heterogeneity in communication domain.
- **The architecture of the system should be scalable:** The system should be able to easily expand as more devices are added and also facilitate the addition of other processing techniques and security development levels. Another important advantage to increase the scalability is its capacity to work in different platform systems.
- **The middleware should be able to react to a failure:** In a real world there will be always situations more difficult or impossible to control once we not leave in a perfect environment. So the main idea of this requirement is "obligate" the middleware to be more robust to external flaws.

- **The middleware should be able to pre-process data before sending it to DCF:** One of the main requirements of this lightweight middleware is doing a pre data filtering according with specifications of each device.

- **The middleware should be able to identify the data belonging to each device:** Despite of having lots of sensors coupled at the same smart device, the idea is to maintain the independence of each one.

- **The middleware should be capable to identify which devices are reliable:** The data collection is not made to acquire data of all kind of sensors. The architecture must be done to choose which devices we want to insert in the hub.

- **The system should be capable to store data until DCF's request:** The fundamental idea of collecting data is using it for a determinate purpose. Since the final user are the clients, these hold the decision of when the data information provided by the sensors is important. So, the middleware must be capable to acquire sensor data all the time, but only send it when is requested by the Cloud application.

- **The system should guarantee data security:** This is one of the main issues in our digital world and not only in IoT systems. The idea is to provide data confidentiality, integrity and availability. Since the main idea of this dissertation is to study and develop mechanisms of pre-processed data in different communication protocols, the security was not the main focus. However, this is a complex and very important requirement in every IoT system.

Functionalities

- **Data collection is done only by known devices:** The middleware receives a message that contains the device's characteristics that is going to be registered and only after that is created the channel communication that allows the acquisition of data.

- **The middleware is capable to collect data from devices with different communication protocols:** The middleware was developed with the ability of collecting data by sensors connected with three different communication protocols.

- **The middleware is prepared to easily add more communication protocols and more pre-processed techniques:** Each communication protocol is a Java Class, so if we want to add more protocols (e.g. Bluetooth or RFID) we have to add the respective dependencies and create another Java Class. The pre-processed techniques follow the same strategy, however, this part will be dependent of the DCF's message once the characteristics of filtering of each device are sending by the Cloud.

- **The middleware has a bidirectional communication with the Cloud and unidirectional communication with devices[2]:** The bidirectional communication is for middleware receive device's information from the Cloud and then send the data collected. The unidirectional communication is in the direction of data flow, devices to middleware.

- **The middleware stores each device's data independently from each other:** Each device has its own stack where data is stored, in memory, before it is sent to the DCF.

- **The middleware store device's information after switched off:** After received by DCF, this information is saved in a file.

- **The middleware guarantees a Plug&Play functionality:** Since the moment that is plugged in, the device launch automatically the software.

4.2. Technology Adopted

In this section it will be described and explained the technology used in this dissertation. Since the development of this system is separate into a middleware and a sensor node, this section divides the technology in two different parts: software and hardware. So, this section sets out the technology used in the implementation of the hub and sensor nodes.

4.2.1. Software Technology

Middleware Software

The programme language used to develop this platform was Java. The main reasons for this choice were its ease of writing, compiling, debugging and learning. It presents very useful features such as the fact that is object-oriented, this allows the creation of modular programs

[2] Since the proof of concept uses only sensors as devices, the communication with the middleware is unidirectional. However, if the system is formed by sensors and actuators (that need to receive input commands) it is perfectly feasible to have a bidirectional communication.

and reusable code. Also the capability of multithreading is an important advantage, allowing the program to perform several tasks simultaneously within a program.

Moreover, the ability to run the same program on many different systems is crucial to World Wide Web software, and Java succeeds at this by being platform-independent at both the source and binary levels. This important aspect allowed to run the code on the computer (in NetBeans IDE installed in Windows environment), allowing correct the errors in a more effective way and testing it before inserting the program in the device (in Linux environment). In fact, this induces further advantage of this programming language, its reliability, once Java puts a lot of emphasis on early checking for possible errors, as Java compilers are able to detect many problems that would first show up during execution time in other languages. Another important aspect for this choice of language was security. Although it is not considered a main focus in this dissertation, Java considers security as part of its design. The Java language, compiler, interpreter, and runtime environment were each developed with security in mind.

In the code transfer was used FileZilla[3] program, which greatly facilitates the communication and files transfer between computer and the device in which was built the hub. Widely used in the access of the device from the command line was Putty software.

Dependencies Usability

The implementation of the project required the use of some Jars, library Jars and other specific Artifacts[4]. The local repository used was Maven (could be three types: local, central or remote repository) that keeps all the dependencies used. When a Maven build command is executed, it starts looking for dependency libraries in the following sequence:

- Step 1 - The first place to search is in local repository;
- Step 2 - If not found locally, the search will be extended to the central repository. If not found there are two options: a remote repository has been mentioned – Step 4 or not - Step 3;

[3] FileZilla Client is a cross-platform FTP, FTPS and SFTP client with lots of features and an intuitive graphical user interface.

[4] An artifact is something produced by the software development process, whether it be software related documentation or an executable file – Jar.

- Step 3 – If a remote repository has not been mentioned, Maven simply stops the processing and throws error;
- Step 4 – Search dependency in remote repository, when it is found it is downloaded to local repository for future reference.

Sensor Nodes Software

The sensors used were coupled, each of them, to a microcontroller responsible for reading the input (sensor) and turn on output for subsequent delivery. To this end, it was used the Arduino Programming Language, based on wiring, and the open-source Arduino Software (IDE), based on processing. The programming language used was C++.

The implementation of sensor nodes' communication in Arduino IDE required the addition of appropriate libraries for each protocol:

- The Serial communication, as having no hardware layer connected to Arduino, not required extra libraries.
- In Wi-Fi communication, it was integrated a CC3000 shield to Arduino, whose use required the addition of the respective files.
- However, in ZigBee implementation, in addition to the required libraries, it was necessary to connect the ZigBee Arduino's shield – router – with the ZigBee module connected to the Raspberry Pi - coordinator. For this, it was used the XCTU program, from Digi International.

4.2.2. Hardware Technology

Arduino

Arduino is an open-source prototyping platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor or a finger on a button - and turn it into an output - activating a motor or turning on an LED. All Arduino boards are completely open-source, empowering users to build them independently and eventually adapt them to their particular needs. The chosen board for this thesis was the most common: Arduino Uno R3.

There are many other microcontrollers available for physical computing. Parallax Basic Stamp, Net media's BX-24, Phidgets, MIT's Handy board, and many others offer similar functionality. All of these tools take the messy details of microcontroller programming and wrap it up in an easy-to-use package. Arduino also simplifies the process of working with microcontrollers, but it offers some advantage over other systems, such as:

- Inexpensive - Arduino boards are relatively inexpensive compared to other microcontroller platforms.
- Cross-platform - The Arduino Software (IDE) runs on Windows, Macintosh OSX, and Linux operating systems. Most microcontroller systems are limited to Windows.
- Simple - The Arduino Software (IDE) is easy-to-use for beginners, yet flexible enough for advanced users to take advantage of as well.
- Open source and extensible software - The Arduino software is published as open source tools and the language can be expanded through C++ libraries.
- Extensible hardware - The plans of the Arduino boards are published under a Creative Commons license, so experienced circuit designers can make their own version of the module, extending it and improving it.

Raspberry Pi

A Raspberry Pi is a small device with an affordable price and works quite similar to a computer. It is open hardware (with the exception of the primary chip), which runs many of the main components of the board – CPU, graphics, memory, the USB controller, etc. These devices were developed with the goal to create a low-cost device that would improve programming skills and hardware understanding. It is slower than a modern laptop or desktop but it can provide all the expected abilities that implies, at a low-power consumption level. Additionally, Raspberry Pi has the advantage to have a large number of people who might be able to help if you have any question regarding a project that you are working on because of the large reach of the community. This is the big difference between choosing this device to any other available on the market such as Allwinner A10 or CuBox. The available board to work in this thesis was the Raspberry Pi 2 Model B.

Sensors

The sensors used in the implemented system were:

- Temperature – The sensor used was TMP36 and it has three output pins: +Vs, Vout and GND. This sensor is low voltage (+2,7V to +5,5V) precision centigrade temperature. Provides a voltage output that is linearly proportional to the Celsius temperature and does not require any external calibration to provide typical accuracies of +-1ºC at +25ºC and +-2ºC over the -40ºC to +125ºC temperature range. TMP36 provides a 750mV output at 25ºC and has an output scale factor of 10 mV/ºC.

- Ultrasonic - Ultrasonic ranging module HC - SR04 has 4 output pins: Vcc, Trig, Echo, GND. This module provides 2cm - 400cm non-contact measurement function, the ranging accuracy can reach to 3mm. The modules include ultrasonic transmitters, receiver and control circuit. The basic principle of work:

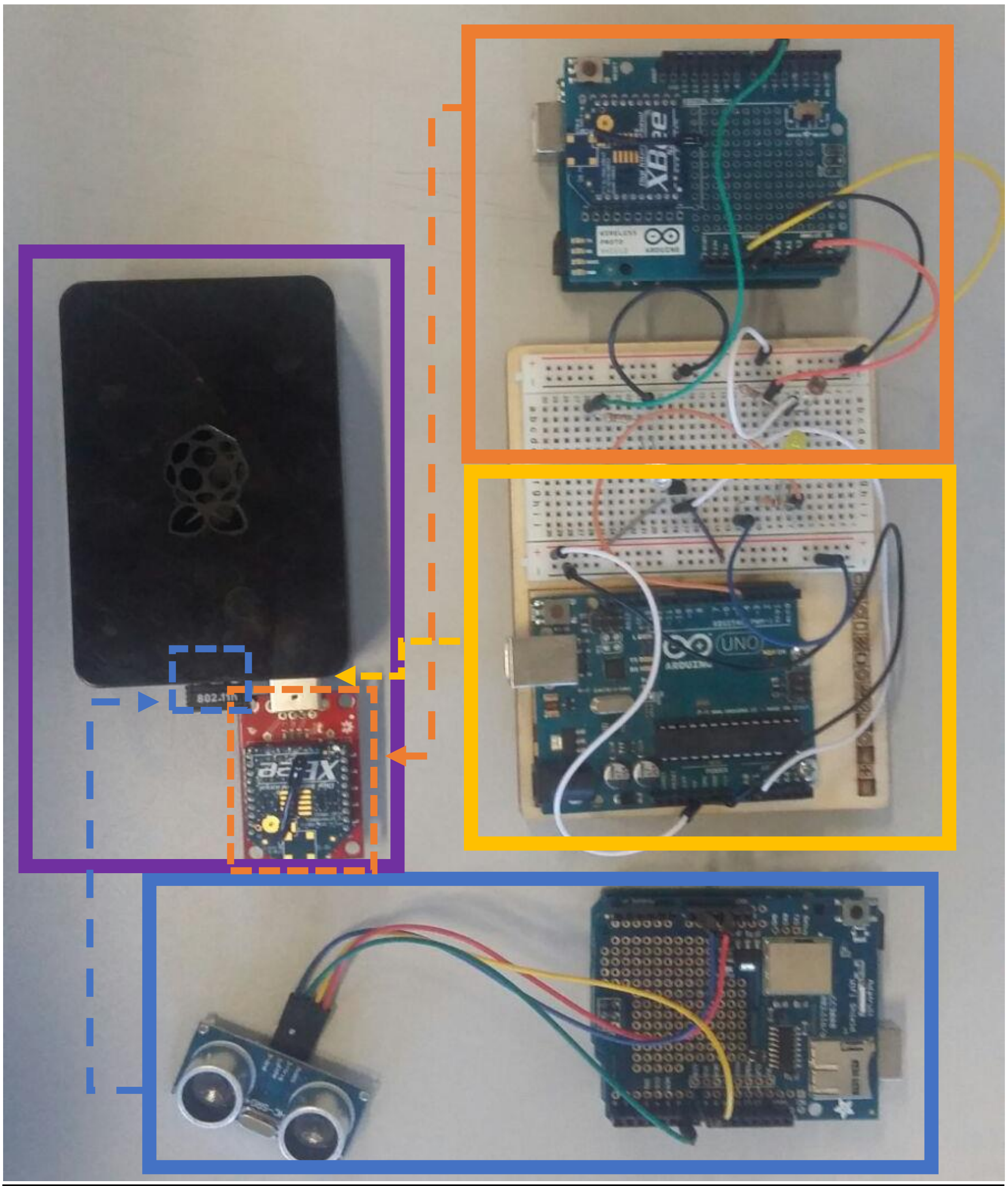
  - 1) Using IO trigger for at least 10us high level signal,
  - 2) The Module automatically sends out an 8 cycle burst of ultrasound at 40 kHz and detect whether there is a pulse signal back.
  - 3) If the signal back, through high level, time of high output IO duration is the time from sending ultrasonic to returning.

  It is possible to calculate the range through the time interval between sending trigger signal and receiving echo signal. Formula: the range = high level time * velocity (340M/S) / 2. For this kind of sensor, it is suggested to use over 60ms measurement cycle, in order to prevent trigger signal to the echo signal.

- Photoresistor – The sensor used is a light dependent resistor (LDR) photoconductive cell VT900 Series. The resistance decreases with increasing incident light intensity. A photoresistor is made of a high resistance semiconductor. In the dark, it can have a resistance as high as several mega ohms, while in the light, it can have a resistance as low as a few hundred ohms.

In Figure 18 is depicted the developed hardware system, in order to clarify the integration of the elements earlier described. Since the circuits implemented were simple, the breadboard presented in the figure was used for photoresistor and temperature circuit at the same time. However, they are completely independent from each other. The ultrasonic sensor did not necessitate an auxiliary breadboard because the outputs pins of the sensor (two digital ports, VCC and GND) were directly attached to the Arduino's Wi-Fi shield. The Wi-Fi dongle and the

Zigbee coordinator were the physical devices attached to the Raspberry Pi (where middleware runs) responsible to connect with the ZigBee and Wi-Fi shields. In order to facilitate the system understanding, the serial cable responsible to connect the temperature sensor node to the Raspberry Pi was not introduced in this figure.



Legend:

- - - -▶ Data flow between sensor node and middleware

☐ Hardware system entities

⬚ Hardware dongles communication – Wi-Fi and Zigbee Coordinator

Arduino with Wi-Fi shield and ultrasonic sensor
Arduino with temperature sensor
Arduino with ZigBee Shield (Rooter) and photoresistor ultrasonic sensor
Raspberry Pi 2 - Middleware

Figure 18 Implementation of the physical system

4.3. IoT Hub Detailed

In this section we will present the details on IoT hub, which acts as the intermediate solution between the shopfloor devices and cloud service. It is to be noted that even though the overall solution is implemented as one java project, the idea is to describe each module separately facilitates both the understanding and scalability for further enhancements. Lastly, it is presented the synthesis of the global system's modules along with the interactions between modules in the hub as well as a sequence diagram of the system that represents a detailed view of the interactions between the internal components (clearly marked in Figure 19).

4.3.1. Controller

This package is constituted by three Java classes responsible to manage devices' data and post it in the cloud:

DataPoster – Responsible for sending the information of th5e conglomerate of devices to the cloud. Only one *DataPoster* object is created. This object is then shared by all the listeners. When a measure is received by one device, the *DataPoster* is informed, that measure is added to data structure with key/value (Device ID/Measure) and check if it is time to send that information. If it is not, remains idle. Otherwise, retrieves all the information from that data structure, with the help of Json's message builds the message in a correct way, calls object *Monitoring* to monitor the hub at that point in time and when it has all this information, then posts to a server it via http post.

DeviceManagement – Core Implementation for managing the devices. The steps are:

1) Initialize the registered listeners (available data listener are added in the Resources/configs.xml). This is done using *DataListenerFactory*, a class that follows the factory pattern[5];

2) Initialize the registered devices (received by DCF). Available devices are in Resources/devices.txt. This is the trick to deal when the machine is off. The devices are written in a file, since the implementation of a lightweight Hub does not allow (although it is possible) storing any information in a local database;

3) Add each device to its own listener;

[5] It can be explained in (Object Oriented Design 2016).

4) Monitor the overall life cycle of a device added on the hub.

FileChangedWatcher – Implementation of *ChangeListener* that will allow us to monitor the Resources/devices.txt. The file devices.txt is used to store all the details of the devices that have been added to the hub via DCF. When the file undergoes any modification, this class notifies *DeviceManagement* to the initialization of new devices. The changes occur in this file whenever the system admin adds/deletes/updates the device details via the interface provided in the DCF.

RESTservice – This class launch the REST service to receive the information from DCF - hub's configuration. Upon receiving a Json's message from some link (for instance, localhost: 3000/DCFconf), it proceeds with an analysis of its content and verification that is indeed a message that comes from DCF. If passes the validation builds a string with the extracted information to be written in the configs/devices.txt with the *FilerReader* object.

4.3.2. Data Listeners

This package is constituted for the communication protocols supported by the hub. To authorize the devices registration in the hub, each protocol checks the received ID in DCF's message. This ID is used to query data structure of the channel, using the *contains* method. If data structure has the ID, the system proceeds as explained below. If not, the values received are eliminated.

Serial – This class initialize data listener serial port where the Arduino is attached. As in Linux is impossible to listen the Arduino ports directly, it takes a symlink to another port of my choice (e.g. /dev/tty63) and then is synchronized. It is made the connection with serial port and set the serial port parameters (such as data rate, data bits, stop bits and parity none). Finally, the system starts to listen if there are data transmission in that port. If not, it remains in loop until some data appear in that port.

ZigBee - Instantiates a new object physically connected to the given port name (e.g. /dev/ttyS88) and configured at the provided baud rate. From the device is necessary to know the serial port name where XBee device (the coordinator) is attached to and the baud rate to communicate with the sensor node. Other connection parameters will be set as default (8 data bits, 1 stop bit, no parity, and no flow control). This class has an XBee message containing the remote XBee device the message belongs to, the content (data) of the message and a flag indicating if the message is a broadcast message (was received or is being sent via broadcast).

Wi-Fi - This class implements server sockets (by TCP protocol). A socket is an endpoint for communication between two machines. A server socket waits for requests to come in over the network (sensor node made a request to send data acquired). Then it is performed the operations of filtering based on that request.

4.3.3. Models

This package is used for creating the model of the devices that are connected to the hub. This class models of the overall IoT system by providing different types of properties (properties can be complex ones such as device, monitoring etc. which themselves have properties defined within themselves) such as:

DataField – This class implements concept hierarchy generation filter based on the information in Resources/devices.txt;

DataRangeTypeLoHi – This class implements the data range filter based on the information in Resources/devices.txt;

Device – This class keeps information about device such as id, name, protocol, datatype, range and stack of measures. It is this class that prepares the string with the information required to send to the DCF. The string messages from this object was overwritten in order to be structured in a way that is ready to send to the DCF.

Measure – This class keeps value and timestamp of data collected. It belongs to Device's class;

Monitoring – This class keeps track of hub status such as free disk, disk size, total ram, free ram and CPU temperature. Linux keeps all your information on file and it was intended to make a call to the operating system about the desired commands. More information can be acquired, if necessary, in another application. This information is sent to a server for further analysis of hub's health.

4.3.4. Utilities

All Java classes responsible for reading files and preparing messages for sending or reading information were implemented in this package, such as:

FilerReader – This class is responsible to read the information of Json's message and store devices' information in a file Resources/devices.txt. It is called in *DeviceManagement* to initiate the devices;

HttpUtils – This class is called in *DataPoster*. Its function is establish the connection with URL server where Json’s message will be sent. The object belongs to dataposter and its simple function is to curl the Json content to web server.

JsonMessage – Build the Json message to be sent to the server (with measure and monitoring). This class is called in *DataPoster* to transform the information store in the string to a Json object in order to be sent through the service REST;

xmlReader – Responsible to read the file Resources/configs.xml. This class is called in the *DeviceManagement* to initiate the listeners.

4.3.5. Synthesis

In order to clarify the objective of the modules implemented inside the hub and its interaction with outside components, in Table 6 is shown the major information flow in this system:

Table 6 Information flow between the modules of the system

Interaction	**Information Flow**
Device / IoT Hub	Arduino starts to acquire analog inputs and transforming in digital values; Devices get connected to the IoT Hub; Devices communicate to provide data via. Protocol Adapter depending on the communication protocol of the device.
Inside IoT Hub	Communication component interacts with the Device Management component to check authenticity of the device before starting collecting data from it; Device Management initiate the communication and devices listeners to start the communication with sensor nodes. Device component updates itself with a stack of data already pre-processed and defined by the DCF.

IoT Hub / DCF	DCF Resource Management communicates with the IoT hub to provide the details of the resource instance being created; IoT Hub communicates with the DCF Request/Response Message Queue (API) to push data being collected into the DCF and to monitoring hub's health; DCF communicates with IoT hub to update the devices registered in the hub.

Specifically described and explained the internal operations of the hub implementation in the earlier sub-sections, is shown in Figure 19, the sequence diagram representing the functionality of the whole system encompassed around the developed middleware. This solution has emerged based on the concept outlined in section 3.2 and also through the objectives that this thesis intended to achieve. So, the mainly steps done by the system are:

1. Launch the *DeviceManagement* class;
2. Initialize the listeners. The *xmlReader* is called to read the settings in Resources/configs.xml;
3. The listeners are launched using DataListenerFactory way. Every time that xmlReader "send" a listener, *DeviceManagement* launch the *DataListenerFactory* to obtain the channel communication. After that, the channel is initialized according with your protocol adapter;
4. Initialize the devices. The *FilerReader* is called to read the settings in Resources/devices.txt;
5. Each device is added to your own listener (according with communication protocol);
6. Launch *RESTservice*;
7. Execute the function *MonitorForNewDevices* that contains a *FileChangedWatcher* object that is constantly monitoring the changes in devices.txt file, in order to initialize new devices added (by DCF through *RESTservice*) in this file;
8. After the communication process is being done, the system starts to collecting data coming from data sources;
9. The concept hierarchy generation and range filter are executed (by *DataField* and *DataRangeTypeLoHi*, respectively);
10. After data filtering, is created an object *Measure* (with device's ID and the value collected) that will be added to the stack of this *Device's* class;

11. The string containing device’s information is sent to *DataPoster*;
12. In DataPoster, if the time defined by DCF to send the message is reached, the string that contains device’s information is conglomerate with the string responsible to *Monitoring* (this class is executed at this point) the hub’s health.
13. The *JsonMessage* class is called in *DataPoster;*
14. Posteriorly, is sent the Json’s message (measure and monitoring) through a class called in DataPoster – *HttpUtils*.

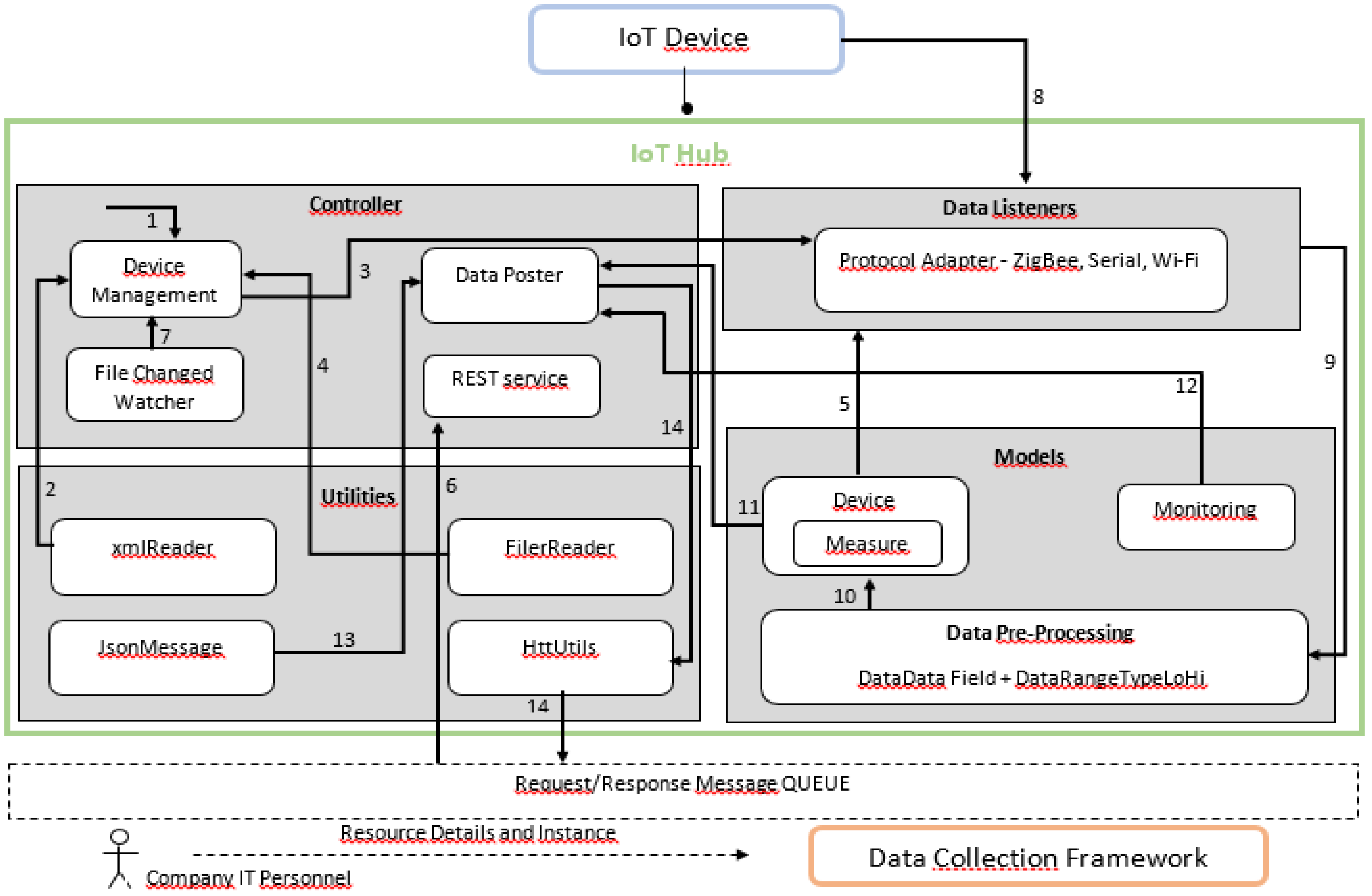


Figure 19 Information flow in IoT Hub

5. Testing and Hypothesis Validation

In this section the testing of implementation will be addressed by validating the requirements and functionalities of the system. The testing aims to evaluate the level of confidence of using the system in normal circumstances. However, since testing of realistic systems can never be exhaustive because it is limited to a restricted period of time, it is not possible to ensure complete accuracy of a system implementation. Testing can only show the presence of errors, not their absence (Tretmans 2001).

To sum up, in this chapter will be presented:

- The methodology applied to the proof-of-concept implementation;
- The main tests performed based on the chosen methodology;
- The validation of hypothesis and the implemented concept.

5.1. Testing Methodology

The importance of testing is explicit explained in Volume 2 of (Marciniak 2002). In this book is concluded that, as maintenance and upgrades of existing systems increase in number and depth, a significant amount of testing will also be needed to verify the systems after the changes are made.

In this perspective, there are number of methods that can be applied to guarantee the quality of a deployed system. Testing is involved in every stage of software life cycle, but the testing done at each level of software development is different in nature and has different objectives. Mainly there are four key steps (Luo 2001):

- **Unit Testing:** is done at the lowest level. It tests the basic unit of software, which is the smallest testable piece of software;
- **Integration Testing:** is performed when two or more tested units are combined into a larger structure;

- **System Testing:** tends to affirm the end-to-end quality of the entire system, evaluating its functionality;
- **Acceptance Testing:** is done when the completed system is handed over from the developers to the customers or users. The purpose of acceptance testing is rather to give confidence that the system is working than to find errors.

Based on the information flow, a testing technique specifies the strategy that is used to select input test cases and analyse its results, as different techniques reveal different quality aspects of a software system. There are two major categories of testing techniques, functional and structural:

- **Functional Testing:** the software program or system under test is viewed as a "black box". Is evaluated by observing the box externally with no reference of its internal details or implementation. The selection of test cases for functional testing is based on the requirement or design specification of the software entity under test. Functional testing emphasizes on the external behaviour of the software entity;
- **Structural Testing:** the software entity is viewed as a "white box". The selection of test cases is based on the implementation of the software entity. The goal of selecting such test cases is to analyse each code line executed, at least one time, covering all possible paths of execution, specific statements and branches. Structural testing emphasizes on the internal structure of a computer program.

5.1.1. Testing and Test Control Notation

Testing research techniques leads to obtaining practical testing methods and tools. Progress towards this achievement requires fundamental research, and the creation, refinement, extension, and popularization of better methods. For this reason, the chosen methodology was Testing and Test Control Notation (TTCN).

The Testing and Test Control Notation, previously called Tree and Tabular Combined Notation, which is defined in (ETSI 2013), is a notation standardised by the ISO/IEC 9646-1 for the specification of tests for communicating systems and has been developed within the framework of standardised conformance testing.

Based on the "black box" testing model, the tests are defined through tables containing general description, constraints, behaviour and verdict. In TTCN, the behaviour test is defined by a sequence of events which represent the test per se. The sequence of events can be represented by a tree with branches of actions based on the evaluation of the system output after one (or a series of) executed event(s). Each event has its own respective level of indentation and can be of one of two types, action or question:

- Actions are preceded by an exclamation point before its brief description, and represent actions performed on the SUT;
- Questions are preceded by an interrogation point, and represent evaluations of the output of the SUT after one or more actions are completed. Since the answer can be positive or negative, multiple questions can exist at the same indentation level, covering all possible outputs of the system.

After a completion of a TTCN test table a verdict must be deliberate: "Success", "Failure" or "Inconclusive". This verdict is based on the sequence of events which travel through the tree, and was conditioned by the outputs of the system and evaluated by the question events. Table 7 is a simplified example of a TTCN table test.

Table 7 Example of a TTCN test in table format (Tretmans 2001)

Test Case Dynamic Behaviour		
Test Case: **Conn_Estab**		
Purpose: **Transport / Connection**		
Purpose: **Check connection establishment with remote initiative**		
Behaviour	**Constraints**	**Verdict**
+preamble		
LT ! T-PDU-connect-request		
UT ? T-SP-connection-indication		
UT ! T-SP-connection-response		
LT ? T-PDU-connect-confirm		Success
OTHERWISE		Failure
LT ? T-PDU-disconnect-request		Inconclusive
OTHERWISE		Failure

5.2 Testing Implementation

As explained in 5.1, there are two main techniques for testing: functional and structural. Although both techniques were used, the structural test was performed during the code development (using the tools provided by the IDE NetBeans). Thus, this section lists the functional tests (intended to demonstrate the capabilities of middleware) resulting from a subsequent acceptance of structural tests. In testing process of the architecture implemented in this work, it was taken into consideration more specific criteria such as:

- Interoperability – between devices and the hub, as it is a key element in its development;
- Recovery capacity – what is the hub's behaviour when the communication wires are physically disconnected, power is turned off or the devices and communication channels are turned down;
- Performance - to determine how fast a feature of a system performs under a particular workload, in order to validate that the system meets the expected response time.

To address the functional and non-functional testing of the implementation, all the models that were explained in the section 4.3, will be demonstrated and followed by showing how the middleware works. Figure 20 presents the main perspective of the tested system divided by five layers (respectively from down to up: acquisition, transport, collection, transport and delivery) where the data has to pass from the edge – sensor nodes, to the core – cloud platform.

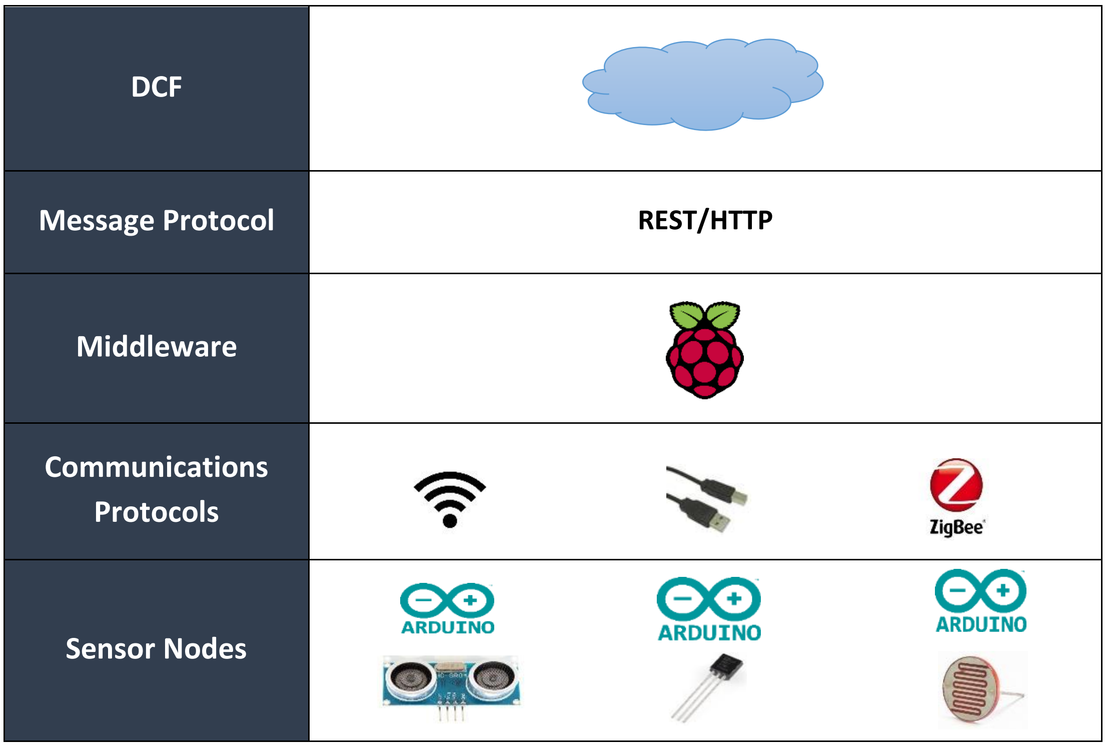


Figure 20 Technologies used for testing

5.3.1. Functional Tests

In the test definition, it is intended to describe the general purpose of the test implemented. Later, in test execution, it is intended to demonstrate the different tests that have occurred and that demonstrate the system reliability.

Test Definition

Since the goal is to test whether the data collection is carried out in a correct way, the only test that serves associated with the ultimate goal is the functionality of the entire system, defined in Table 8. The system fails if it is not established communication or data filtering is not being done or not send data in the time set by DCF.

Table 8 Middleware Definition Test - Entire System

Collection of Pre-Processed Data from Devices to the Cloud		
Test Name:	System of Data Collected	
Purpose:	Evaluate the sensor's communication with the middleware and it capacity to filter faulty data before sending to DCF	
Line Number	**Behaviour**	**Verdict**
1	! Reading detailed device information	
2	? Stablish communication with Sensor Node	
3	! Reading detailed device information	
4	? Filter sensor data and store data in the stack	
5	? Store unfiltered data in the stack	**FAIL**
6	! Reading detailed device information	
7	? Sending Data to the DCF	**SUCCESS**
8	? OTHERWISE	**FAIL**
9	? No data is received	**FAIL**

Test Execution

As explained in the previous subsection, only a test that demonstrates the functionality of the entire system serves to validate the whole architecture. However, the implementation was done gradually, for several steps. Therefore, tests were performed to each unit/module developed.

The presented tests intended to demonstrate the system development order, with a gradual increased complexity. First, it was tested the communication of each sensor and afterwards the integration of all sensors and the respective data pre-processing. Is important to note that in addition to the communication and processing, were taken into account three key aspects that were tested and that increase the system reliability, which are:

- Beginning of data collection after registration of the device in the hub;
- Sending Data to the DCF in appropriate time.

The tests were executed several times with different inputs to verify the consistency of the results. In Table 9 is shown the succinct conclusions of Test 5, since it is the test that includes all features. It should be noted that

- **Test 1:** The simplest case to be tested occurred with the Serial. Since the communication is done via cable, the data transmission is safer than other types of wireless communication. So, it is easier to test if the problem is the implementation of the hub and not the configuration between communication modules once they do not exist. To test if data collected was real, the temperature sensor was heated by hand for a few seconds to check that the values increased and then turned to decline to relatively constant value that remained before being heated.

- **Test 2:** The second protocol to be tested was ZigBee. To avoid connection problems between the communication modules relating to its operating range, the router was tested at a maximum distance of 5 meters from the coordinator. Considering that the router (the shield that communicate with Raspberry Pi coordinator) did not use the only Arduino serial port, it was possible to verify the sensor data by the output window of the Arduino IDE. Afterward, these values were compared with the values read by the middleware. As in the first test, it was also verified the reliability of the sensor. During data collection, the sensor was covered and uncovered, to see if the values were changing in case of the sensor has more or less light shining on it.

- **Test 3:** The last protocol to be tested was Wi-Fi. In the test laboratory, the only network available was the Eduroam (European network for the academic community) that contains security services that made it impossible to connect the devices. The alternative was to connect both devices to a network created by a smartphone – a portable hotspot. As in the second test, to avoid range problems, the Wi-Fi Arduino's shield and the dongle connected in Raspberry Pi were placed to a maximum of 5 meters from the hotspot to ensure that there were no range problems. The data collected by the sensor was compared in the same manner as the second test. Finally, the reliability of the ultrasonic sensor was also tested, towards and away of objects so that the sensor could read different distances.

- **Test 4:** After testing the communication of all units separately, it was executed the integrity test. The main objective of this test was to verify if there was no problem with the three threads running simultaneously. Since the goal was to have sensors completely independent and different from the others, the data collection was performed with different sending times.

- **Test 5:** The last test to be executed was the system test. After the communication only the data pre-processing strategies needed to be tested. In order to test data filtering, was introduce in the system three devices with different purposes. It should be notice that both filtering techniques was tested in all sensors. The test presented in Table marks the first experimentation of the system test. The input 1 is protocol adaptation, the method is connect both parts (input 2), the event is acquisition of data (input 3) and lastly, the input 4 is the acquired data in the sensor node. The output 1 represents the value received in the channel communication before the acquisition of data (always none, obviously) and output 2 the data pre-processed, stored in memory, before being sent to DCF. The devices' characteristics were:

Serial

{"action":"add","id":225712,"name":"test10","dataType":"units","dataRange":{"lowerRange":0,"higherRange":100},"datafilterrule":{"dataFilterRule":"N/A"},"CommunicationListenerType":"DataListenerSerialPort"}

ZigBee

{"action":"add","id":214713,"name":"test11","dataType":"units","dataRange":{"lowerRange"250:,"higherRange":600},"datafilterrule":{"dataFilterRule":"N/A"},"CommunicationListenerType":"DataListenerXbee"}

Wi-Fi

{"action":"add","id":215785,"name":"test12","dataType":"units","dataRange":{"lowerRange":0,"higherRange":500},"datafilterrule":{"dataFilterRule":"N/A"},"CommunicationListenerType":"DataListenerWifi"}

The *dataType* filter was tested in serial communication. In this case, the node is constituted by the temperature sensor that provides values with decimals. Here we also tested the concept of hierarchy generation. For instance, if sensor node reads 25,7 Celsius degrees, IoT hub stores in memory 26 Celsius degrees.

In ZigBee communication was tested *dataRange*. The sensor measure values between 100 and 200 when a hand is put over the sensor instead of values near to 500. So, the lower range of this device was 250. Which was tested to see if this values is eliminated for being too low. The same procedure was performed for higher values.

In Wi-Fi communication the filtering process was not tested. This happens to be test case to ensure that, both lower and higher range were set to be too low and high, respectively, in order to include all values.

Table 9 Middleware Execution Tests - Entire System

Input				Output		Result (Test Definition Line Number)	
I1: Protocol	I2: Method	I3: Event	I4: Sensor Node	O1: E.R.b.e	O2: E.R.a.e	Expected	Actual
Serial	Connect	Acquisition	25,7 Celsius	No Data	26	(7)	(7)
Zigbee	Connect	Acquisition	138 units	No Data	No Data	(7)	(7)
Wifi	Connect	Acquisition	53 cm	No Data	53 cm	(7)	(7)

5.3.2. Non-Functional Tests

In an IoT data collection system, an important non-functional requirement is the response time. That criteria can be used to judge the entire architecture implemented and to change results thought to be correct at the outset. Therefore, in Table 50 is presented the time response of the communication stablished between the sensor node and the middleware when the system works without problems, while in Table 61 is presented the time response when the devices are switched off (for unexpected reason). In both of the tables, device's communication are tested in separate and in integrity with the other devices, in order to test the performance and the efficiency of the architecture implemented. In Table 72 is presented the behaviour of each sensor when the hub is restarted.

The "Real Time" that was taken account is seconds and the measurement was made with a chronometer since the moment that the system starts until the moment that the first value of each device appears in the window's output of raspberry pi. In order to ensure more reliability on the results, the tests were performed three times.

Table 50 Non-functional test in normal conditions

	Communication Conditions	Test 1 (seconds)	Test 2 (seconds)	Test 3 (seconds)
Stablish Serial communication	Single	3	2	2
	Integrated	2	2	2
5S4tablish ZigBee Communication	Single	4	5	4
	Integrated	5	6	5
Stablish Wi-Fi Communication	Single	51	48	50
	Integrated	46	51	48

Table 61 Non-functional test in abnormal conditions

	Communication Conditions	Test 1 (seconds)	Test 2 (seconds)	Test 3 (seconds)
Serial device restarting	Single	2	2	2
	Integrated	3	4	2
ZigBee device restarting	Single	3	3	4
	Integrated	4	4	4
Wi-Fi device restarting	Single	49	47	48
	Integrated	48	49	48

Table 72 Sensors' behaviour in an abnormal situation in the hub

	Protocol	Test 1 (seconds)	Test 2 (seconds)	Test 3 (seconds)
Hub restarting	Serial	3	3	3
	ZigBee	5	5	3
	Wi-Fi	47	52	47

5.3. Hypothesis Validation

From the executed tests, the main conclusion that can be drawn is that the implemented proof of concept successfully passed all the tests. The main improvement that is necessary to be made from the observed tests is that the delay that occurred in the Wi-Fi communication to start collecting data needs to be solved. This delay comes mainly due to the handshaking (about 20 seconds to connect in the network) and the request message sent to the hub (about 25 seconds to find the IP address of the hub). However, after connection, this protocol works perfectly equal to the other protocols. In final analysis, it provides a system capable to transmit the data from the sensors to the cloud. The tests done to the system were designed taking into consideration the problem characteristics presented in section 4.1. However, some features and functionalities can be added and improved as it is explained in future works (c.f. section 6.2).

In summary, it can be concluded that the hypothesis formulated in section 1.3 is a valid hypothesis, and that the created architecture is capable of handling with the objectives defined. Furthermore, since the industrial target of this implementation was the SME's, the proposed middleware solution was achieved successfully once it fulfilled the main objectives and it was able to collect data from sources and send it to the cloud, detecting and filtering the unnecessary data. The main achievements are the realization of IoT middleware solution that allows extendibility across different protocols and increase the dependability of the data collected by eliminating faulty data at the source. At the same time the solution presented decreases communication and processing overload between the data producers and consumers.

Another important aspect of the developed solution is affordability both from the perspective of installation cost and resource consumption. In fact, the technology used is quite affordable. The sensors and microcontrollers used are easily to acquire as well as the device to develop the hub. This last one, despite of being affordable, has a considerable processing capacity, being capable of supporting communication with multiple sensors and respective acquisition and pre-filtering data for onward delivery to the DCF.

5.4. Scientific and Industrial Validation

The research results of this dissertation mainly the implementation has been performed in close collaboration with GRIS, UNINOVA. The Group of Research in Interoperability of Systems (GRIS) is inserted in the centre of technology and systems Uninova research institute, which belongs to the Faculty of Science and Technology of Universidade Nova de Lisboa (UNL), and is part of this project. Its main contribution is the scientific development and technological solutions in the field of interoperability of systems and applications, to be subsequently used in industry (Uninova 2014). Besides the industrial use-cases from the FP8-FoF project C2NET, the implementation is based the following publication of the fellow researchers at GRIS, UNINOVA:

- Sudeep Ghimire; Raquel Melo; José Ferreira; Carlos Agostinho and Ricardo Gonçalves: "*Continuous Data Collection Framework for Manufacturing Industries*". OTM Workshops 2015: 29-40 (Ghimire et al. 2012)

- AGOSTINHO, C. et al., 2016. *A Distributed Middleware Solution for Continuous Data Collection in Manufacturing Environments*, IESA-2016 Workshop on Cloud Collaborative Manufacturing Networks (AGOSTINHO et al. 2016)

On the industrial validation front, this research work has been performed in the scope of C2NET - Cloud Collaborative Manufacturing Networks – which aims to increase productivity, reduce complexity for the decentralization of production systems, as well as to increase the reaction of businesses to changing tools and optimization that the market demands. This project is mainly directed to SMEs, due to the fact that it has scarce access to self-management as it requires more advanced efficiency tools and help increase competitiveness systems (C2NetProject 2015).

The research results from this thesis are being applied in the industrial use-cases being developed in the C2NET scope which can be understood in details from (C2NET Consortium 2015). C2NET is an ongoing project thus, actual industrial validation results are not available currently.

6. Conclusions and Future Work

6.1. Conclusions

In an IoT paradigm, distributed scenario prevails where the data sources are physically separated and are often consumer by autonomous data consumers, which are often the higher level applications with functionality for high-end data analytics and event detection. But, these type of distributed scenario can create lots of problems for scalability and maintenance if the data sources and data consumers are tightly coupled. It, means the changes in the standards of data sources or consumers for communication and data exchange changes, the overall systems needs to undergo respective changes to deal with the new requirements. So, it is an utmost industrial and technological solution need to have a system for seamless integration of data sources with high level of abstraction between the data sources and consumers. . Middleware aims to reduce the complexity of such systems by hiding unnecessary details. As with most types of software, there are many different types of middleware, each having different aims and their own set of advantages and disadvantages. There are no good or bad types of middleware; the best choice depends on both the task at hand and the skills of the team who will be using it.

This research work presents a technological solution along with necessary reference architecture for scalable for IoT Middleware. The approach that has been presented will enhance the use of IoT in the industrial world and seamless integration of existing legacy devices. Besides the technological solution this research work also provides detailed study on the challenges and issues in IoT paradigm that can pave path for further research and implementations. The results from this dissertation also play an important part for realization of complete C2NET data collection framework. In comparison to some existing solutions in IoT paradigm, the main advantage of this solution is affordability because the test results by utilizing low-powered computing resources such as raspberry-pi has produced results as expected. Thus, the technical results from this research work can be an affordable solution for SMEs who want to deploy IoT based solutions.

6.2. Future Work

One of the possible enhancements that could be applied to the architecture developed is the integration of **security** constraints such as data authentication, access control and client privacy.

The issues that can be associated in an unsecure system are enormous and to deploy this software in an industrial vision is crucial to put data security on a par with the quality of a product. Since there are several aspects to consider and data security must be made at a later stage to the implementation of the product, this aspect was taken into account in some parameters but was has not been developed in the current implementation. Building security and trust over IoT ecosystem can be an interesting and challenging future work.

The next future work that needs to be undertaken is extending the solution and testing with other different types of devices and their respective standards. Even, though the solution supports easy integration of protocol adapters, it requires the implementation of protocol adapter module to handle more protocols such as Bluetooth, RFID or NFC. At the same time some further enhancements are necessary in the data filtering component to enable specification of more complex data filtering for instance by utilizing the rules that can be applied over a long stream of data rather than a single data stream. Other direction that be taken for the data filtering process is making use of statistical analysis to re-construct missing data in the collected stream. Note that statistical analysis consumes quite a lot of resources, so doesn’t fit in the requirement of light-weight IoT middleware, but can be a very interesting solution for cases with higher computing resources.

Another future work is towards the compatibility of the solution across various platforms. Currently the solution is compliant with Debian OS and all the tests were performed in the scope of Debian OS. It will also be an interesting challenge to further reduce the resource consumption by the solution and test them on other low-resources computing devices.

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