SUPPORTING THE INDUSTRIAL TRANSFORMATION: A SMART RETROFIT ARCHITECTURE AND A LEARNING PLATFORM FOR INDUSTRY 4.0

by

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(Under the Direction of Jaime Camelio)

ABSTRACT

With the rise of Industry 4.0, it is critical to manufacturers from all different sectors to begin integrating the new paradigms that come with it. However, SMEs are at a high risk of falling behind due to the complexity and economic barriers that are involved in this process. As a potential approach, Smart Retrofitting has gained traction as a way of transforming available equipment into I4.0 enabled machines, and researchers have throughout the literature proposed various frameworks that seek to reduce the existing knowledge gap; however, the focus has been heavily towards retrofit for sensing capabilities, leaving smart control unexplored. This work addresses this gap by expanding on the literature and presenting a more comprehensive architecture that takes into account the complete potential of smart retrofit. Additionally, a learning platform is developed which intends to bring awareness of the potential of I4.0 technology to both manufacturers and students.

INDEX WORDS: Internet of Things, Smart Retrofit, Legacy Equipment, Industry 4.0, Smart Manufacturing

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DEDICATION

I want to dedicate this thesis to my family who has supported me throughout my entire life, my friends for always supporting me (yes, especially you, Jose) and, more than anything else, I want to dedicate this work to my amazing wife Carolina Araya who has been, in her infinite patience, nothing but helpful, supportive and an incredible life partner, which whom without her I would probably not have achieved this degree.

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CHAPTER 1

INTRODUCTION

Motivation

The Digital Transformation has been a rising topic in manufacturing, as the advances in Industry 4.0 (I4.0) and the value of these technologies keep on advancing over time. Through these, organizations will be able to achieve levels of optimization that was previously not possible, thanks to the immense amount of information that will now be possible to not just collect, but fully utilize through I4.0 technologies [3]. This incoming industrial revolution does not come only with benefits, however, as it also comes with the risks of falling behind should manufacturers fail to integrate it. Companies that ignore what Industry 4.0 entails and do not make an effort to incorporate these new technologies and exploit the value that comes with them risk not just being outperformed by competition, but entirely falling out of relevancy in the industry [3]. It is no surprise that I4.0 has caught the attention of organizations both large and small. However, adjusting to this large paradigm shift is not a trivial matter. While larger companies may have an easier time integrating themselves into the Industry 4.0 environment due to larger investment power as well as capable personnel, it's a different situation for small and medium-sized enterprises (SMEs). For them, the adoption of I4.0 comes with economic requirements that may not be possible or not considered worth it for their comparatively smaller scale context [4], especially as this adoption requires the inclusion of I4.0-capable equipment which may not be already present on their respective facilities. There is also a large knowledge gap introduced by the complexity of these technologies, and their rapid advancement has only been making this gap even larger [5]. SMEs may not possess capable engineers to integrate advanced systems like Industrial Internet of Things (IIoT) or Digital twins, and the requirement of these experts only further increases the cost of I4.0 adoption.

Definition of the problem

To aid in the introduction of Industry 4.0, the idea of smart retrofitting has been gaining popularity as it presents a new alternative to manufacturers on how to integrate their processes into the I4.0 space. The core idea of retrofitting revolves around reutilizing already existing machines and systems, as opposed to replacing them with more capable equipment, and seeks to achieve this through the addition of smart components that would enable these legacy machines to function along these new I4.0 technologies like IIoT. Essentially, instead of replacing old equipment, it is upgraded and brought up to a level that enables them to be integrated into an I4.0 system by introducing smart monitoring and control capabilities. The process of retrofitting does come with its own challenges and technical knowledge barriers, which makes the entry for SMEs to an I4.0 environment much harder. As such, researchers have proposed numerous Frameworks, Methodologies, Architectures and presented various use case examples to facilitate the understanding of the retrofitting process, its requirements and its potential value and capabilities. Due to the novelty of retrofitting, however, a large part of the coverage by literature is focused only on adding smart sensing capabilities while smart control, which inherently requires sensing to function, has been less explored.

Another issue that some SMEs may be facing is that, while they may be aware of the potential of I4.0, they may not be able to consider applications to their own scale viable, thus giving them the wrong idea that I4.0 may only be reasonable to apply on larger systems. In some cases, some SMEs may only have a rough idea of what concepts like IIoT, Digital Twins and other I4.0 technologies mean, but may not possess a full image or what these actually involve and the value they bring. There is also the misconception that these technologies require extensive teams of experts to begin grasping an idea of how to introduce to the present systems which, while this notion may have been correct on the infancy of these technologies, is nowadays an outdated understanding of the requirements of I4.0, as the advances of technology and commercially available tools have made the introduction of these systems much easier than one may initially perceive. In a similar manner, due to most of these concepts and knowledge being somewhat recent, students may not be fully aware of the knowledge that is being desired in future engineers, as well as the general existence of this upcoming industrial revolution and its importance on manufacturers.

Research objectives

As an attempt to alleviate the previously mentioned problems, this thesis presents two research objectives:

1) To address the existing knowledge gap in retrofitting frameworks, this thesis will dive deeper into the literature to fully understand this gap and help mitigate it by proposing an architecture that encompasses the addition of both sensing and control through retrofitting, focused towards helping manufacturers perform their first steps into a smart system through a low complexity implementation. To contribute further aid, a deeper differentiation will be made between the types of sensing and control components that can be added through retrofitting, which directly depends on the already existing capabilities of the equipment to be retrofitted. While this has been mentioned previously in the

literature, it has been done so more on a surface level. For this differentiation, a taxonomy will be proposed that explains the functional requirements of each type of sensing and control components, or modules as denominated in said taxonomy, as well as in which case each is used. Through this taxonomy, a clearer idea will be presented on the functional additions that must be performed based on the existing capabilities of the legacy machine to be retrofitted.

2) To further address the knowledge gap and misconceptions of I4.0 from SMEs and students, a physical learning platform will be created using the proposed retrofitting architecture, which will expose both manufacturers and students to the different aspects and technologies of Industry 4.0, while also demonstrating the implementation of the architecture. This platform aims to diminish this false perception of extreme complexity and cost of Industry 4.0 technologies from manufacturers, as well as bringing awareness to the skills and capabilities that these require as a potential career option for future engineers.

Organization of this thesis

The organization of this thesis is as follows. Chapter 2 will begin with a formal definition of Industry 4.0, followed by a review of the literature regarding smart retrofitting, covering the current state of the art of retrofitting frameworks, methodologies, architectures and applications. It will categorize the found literature and through a discussion of it present a gap in current architectures. Chapter 3 will propose a Smart Retrofit architecture that expands on the literature previously presented, which has the intention of filling the mentioned gap through a more comprehensive definition. Separately, Chapter 4 will then shift to the Industry 4.0 learning platform developed as part of this thesis. It will detail the design process of the physical demonstration, as well as mention the changes and the reasoning behind them between iterations of it. Finally, Chapter 5 will conclude this thesis, going over the contributions of the presented work, as well as proposing future works to be carried out.

CHAPTER 2

LITERATURE REVIEW

One of the goals of this thesis is to provide a valuable contribution to the literature of smart retrofitting, with the intention of aiding SMEs in their process of introducing themselves into Industry 4.0. As such, a review of the literature regarding retrofitting, Internet of Things (IoT) in manufacturing and Industry 4.0 was performed, in order to identify a knowledge gap. Before diving into this review, it is important to properly understand the context and concepts that are the foundation of the entire idea of smart retrofitting, and so this chapter will begin by formally defining the concept and the importance of Industry 4.0, as well as some challenges present when adopting this new paradigm. With this clear baseline, this chapter will then go into explaining what smart retrofit is before presenting a review and compilation of its literature, finalizing with an analysis of this in order to identify a knowledge gap in the state-of-the-art.

Industry 4.0

The concept of "Industry 4.0" (I4.0) was initially introduced in Germany in 2011 by Kagermann et al. [6], a term that has been since then used to describe the upcoming 4th industrial revolution. There are a few definitions about the idea of Industry 4.0 in the literature, however all of them remain somewhat similar. Overall, Industry 4.0 is referred to the next step in manufacturing evolution, driven by Data science and fully interconnected systems. It encompasses the advanced development and application of Cyber-Physical systems technologies, such as advanced data acquisition and control, Internet of Things, Cloud computing, Artificial intelligence and Augmented and Virtual reality applications [3][5][7][8]. Through the implementation of new technologies and communication protocols, the exponential growth of data acquisition enables the extraction of information and insights never before achievable. Data-intensive applications, such as any type of Artificial Intelligence, are now able to be developed and applied faster, while also being more accurate and capable than before, allowing the integration of these technologies into even more sectors of manufacturing. On top of that, the higher interconnectivity of different systems opens the possibilities for higher degrees of automation and the generation of smart factories, through the use of advanced simulation and Digital Twin technologies.

It suffices to say that adopting Industry 4.0 technologies and capabilities is a necessity for the manufacturing sector. Not adopting these is not simply a matter of missing out on better performance all around, but also a matter of remaining relevant to the industry altogether. Organizations that fail to adopt Industry 4.0 risk being replaced not just by competitors, but also by entire sectors [3]. Adopting these new technologies and paradigms is, however, not a trivial matter. If Industry 4.0 enabled equipment is not already in possession, it may be too complex to reshape and reconstruct the entire manufacturing process already in place, either because an entire process or even an entire facility revolves around a single piece of equipment or simply because the expenses for such an upgrade are way beyond the capabilities of the manufacturer, as it is especially the case for a large amount of SMEs [9]. In some cases, there may not even exist “better equipment” for more niche specialized equipment. Among the potential solutions to this problem, one in particular that has been gaining more popularity in the manufacturing sector is smart retrofitting, which allows manufacturers to join the Industry 4.0 space without having to entirely reshape their entire businesses.

Smart retrofitting

Smart retrofitting (also referred to as IoT retrofitting or digital retrofitting) refers to the process of taking a device or machinery that does not possess IoT capabilities and applying modifications or additions to it that would enable it to be integrated into a Cyber-Physical system. These modifications expand the original capabilities of the machine by adding remote connectivity and communication functionality, thus improving on the data acquisition and control of the machine [10][11]. Smart retrofitting exists as the alternative for manufacturers to bring existing equipment or legacy machines into an Industry 4.0 standard, without the need for high capital investment that would come with the replacement of a more state-of-the-art version, if there even is one. This approach is also more financially and environmentally sustainable thanks to the reuse of old machinery and the increase of efficiency that comes with the retrofitting, as well as bringing more social sustainability as operators are provided with more information and control over their equipment, thus enhancing their safety and decision-making [11]. Retrofitting is more commonly performed on legacy or older equipment that does not already possess IoT or digital capabilities, however it can also be applied to more state-of-the-art equipment, especially if these can't already have the collect some specific type of data, or if the communication protocols compatible with the equipment are different from the ones in use on the current IoT system [10][11]. It's also worth mentioning that, while it's more common to think of the owners of the machinery as the ones applying smart retrofitting to their equipment, retrofit has also been proposed as a service from the Original Equipment Manufacturers as a new market opportunity [12].

While retrofitting is a very promising direction to take, especially for SMEs as a method of integrating themselves into what Industry 4.0 entails, it remains a complex process. To successfully retrofit legacy or new equipment, a high degree of technical expertise is required both in terms of hardware and software knowledge [13]. This then comes as yet another roadblock, as knowledge of communication protocols, electronics, mechanical engineering, programming, available sensors, controllers and their required hardware may not come easy especially for SMEs, which are unlikely to have enough capable personnel. With the purpose of aiding manufacturers in the application of retrofitting technologies, many use case examples and frameworks have been proposed in the literature.

State of the art on retrofitting

In order to design a Smart Retrofit Framework that represents a contribution to the literature, a review of the state of the art in smart retrofitting literature is performed to understand what is currently presented, what works and what is missing. Before diving into existing Smart Retrofit Frameworks and Methodologies, it is worth first mentioning the Reference Architecture Model Industrie 4.0 (RAMI 4.0) [14], which could be considered the current base standard when referring to most I4.0 models. The architecture, shown in Figure 1, is separated into 3 different axes. The Hierarchy axis, which expands from the IEC 62264 standard, presents the different layers in a system, from the product itself all the way to the Enterprise and the connected world, and emphasizes a complete interconnection across all levels, where normally in previous architectures each would only be interacting with their "neighboring" level. The Life cycle and value stream axis expands on the IEC 62890 standard and is used to represent an element on the different states of its lifecycle. Finally, the Layer axis is used to position different aspects of an element, from the actual physical and tangible Asset, to the Communication protocols and data transmission involved in it, all the way to the business processes associated. RAMI4.0 presents the fundamental structure of Industry 4.0 and intents to help visualize it, by enabling the mapping of different components and processes from different levels and lifecycle states of a manufacturing system, which in turn helps identifying gaps and opportunities.

RAMI4.0 also introduces the concept of the Asset Administration Shell (AAS). An AAS corresponds to the virtualization of a physical non-I4.0 compliant device, which it brings into an I4.0 enabled space through the connection, capture and control of this asset. Through its AAS, the device is capable of communication with other devices' AAS and I4.0 components, while still maintaining its core functionality.

While these frameworks serve as a good foundation of the architecture of an IoT system, they remain somewhat vague in the procedure to implement them, as well as in the components required to do so. For this reason, many researchers have developed various Frameworks that would help manufacturers through the process of retrofitting.

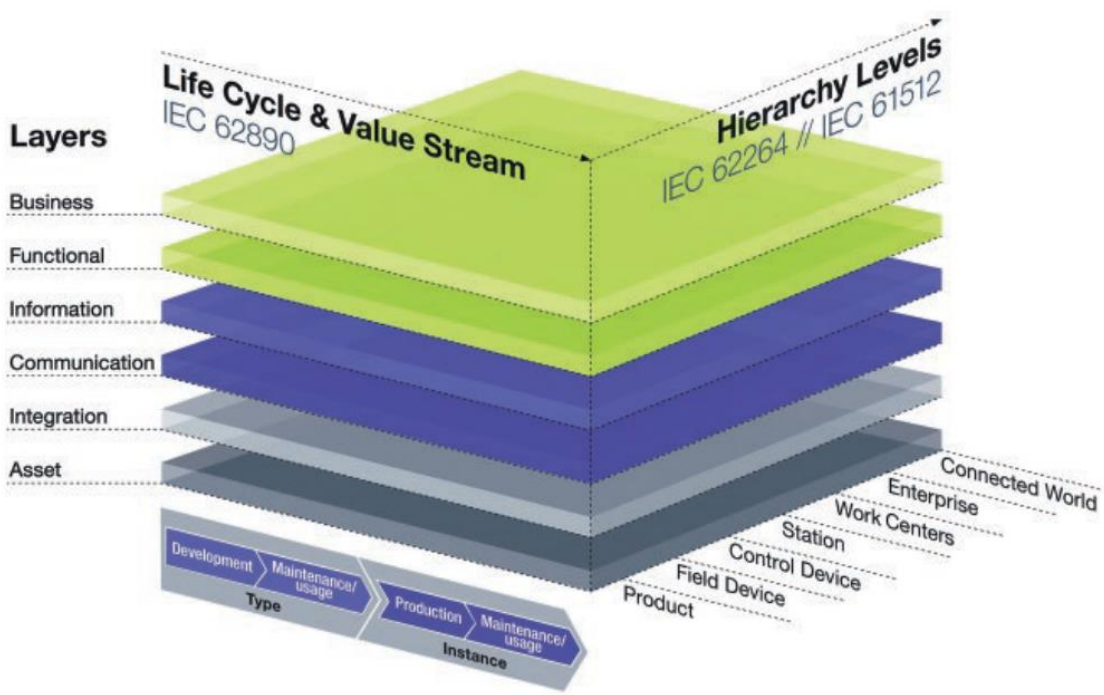

Figure 1: Reference Architecture Model for Industrie 4.0 (RAMI4.0). Source: [14]

To understand the state of the art of Retrofitting frameworks and methodologies, a search of the literature is performed in platforms such as Google Scholar and IEEE with various combinations of the keywords “IoT”, “Retrofit”, “Retrofitting”, “manufacturing” and “Industry”. Between the relevant papers compiled, a few Literature Reviews were also found, out of which Alqoud et al.’s [8] was of particular interest as it performed a review related to smart retrofit on legacy equipment, where it aims to filter and compile papers that specifically enter into the detail of smart retrofitting either in terms of application or theory, which align with the interests of this thesis. After compiling relevant literature alongside the one found in Alqoud et al.’s work [8], a total of 55 papers were gathered that contribute to the smart retrofit framework literature.

In terms of what can be found in the literature of smart retrofitting frameworks, a trend was noticed where most papers would present one or more of three common topics: Methodologies, Architectures and Use cases. Methodologies refer to a step-by-step guide on the process of retrofitting, including steps such as requirement analysis, economic considerations and post-retrofit validations. Architectures on the other hand provide an abstract representation of the retrofit structure, giving an idea of the different elements, components and requirements that would be involved in the retrofit process or a retrofitted system, and proposing the abstracted structure they would have, as well as their interactions with each other. For this review a difference is also made between Architectures and Use cases. Where the former presents a generalized way of defining the structure of a retrofitted system, an Use case explains one well defined solution with specific technologies, or the application or implementation of a previously presented Methodology or Architecture presented as a case study.

A different combination of these three topics is found in the literature. To show a few examples, Tantscher et. al. [10] presents a step-by-step guide on how to design, develop, integrate and later verify and validate an IoT system *(Methodology)*, followed by presenting an example of the application of this methodology *(Use Case)*. Hawkridge et al. [15] proposes a low-cost IoT *Architecture*, in which they separate it in Data Collection, Data Management and Storage, Analysis and User Interface blocks, while also describing the general contents of each block and, alongside a questionnaire and guide to implementing this proposed blueprint *(Methodology)*. They finish off with a case study in which they implement the proposed Methodology and Architecture through the retrofitting of a 3D printing system *(Use Case)*. Some papers also focus entirely on a specific application or *Use Case*, as is the case of Jónasdóttir et al. [16], where they showcase a non-invasive form of retrofit through the development and use of an external device, which latches on to the controls of a CNC machine that an operator would use, and controls it through actuation that mimics button presses, as well as being able to monitor specific parameters of the machine. Lima et al. [17] too focuses only on a specific solution, showing an example of retrofitting a 20 year old CNC machine for the purpose of maintenance, where with the help of an energy sensor along with an IoT gateway they are able to send energy readings into an IoT Cloud platform where it can be further monitored, as well as used in a Genetic Algorithm and a Neural Network to predict power consumption.

In order to further organize the found literature Table 1 is created, which compiles the found literature indicating whether each paper includes either of the three described topics. The distinction is also made between papers that only consider retrofitting for the purposes of incorporating new sensing capabilities or if they also take into consideration the possibility of remote or automated control that can be gained with the retrofit. The reason a third category of “Only control” is not present is due to the fact that control inherently implies sensing, as in order to control a particular parameter it is necessary to know its value in the first place. The purpose of this categorization is to better visualize how much each of the three common topics are covered in the current literature. With the separation of “sensing only” and “sensing and control” it is also possible how as well as how many of the proposed frameworks and use cases actually cover the whole spectrum of retrofitting, or if they focus only on sensing and monitoring. Thus Table 1 was constructed with the aim of aiding the search of a gap for this thesis.

Control in smart retrofitting

As mentioned before, most if not all remote control capabilities are directly dependent on the ability to measure, as it is necessary to know the parameter to be controlled before being able to control it, lest one blindly operate the respective device or equipment. It is of no surprise then that most of the present literature regarding retrofit frameworks and applications focuses only on the addition of sensing capabilities. Just the addition of monitoring of a single new parameter can produce an immense value through the new insights and information it can produce, be it for the purpose of predictive maintenance, process improvement through historical data analytics, or simple remote monitoring.

Because of this, however, there is a noticeable lack of coverage of smart control. Only focusing on sensing leaves out half of potential of smart retrofitting not fully explored. This is not to say that Methodologies that only mention sensing and monitoring are incomplete, as most of them are thorough enough to be used for a control environment as they are or with very minor additions. It is however the Architectures that suffer more of this lesser coverage, as while they are complete in the scope of sensing, may not represent the complete capabilities of Retrofitting.

Out of the 55 papers found and presented in Table 1, only 14 mention or utilize retrofitting as means of remote smart control, where 3 papers present a Methodology (Pueo et al. [18], García et al. [19] and Carlo et al. [20]), 2 papers present an Architecture (Etz et al. [21] and Dietrich et al. [22]) and 2 papers present both (Lins et al. [23] and [24]). Out of these 16 only 3 do not include a Use Case, Lins et al. [23] being one of these, as it only proposes a design methodology and applies it through a theoretical architecture but does not bring it into realization. The design methodology they propose focuses on mapping and defining Customer Needs and building the design constraints and requirements around these. While this methodology is specifically aimed at the retrofit of CNC machines, it should be able to be adapted outside of these. Their architecture, however, is more a result of theoretically applying their methodology rather than something that can be utilized in other systems. On the opposite side, Etz et al. [21] proposes a more generalized architecture to retrofit legacy robots into an OPC UA enabled space. It however falls short as the proposed architecture is too generic and focuses too much on the structure of the information transmitted instead of how to enable this data collection and control, or assumes the retrofitted device already comes with network interface to do this connection. Dietrich et al. [22] focuses more on the software side of smart retrofitting, proposing a control software architecture that deviates from the usual multi-layer architecture used to define software systems in favor of an hexagonal structure that properly captures how interaction with the system from different sides (users, programs, automated tests, etc.) all affect the application equally. This paper's architecture does not touch however on the physical side of smart retrofitting, and instead use Lins et al.'s [24] work as a reference to build their use case. Finally, Lins et al. [24] proposes a retrofit methodology that takes into consideration both the technologies and functions that are desired to be added to the machine and the ones it already has, making emphasis on integrating what the original equipment is already providing in terms of infrastructure, communication and applications. Using RAMI4.0 as a baseline, it defines a general retrofit architecture, with which it then proposes a machine independent retrofit platform, validating it through a case study implementation.

Moving into Methodology-only papers, and still using RAMI4.0 as a reference, García et al. [19] proposes a guide to retrofitting, this time focusing on the application of the AAS proposed alongside RAMI4.0, as well as using OPC UA as their main communication protocol. They define the steps involved in the process of retrofitting, essentially building up the AAS of a specific piece of equipment, beginning with the definition and design of the system architecture, its IT platform, information model, the specific views to access information and a later validation of the design. This is then followed up with guidance on how to implement the designed retrofit. They don't exactly propose a specific architecture, as they indicate the one presented is specific to the use case they are presenting, rather than a general AAS architecture. Pueo et al. [18] proposes a 7 step Methodology to aid SME's engineers through a retrofit process, as they must temporarily become designers of this one-off product. This methodology goes into detail from planning and design all the way to implementation and validation phases, specifying intermediate steps and requirements, and the deliverables of each phase. They follow up by retrofitting a "gear profile tester" to showcase the implementation of their proposed methodology. Carlo et al. [20] proposes a more general methodology with the purpose of retrofitting an old process plant. It is divided into 4 steps: Definition of objectives, Analysis of the current state of the plant, the retrofit process and the implementation of user interfaces. The intentions of this paper are focused more on their retrofit use case, which is why the methodology is left in a more generalized state. Despite this, it still presents a good reference of the retrofit process itself.

Gaps in the literature

From the reviewed literature, it is possible to assert that the retrofit process has been thoroughly defined and explained. It may be more beneficial to follow a more detailed and complex or more generalized and simpler methodology, all depending on the possessed knowledge on the relevant technologies as well as the desired scope. Between methodologies whose focus leans more towards retrofit for maintenance like Duque et al.'s [25], methodologies which consider economic feasibility and attempt a retrofit without stopping a running system such as Nowacki et al.'s [26], to more generalized guidelines for smaller implementations like the one presented by Pessoa et al.'s [27], the retrofit process seems to be properly covered. As mentioned before, methodologies do not suffer greatly from the lack of control-oriented literature, as most of them either refer to a function-agnostic guideline or can easily be brought into the scope of sensing and control with minor additions. Architectures on the other hand do not possess this advantage, and while there are plenty of architectural frameworks to build I4.0 systems for the purpose of adding data collection capabilities, there is a scarcity of smart control retrofitting architectures, leaving those interested without a clear image or structure on how additional control capabilities look like and what they are composed of.

Another point of interest that was caught during the review of the presented literature regarding the elements introduced in a smart retrofit, particularly those directly applied to the retrofitted equipment. It is clear that taking into account the current capabilities of the retrofitted machine is an important factor in the manner it will be retrofitted, with some methodologies explicitly stating that this is a key consideration to take into account on the steps prior to the actual retrofit [23][26][28][29][30]. Despite this, current architectures do not take into account or explicitly mention the potential differences that different implementations of sensors and controllers may have, as they may or may not greatly differ depending on the capabilities that the equipment to retrofit already possesses and may change the functions that the elements introduced during the retrofit may need to perform. For example, Hawkridge et al. [15] explains on its proposed architecture the different parts, or blocks as they refer to them, of a retrofitted system as most architectures do, while also go into detail of what each block is composed of. However, they bundle all the possible functions that their data collection block could have and cover differences in implementations through their optional building blocks that may or may not be needed. Nowacki et al. [26] makes a more explicit differentiation of sensing components on their reference architecture, where the elements added for data capture and transmission directly depend on what the machine has to offer. However, since their contributions were focused more on their proposed methodology, these differences are made on a surface level, mentioning only the names of the different technologies that can be applied and not diving any deeper on what each of these are.

With these two previous points into consideration, this thesis aims to propose a smart retrofit architecture that expands on the current literature and expands on these gaps. First, the presented architecture will consider the addition of both sensing and control capabilities into the retrofitted legacy equipment, taking more advantage of the benefit from both sides of retrofitting. Secondly, an explicit distinction will be made between the components that need to be added during retrofit based on the existing capabilities, or lack thereof, of the legacy equipment to be retrofitted. A comprehensive taxonomy will be proposed in order to clearly define these differences, where the concept of sensing and control modules will be introduced, as well as the definition of different module types for both of them. These types of modules will differ from each other based on the context that they should be applied, which directly depends on the capabilities of the legacy machine prior to its retrofit. Through the proposed architecture, the functional requirements of each of these types of modules will be described, focusing on the different tasks that the components of a module should perform based on its type. The module compositions focus on these functional requirements rather than defining specific hardware, as the same kind of functionality can be achieved with different numbers of elements based on how it's implemented.

A retrofitted machine requires an IoT system to be part of, or else the retrofit loses its purpose. As such, to present a more comprehensive architecture the implementation of an IoT platform will be included as part of the architecture. The main goal of this architecture remains to be an aid for SMEs to begin their introduction into I4.0 environments, and as such the proposed system architecture will intend to present itself through a simplified structure. To achieve this, an expanded system architecture will be designed expanding on the work done by Hawkridge et al. [15], whose proposed retrofit blueprint is meant to be a first step into IoT systems for SMEs, which can later be expanded into more complex ones. Some inspiration will also be taken from Hawkridge et al. [15] for this architecture on its definition of the previously mentioned module types, particularly from the composition of their data collection block. While they do not perform the differentiation that this architecture aims for, the composition of this data collection block showcases both in a simple and comprehensive manner the set of components that this block requires. As such, a similar way of defining the functional requirements of each type of module will be presented.

Table 1**:** Smart retrofit frameworks and applications found in the literature.

REFERENCE	*METHODOLOGY*	*ARCHITECTURE*	*USE CASE*	*SENSING ONLY*	*SENSING & CONTROL*
[31]			✓	✓	
[32]			✓	✓	
[23]	✓	✓			✓
[33]		✓	✓	✓	
[34]			✓		✓
[35]			✓		✓
[36]		✓	✓	✓	
[37]			✓	✓	
[38]			✓	✓	
[26]	✓	✓		✓	
[39]		✓	✓	✓	
[40]		✓		✓	
[24]	✓	✓	✓		✓
[41]	✓		✓	✓	
[18]	✓		✓		✓
[28]	✓		✓	✓	
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[42]		✓	✓	✓	
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[27]	✓		✓	✓	
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CHAPTER 3

SMART RETROFIT ARCHITECTURE

This chapter presents a novel architecture for the smart retrofit of legacy equipment, designed to fill in the gaps found in the literature of smart retrofitting. By expanding on the retrofit blueprint proposed by Hawkridge et al. [15], an overall system architecture will be defined which encompasses the basic functionality requirements of an IoT system. The proposed architecture will encompass a more comprehensive vision of smart retrofitting by considering the integration of both sensing and control additions capabilities. A comprehensive taxonomy will also be defined, which defines the set of added components as “modules”, and further differentiates between types of sensing and control modules, making a clear separation based on their depth of integration within the retrofitted machine and thus the amount of intervention and modifications required on the original equipment. A complete description of each module type will be presented, describing the different situations where each should be applied depending on the existing capabilities of the legacy machine to be retrofitted, as well as the functionality that each module should fulfill. Finally, a retrofit use case will be utilized to visualize the presented architecture in a real retrofit scenario, where the retrofit performed on a pecan cracking machine will be described through the proposed architecture. Through these contributions, this thesis aims to provide a more comprehensive view of the elements involved in a smart retrofit and thus aid in its design process.

System architecture

Before diving into the differences between sensing and control modules that a machine is subjected to during its retrofit, it is important to present an overview of the complete system that would ultimately result from this process. It does not suffice to retrofit a machine to collect information and enable smart control, but it is also crucial to develop a proper IoT platform capable of capturing, storing, analyzing and displaying the information gathered from the applied sensor modules, as well as its ability to use this newfound data to control and automatize the now smart equipment through its control modules. Following a similar idea from Hawkridge et al. [15], one of the intentions of the proposed system architecture is to remain somewhat simple, as one of its goals is to aid SMEs into understanding the general composition of an IoT system. Where a more extensively detailed architecture may help in higher scale applications, this architecture aims to showcase the first step for manufacturers in adopting the new I4.0 paradigms, which would allow later on for more powerful yet complicated systems.

The complete system architecture, presented in Figure *2*, is separated into the different requirements that an IoT system should fulfill in order to consider it a complete system. More specifically, the top "blocks" represent the functionality of the different elements of an IoT platform, all of which must have the ability to communicate through a common service layer. It is important to note that, while each requirement is shown as its own block, it does not imply that each should be handled individually by separate hardware. A single computing device could encompass the functionality of multiple or even all requirements. Although the latter is often the common implementation, it is left open to the decision of those who implement this architecture whether or not to separate one or more blocks on its own separate hardware. As such, each requirement will be described as if they were independent from each other.

First, a user interface is required, which should enable users to directly interact with the system. This interface can be implemented in various ways, such as a device-specific application or as a web application capable of being accessed through multiple devices. It should possess the ability to display the information that is being gathered either numerically and visually through graphs, gauges or other forms of visualizations, for present and past history of these values. It is also through this interface that users should be able to perform the control of the machine utilizing the introduced control modules. This interface should allow for further organization of these different displays and controls by users, in order to focus on the elements that are most relevant for them. It is also through available user interfaces that users would gain access to other functions of the system to access its databases, manage data processing algorithms, and develop and deploy automations. Unless complete access by all users is desired, the platform hosting this interface

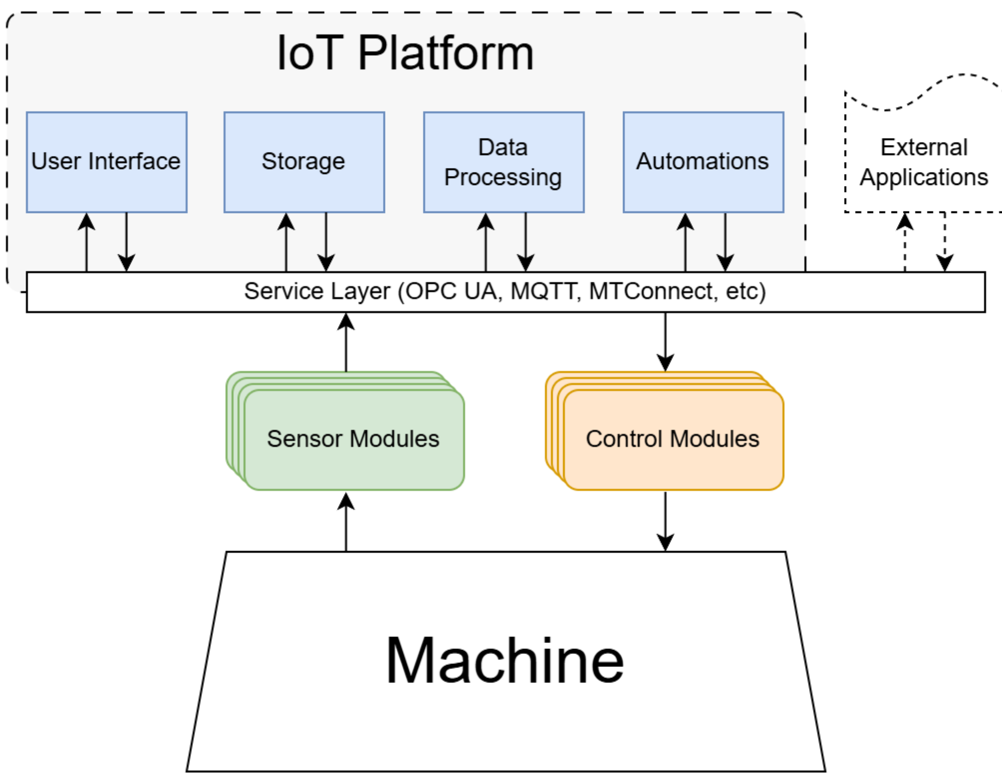

Figure 2: Complete system architecture

should allow system administrators to limit the access of users to only certain parts of the system, as to protect more fragile or critical parts of it from the general user. In the same manner, limitations must be put in place to limit the access to the interface itself to unauthorized personnel through authentication methods, such as the username and password requirements, among other options.

Another crucial requirement to an IoT platform is Storage capabilities. While just the possession of live data on the status of different parameters has its own undeniable value, the quantity of information that can be derived from the knowledge of a parameter throughout time is exponentially higher. Whether for short- or long-term storage, the device performing storage functions should have access to the appropriate physical storage media devices, such as hard drives, SSDs or others. Alternatively, this storage can be performed through cloud storage applications, although this raises the complexity of the system as well as the latency of the interaction with the stored data. On either case, the implemented storage system should allow for writing and reading of information to and from other parts of the system, should they require and be allowed to, which must be handled through an appropriate Database Management System (DBMS).

While not immediately required, a proper IoT platform should allow for the eventual implementation of data analytics algorithms for further Data Processing capabilities. Whether on the same hardware that performs data storage or not, access to the required data should be available to the computing unit responsible for performing the desired processing algorithms, both historical and live data, which allow for further information to be inferred from the already vast amounts obtained from the sensing modules.

In a similar way, the platform should allow for the development and deployment of system automations that take advantage of the access not just of incoming data, but also the ability to generate input towards the control modules introduced into the retrofitted equipment. As such, the hardware in charge of executing the developed automations should have the required access to the historical data of the machine's parameters, as well as the live information about these.

All of these previous components, as well as the sensing and control modules introduced into the machine, require means of communication with each other. For this, a service layer must be deployed which allows for the interconnectivity of the system through the ability to push data into it, as well as passively listen or actively request data from it. This communication should be done utilizing a specific communication protocol (OPC UA, MQTT, MTConnect, etc) and while more than one may be implemented and used, as not every device may "speak" in one protocol, it is recommended to keep the amount of implemented communication protocols to a minimum, as to not increase the complexity of the entire system. Besides the specific medium in which the data will be communicated (Wi-Fi, Ethernet, Bluetooth, etc.), for any communication protocol to function effectively it is essential to implement the fundamental infrastructure and components required by said protocol. For example, protocols such as MQTT rely on the deployment of a broker, consisting of a central messaging server that receives data from publishing clients and distributes it to subscribed clients. This can, once again, be done on its own separate device or be implemented on the same hardware as other parts of the system.

Finally, although not necessarily required, it is recommended to leave the system open to the integration of external applications, either through the IoT platform or directly through the service layer. While it is important to remain cautious while integrating foreign software, open-source applications offer the ability to integrate solutions already solved by developers or other companies that are likely to direct their focus to the betterment of their own work, allowing for the aggregation of complex functionality without spending mayor resources on their development.

Sensing modules

With the overall picture of the IoT system, it is now possible to move onto the retrofitting of the machine itself and the modules involved in this process, namely the proposed Sensing and Control Modules. A sensing module corresponds to the complete set of elements introduced into a machine as part of its retrofitting, with the intention of giving this machine the ability to capture the value of one or more parameters and be able to expose these to an IoT platform or system. A sensing module is functionally divided into 3 layers: *Acquisition* of the parameter's value, the *Pre-processing* of said acquisition to bring it from an analog signal into the digital space in a numeric form and *Transmission* of the resulting values into the present IoT system. Sensing modules can be structured differently depending on their depth of implementation relative to the equipment they

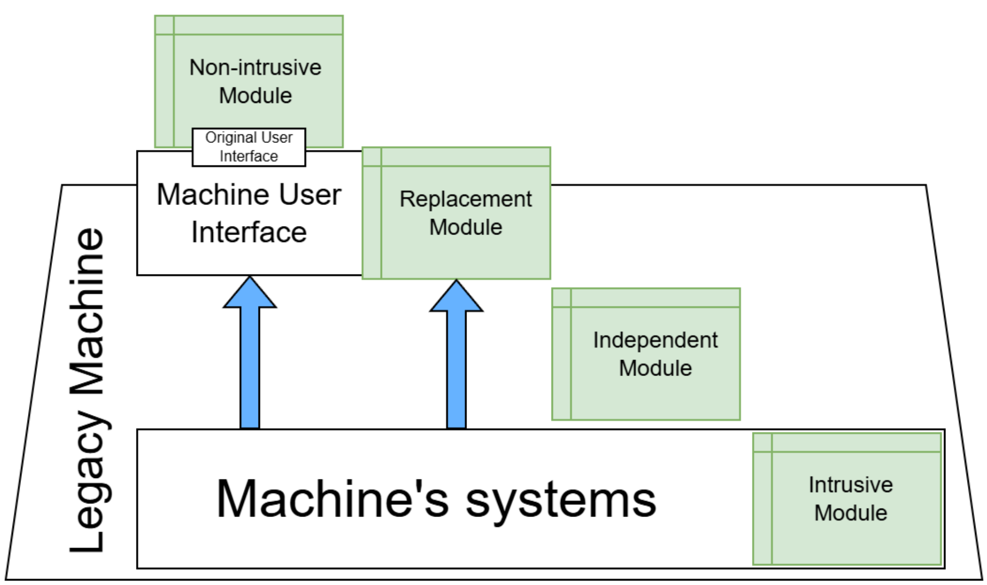

Figure 3: General overview of sensing modules based on their relative position to the original machine

are being integrated into. Four types of sensing modules are identified as presented in Figure *3*: Non-intrusive, Replacement, Independent and Intrusive. The implementation of each comes with a different depth of involvement and modifications of the original machine. Due to this, while their involved hardware may not greatly differ, there still are differences in the functional requirements that each must fulfill. These differences are presented in Figure 4, and will be explained in detail below.

Before explaining these functional differences, their similarities should first be presented. First, all of these modules require the ability to interface with and communicate through the service layer, in order to transmit the captured information, and as such should include components that enable this communication. These modules may also require performing a previous pre-processing of the captured data, be it by aggregation, filtering, or any other transformation over this data to acquire the desired information. It is important to perform these small pre-processing steps through these modules rather than on the IoT platform, should they be needed, as it greatly alleviates the

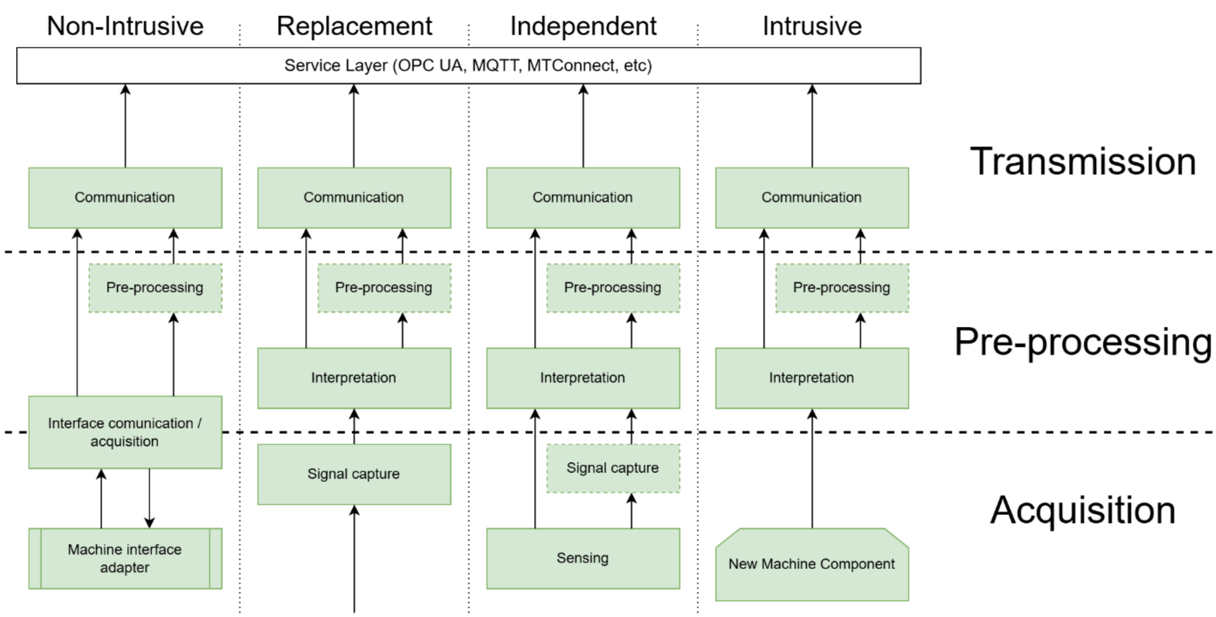

Figure 4: Functional requirements of each sensing module.

computational load that it would otherwise need to handle if tasked with performing processing tasks from every single module. Finally, every type of module can optionally incorporate a physical user interface on the machine or the legacy device itself, if monitoring by a physical operator is required. For sensing modules, it is mostly on the steps before the communication of the capture data where functional differences arise, which will be described bellow.

Non-intrusive

A *non-intrusive* sensing module is one that does very minor or no modifications to the retrofitted machine. It instead exploits an interface already exposed by the machine, be it electronic or mechanical, in order to obtain the values of the desired parameters. The largest advantage of this type of sensor is that, since it does not require modifications to the retrofitted machine, most of the development and construction processes of this module does not interfere with the regular operation of the legacy equipment. Even more, this type of module should be able to be easily removed from the machine if deemed appropriate to do so, and the machine itself and its functionality would not suffer in any way from the loss of this module. As this module takes advantage of the original equipment already being outfitted with the ability to provide information about itself, its task focuses instead on bringing these parameter values into IoT space. Besides the communication requirements, this module greatly differs from the rest as it requires a capable medium or adapter to interface with the machine that directly depends on the machine itself. It also requires the ability to, through the control of this medium, interface with the machine in order to obtain the exposed information, be it by passively capturing values as they arrive or actively requesting the machine to provide them. Once these values are obtained, it’s now a matter of preprocessing and formatting them in the right manner to be pushed into the service layer.

This type of sensor module is one of the more interesting ones in its freedom of application and complexity. The implementation of one of these modules can be done from a simple wired connection to the legacy equipment through an available Ethernet port or existing PLCs, to using image capture and recognition algorithms to visually "read" the original machine's indicators or gauges, as seen by Tran et al.'s work [67]. It is up to the engineers applying the retrofit to decide when does the complexity involved in the development of one of these modules outweighs the value gained by not modifying the original equipment, at which point it would be wiser to instead start working on the machine with the use of a different type of module.

Replacement

A *replacement* sensing module, similar to an adapter module, seeks to capture the value of a parameter that the machine is already measuring itself. However, in cases where it would be too complex or unreasonable to figure out an adapter to an existing interface is when Replacement sensing modules are used. In this case, modifications are performed on the machine, relative to the machine's interface level, in such a way that it still takes advantage of the machine providing the measurements. While the implementation of Replacement modules may seem similar to Non-intrusive modules there is a significant difference between around the fact that, as opposed to the latter, the former requires work to be done directly in the machine, which may need a halt on its operation.

The addition of this type of sensing module essentially involves upgrading, modifying or completely replacing the current user interface of the machine with IoT enabled technology. Because of this, the data acquisition of this module is simpler than the rest, as its functionality revolves around capturing and interpreting already existing signals into numerical values in a similar manner that the previous interface would, pre-processing these values if necessary and finally pushing them into the service layer.

Independent

More often than not the machine does not provide all the parameters that might be relevant to the functionality of itself or the process it is involved in. As such it is very common to add sensors with the purpose of acquiring information on new parameters. This makes the *independent* type of sensor module one of the most likely to be added while retrofitting legacy equipment. These modules are characterized by, as mentioned before, capturing new information that the machine was not already providing, without interfering with the machine's functionality or structure in a considerable manner. The integration of these sensing modules is performed through the addition of new components to the respective machine rather than the modification of already existing ones. This means that generally the largest alterations to the original equipment required for this type of sensing module mostly involve fixing the components of this module in place, which means that the original structure of the machine is often left intact. In some cases, these kind of sensor modules may not even be located in the machine, as they can be implemented as a previous or next step of the machine's process, to measure for example parameters of the machine's produced output. Besides this, the functional requirements of an Independent sensor module are similar to those of a Replacement module, with the addition of actual physical sensors to measure the desired parameters in the form of electrical signals, as well as a potential components capable of capturing these signals in cases where the physical sensors or sensing devices cannot perform their own communication to the service layer and as such a separate device is needed.

Intrusive

Intrusive sensing modules come into play when information is both not exposed by the legacy machine and not possible to acquire with just Independent modules, or using them would result in data acquisition less accurate than required. In this case, sensors have to be integrated into the inner workings of the legacy machine, which may come with some considerable modifications depending on what parameters must be captured. The addition of Intrusive sensor modules involves the upgrade of key parts of the machine their replacement with newer and “smarter” components that, besides continuing to fulfill their primary function, expose in some manner information about them that can be captured and further transmitted. With information being provided by this newer component, it only remains to be able to be able to gather and interpret the information provided by this newer component, pre-process it, and communicate it to the service layer. This can be either done through separate hardware or even by the upgraded device, if it presents those capabilities.

Control modules

Similarly to sensing modules, a *control module* encompasses the complete set of elements introduced into a machine as part of its retrofitting, with the intention of giving this machine the ability to remotely control one or more of its parameters through instructions generated from the respective IoT platform or system. Also like a sensing module, a control module’s functional requirements can be divided into the 3 layers, with these however being in the reverse direction. A Control module is then functionally composed of an *Acquisition* layer which should receive from the service layer inputs and instructions to be carried out, a *Processing* layer which transforms these digital instructions into the corresponding electrical signals and a *Transmission* layer, where these signals are propagated into the respective actuation component to be operated. As presented in Figure 5, Control modules can be divided into 3 categories, based on the level of involvement with the retrofitted machine and the requirements that must be fulfilled on each case: Non-intrusive, Replacement and Intrusive modules. While the functional requirements of each of these modules may slightly differ, as presented in Figure 6, all of them possess a few common requirements. First, all control modules must be able to interface and communicate with the service layer, in order to receive input generated from other sections of the IoT system. Additionally, all of these modules may include a physical user interface if direct interaction and control of the machine is desired by physical operators. Finally, these modules require means to translate incoming instructions and generate the correct signals to be transmitted into the respective actuator to be controlled.

While not explicitly shown on the presented graphics, there is one final and very important requirement for any control module implemented in a machine's retrofit: the value of the parameter intended to be controlled should also be known to the IoT platform, specifically to users or other

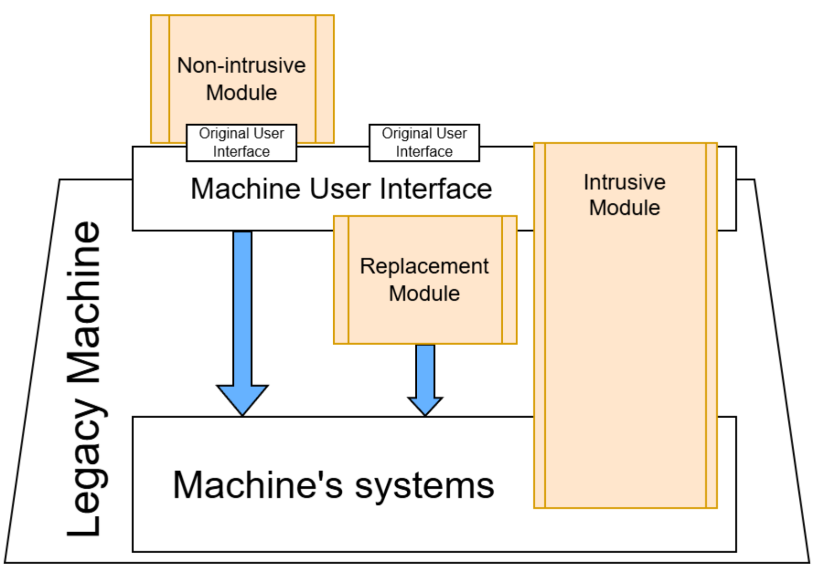

Figure 5: General overview of Control Modules based on their relative position to the original machine

systems that may perform remote control. This can be done either through a separate implementation of Sensor modules, or by incorporating Sensor and Control module functionality on the same device. While it may be possible to perform control without awareness of the status of the parameter being controlled, such as in cases where the state of a controlled device can be inferred post-initialization or “homing” or if the machine itself is the one that handles the control itself as is sometimes the case on non-intrusive implementations, it is generally risky to blindly control any kind of machine parameter, especially if doing so remotely and without direct view of the effects of the control on the machine.

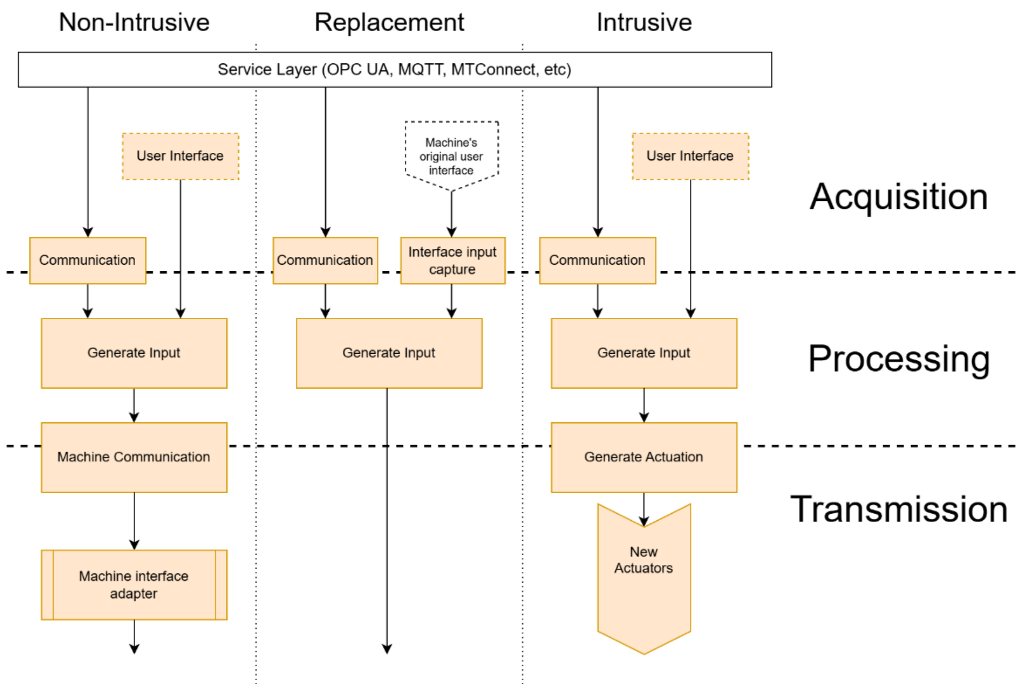

Figure 6: Functional requirements of each control module.

Non-intrusive

A *non-intrusive* control module is characterized by only needing minor or no modifications at all to the original legacy machine. Similarly to a sensor module of the same type, it is instead an external element or device that takes advantage of the already existing controls and interfaces of the machine. This presents once again the advantage of keeping the retrofitted equipment unaffected, at least from the introduction of this module, which enables the possibility of developing this module separately while the machine remains in operation as well as being able to be later removed in a way that leaves the equipment in the same state as it was before the module's introduction. To accomplish this, the module requires components capable of interfacing with the machine through its exposed controls, which can be either through intended sockets or ports, or in a more unintended way like performing actuation over manual switches and buttons. Regardless of the manner in which this module interfaces with the machine, this module should be able to generate the proper instructions from incoming input from the service layer or the optionally implemented local user interface, which must be further transformed in the necessary actions to be performed on the respective adapter, such as transmitting commands through serial communication. Because the implementation of this type of control module may involve direct communication with a machine's controller, it is common to simultaneously implement a non-intrusive sensor module through the same hardware, as actuator controllers would often also provide information about themselves or the parameter being controlled.

Like sensor modules of the same type, these modules present an interesting variety in the ways they can be implemented, as well as the challenges that arise depending on the corresponding machine interface intended to be used. These modules often show up when retrofitting equipment that already possesses forms of communication with other computing equipment, and as such simple interfaces like proper Ethernet or Serial port connections are all that is required to start communicating with the machine, which is often common for more modern equipment like newer CNC machines or robotic arms [19][21]. On the other hand, more complex implementations can be developed when attempting to introduce this kind of module on equipment that only possesses controls intended to be physically operated by a human being. As an example, Jónasdóttir et al. [16] developed a device capable of encapsulating the control panel of a CNC and operating it through actuation that allows the device to press on each button as an operator would normally do.

Replacement

Once direct modifications to the refactored equipment are needed is when it's better to move into *replacement* control modules. This type of modules require a moderate amount of modifications to the legacy machine, as it essentially replaces the functionality of the machine's original user interface in favor of better suited components that would enable their remote access. As such, it must be able to replicate the control signals that would previously be generated by the original controls in order to perform the respective actuation. Alternatively, this module can take advantage of an existing user interface, rather than directly discarding it. By being located between this original interface and the actuators of the machine, it can act as a "Middle-man" which receives input from the original controls and replicates them forward, while still being able to listen for instructions coming from the service layer. In this case, the hardware implemented requires not only a connection to the service layer, but also a way of capturing the original interface's inputs, both which should be transformed into the correct signals to perform the corresponding actuation.

This type of control could be considered the most "operator friendly", as it has the opportunity of maintaining the same user-facing controls that were previously used, allowing operators to perform their respective control without changing the way they would normally interact with the machine.

<u>*Intrusive*</u>

Finaly there are *intrusive* control modules. This type differs from the rest as the modifications on the original machine are not a consequence of the implementation of this module during retrofitting, but rather the opposite: Very heavy modifications are made on the machine or part of it in order to modify and/or add functionality that it previously did not possess, and as such a completely new controller is required to handle it. The implementation of this module includes the addition of new actuation that would allow the machine to perform new functions that would enhance the process or resulting product from it, or perform in an automated manner previously existing functions that originally direct required manual, like a hand crank, in which the speed and precision of this control heavily depends on the capabilities of the respective operator. In these cases, forms of actuation are introduced that can allow not just for automated control, but one that is performed more efficiently and accurately. Like non-intrusive modules, a retrofit component that fulfills the role of an Intrusive control module more often than not would also attempt to fulfill the requirements of an Intrusive sensing module, as the introduction of a smart component would normally, or at least ideally, provide both means of control as well as information about itself. As such, it is common to implement both modules simultaneously through the same hardware.

Use case example

In order to visualize the implementation of the proposed architecture, a retrofit use case of a legacy machine will be examined. This use case was not performed as part of this thesis and was instead developed by laboratory colleagues working on an agriculture research project funded by the USDA. As part of their work, Smart Retrofit was performed on a ME-JC-24 high speed cracker (Figure *7*), a machine used in the pecan industry to crack large amounts of produce. This machine is operated by inserting batches of pecans into its main funnel, where its lower end is covered by a metal plate that can be manually rotated to change its angle and thus the size of the lower opening of the funnel, which in turn controls the flow of the pecans. Through two hand cranks it is possible to adjust the position and angle a metal plate inside the machine, which changes the way pecans are crushed. Once the machine's main motor is turned on through its controller, which acts as a user interface as well, it generates a motion on the metal plate that presses against incoming pecans, cracking them. Despite its lack of "smart" capabilities, this machine still remains as the state-of-the-art equipment for the agricultural sector of pecan processing. Through this retrofit and the

Figure 7: ME-JC-24 high speed cracker, also known as the "JC cracker". Source: [1]

introduction of Industry 4.0 technology done by the members of this project, they hope to increase the efficiency of this machine, as well as being able capture data for further analysis to determine factors that affect the entire process of shelling a pecan.

For this performed retrofit, an IoT platform was first deployed. Home Assistant is used as this system's IoT platform which, while the original intention of this software is to host smart home IoT applications, its functionality bears no difference from what could be considered an Industrial platform. This platform covers all the required functionality mentioned in the architecture: It exposes a user interface from which users can interact with the system, it possesses its own storage using SQLite by default which takes advantage of the SSD connected to the computer hosting it, and it allows for further processing of the available data, as well as the generation of simple automations. Means of interaction with the user interface are added to the machine through an additional touch screen (*Figure 8*), however it is also possible to access this interface through any web browser through the local network. Although more than one

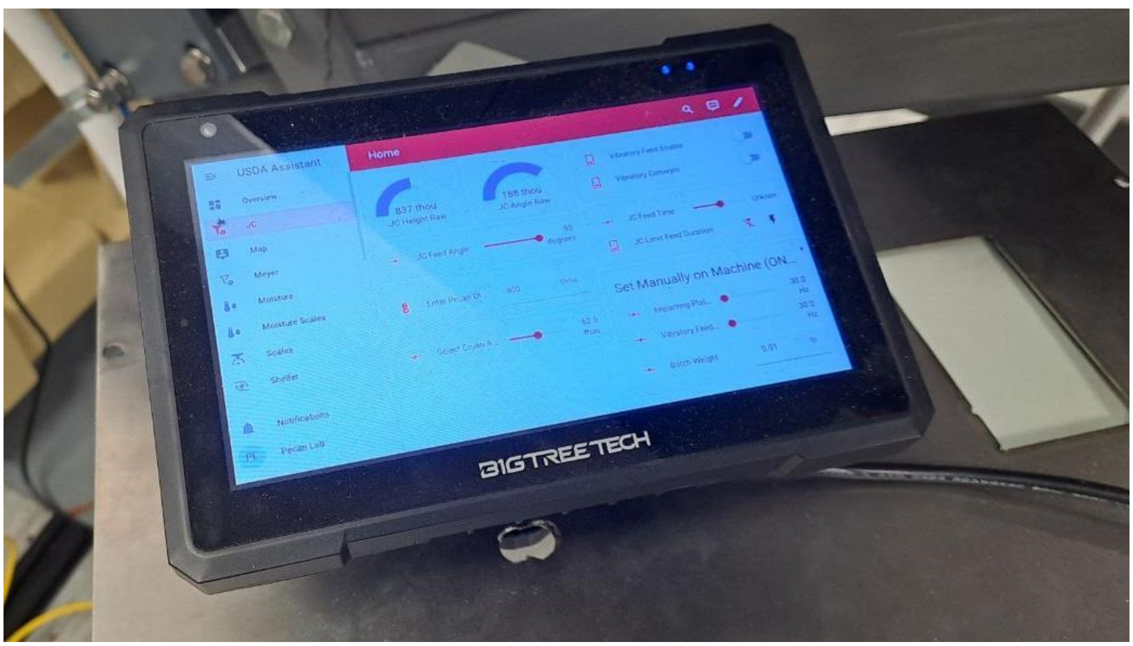

Figure 8: Home Assistant's user interface through local touch screen.

communication protocol is used, as some components require their own, Home Assistant provides service layer functionality by enabling the use of multiple protocols through the addition of add-ons and the use of TCP connections. For example, to communicate with ESP microcontrollers an add-on called ESPHome is added to the platform, which enables communication of these microcontrollers through a custom TCP protocol.

Moving on to the modifications to the machine, a retrofit in the form of non-intrusive modules, both of sensing and control, was performed to the machine's main motor controller. This controller exposed ports for serial communication (*Figure 9*), which simplifies the implementation of the required machine interface adapter down to a direct wire connection to these ports. Through the use of a RS485 to Ethernet adapter directly connected to the computer hosting the IoT platform, it was possible to communicate with this controller using serial communication to obtain both the state of the main motor and control its actuation, fulfilling then the rest of the module's functional requirements.

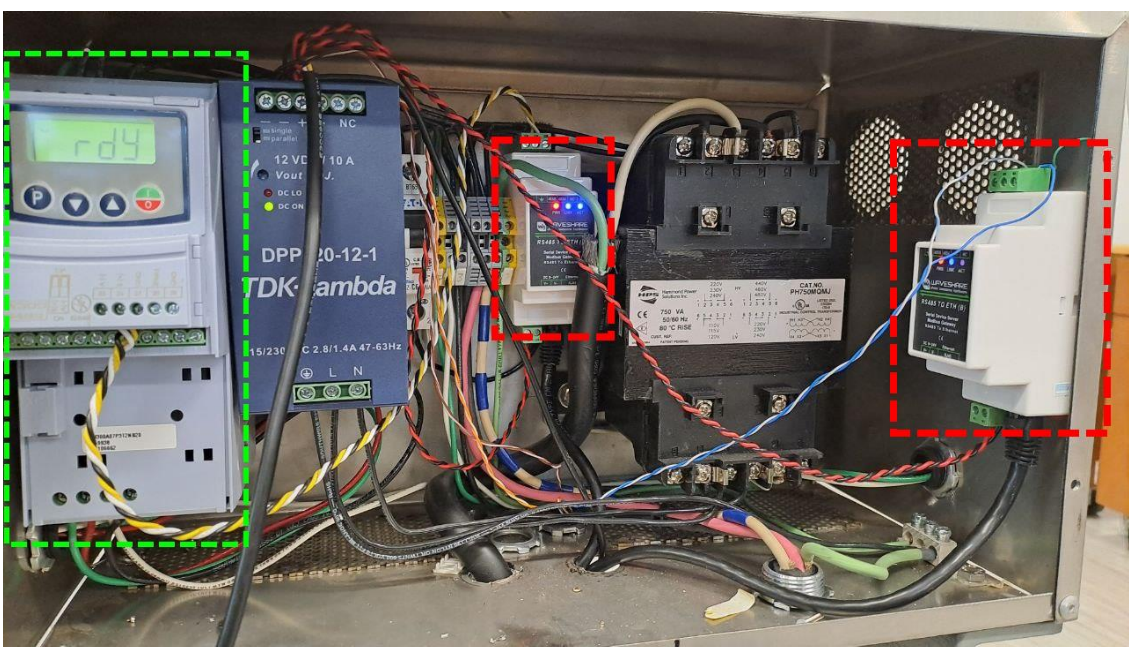

Figure 9: Main motor controller (green) and both RS485 adapters introduced (red)

For the funnel opening plate, intrusive modules were introduced, once again for sensing and control, in which the manual lever used to adjust the angle of this plate was replaced by a servomotor (*Figure 10*). This motor has its own embedded controller that can both actuate this motor as well as provide information about its current angle, meaning that the servomotor alone performs both the generation of actuation and interpretation of information itself, leaving only the input generation for the control module and communication for both control and sensing modules as the missing requirements to fulfill, which were once again implemented using serial communication through a RS485 to Ethernet adapter (*Figure 9*), which connects from the servomotor's controller directly to the IoT platform.

To enable the automated control of the position and rotation of the crushing plate, intrusive control was introduced as a replacement of the original hand cranks (*Figure 13*). Since the inner mechanism that performed the movement of the plate extended across the machine, it was possible to introduce large stepper motors as our module's new actuators for this control without removing

Figure 10: Servomotor introduced to control the funnel's lower opening, highlighted in red.

the original hand cranks. While these do remain on the machine, it is no longer possible to make use of them during normal operation, as they would interfere with the functionality of the stepper motors. Both of these motors' actuation was generated and directed by their own individual stepper driver, which in turn were controlled by an ESP32 microcontroller that directly communicates with the IoT platform through a local Wi-Fi connection and generates the appropriate inputs. In this particular case, no simultaneous sensing modules were implemented. Instead, both stepper motors would perform a homing process at the beginning of their operation. This means that, as long as the machine is kept powered and the stepper motors operate normally and do not lose steps, the position of the motors can be inferred.

Finally, three independent sensor modules were introduced into the machine. The first module introduces a rotary position sensor to gather the main motor's speed, which takes advantage of the same ESP32 used for the stepper motors to perform the subsequent signal capture, interpretation, pre-processing and communication. Afterwards, a module with the purpose of the moisture levels of the introduced pecans was introduced to the machine, as it was deemed a quality that directly affects their cracking. A "no-contact moisture sensor" was attached to the top of the funnel (*Figure 12*) which performs both the measuring and interpretation of this module, and exposes this information through a serial port which, by using a serial to Ethernet adapter as our communication device, was able to be sent to the IoT platform. Lastly, a module was introduced to measure the weight of pecan batches before being introduced into the machine itself. Similarly to the previous module, a digital scale which fulfills both sensing and interpretation was introduced to the side of the machine (*Figure 11*), and through the same serial to Ethernet adapter as the previous module communication with the IoT platform was made possible.

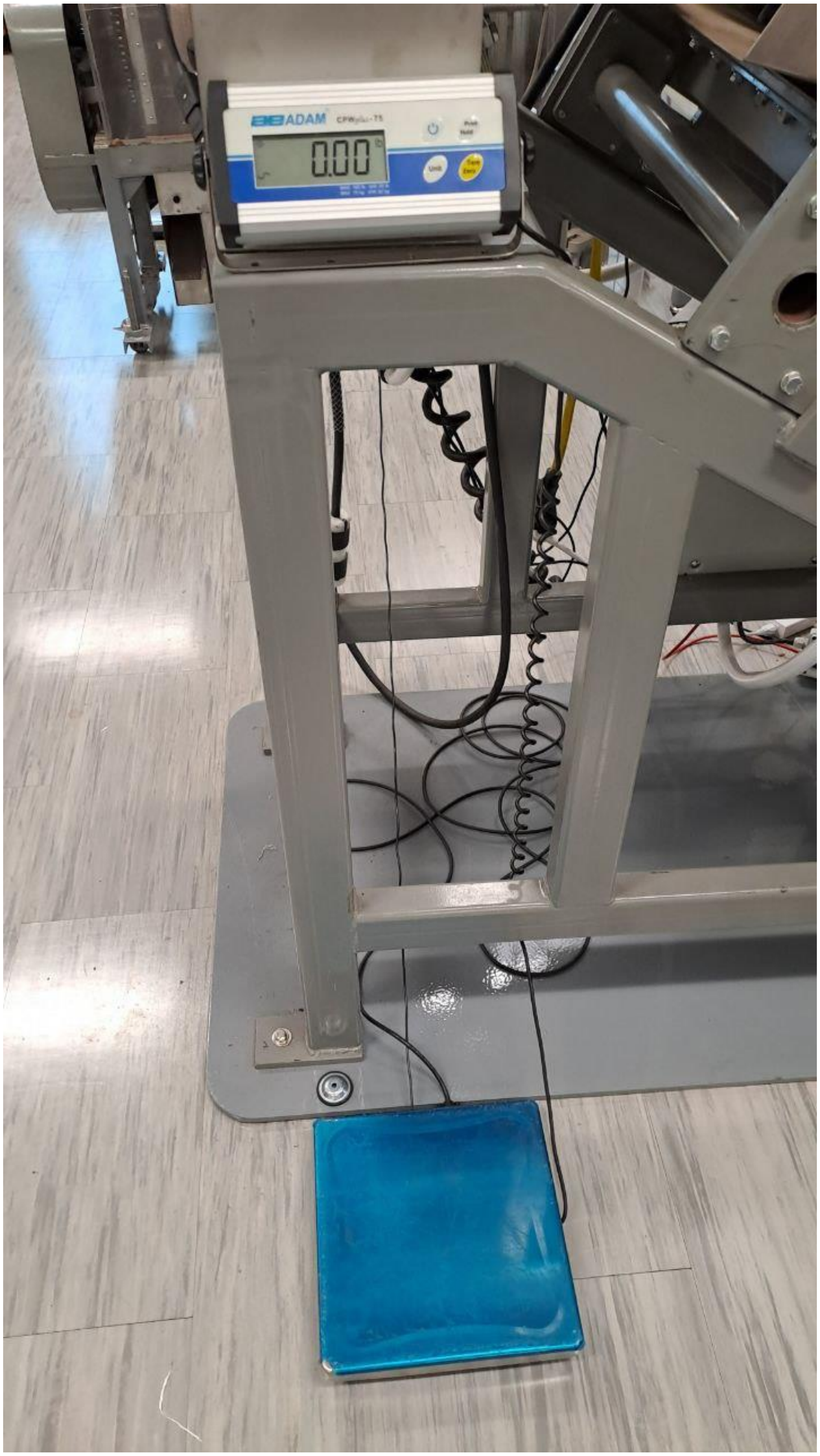

Figure 11: Digital scale added to aid in the machine's process.

Figure 12: No-contact moisture sensor.

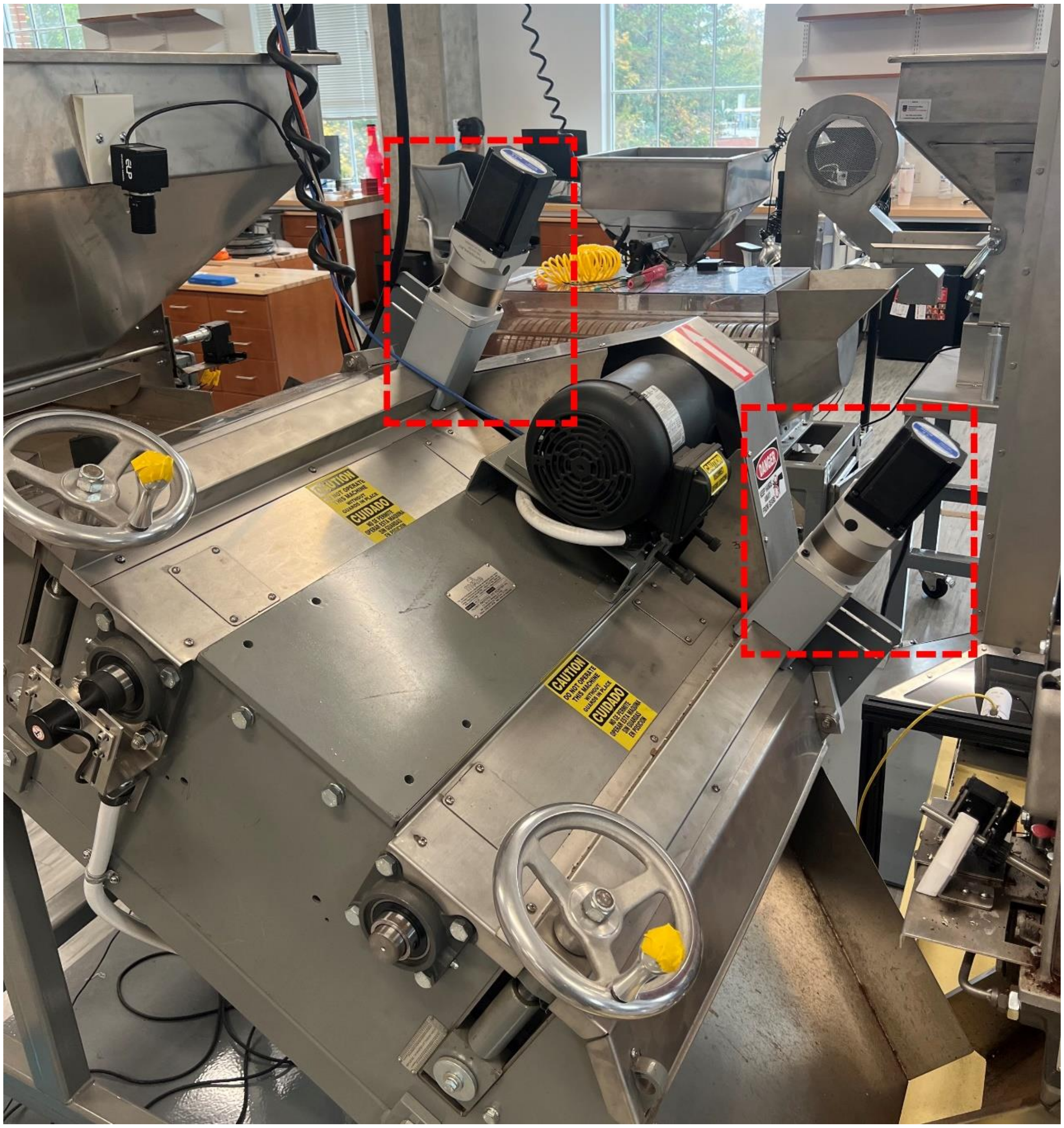

Figure 13: Stepper motors introduced as replacement from the hand cranks, highlighted in red.

Summary

A complete overview of the retrofit performed on the chosen use case example can be found in Figure 14, showing a summary of the modules introduced to the cracking machine, as well as displaying which physical component performs which functions from these modules. As can be seen on this overview, additions to control the main motor involve both sensing and control module functionality, both performed through the same medium. Similarly, the added components on the funnel opening plate fulfill both intrusive module's requirements through the same hardware, showing alongside the previous example how each of these modules is not limited to one device or set of devices for each implementation, and that instead the requirements for multiple modules can be fulfilled through the same device(s). This is displayed more evidently through the modules that introduced the new stepper motors and the rotary sensor, where part of the requirements of an intrusive control module and an independent sensing module were both fulfilled

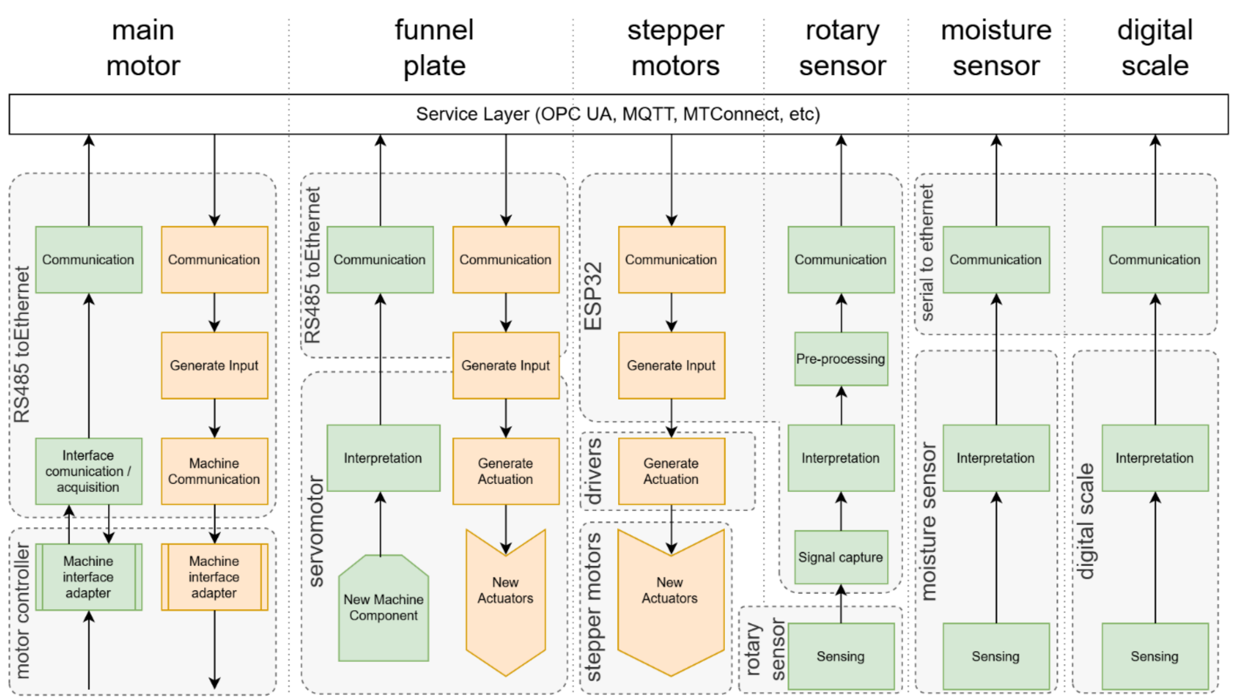

Figure 14: Overview of the retrofitted example use case

by the same microcontroller, despite servicing different type of modules. This can also be seen on the modules for the added moisture sensor and digital scale, where multiple devices can share one communication medium.

An interesting property of independent sensing modules can be observed through the module that introduces the digital scale to the machine. While it can be considered a device separate from the retrofitted machine, the measurement that can be captured by this module directly aid in the machine's usage and its process, as it provides extra information about the pecans to be cracked before they are inserted into the machine. This showcases how independent sensing modules don't necessarily need to be positioned *inside* the retrofitted machine, and can instead consist of independent components that can aid to its functionality by adding capabilities related to previous or following process steps.

While in this case the entire IoT platform was implemented through a single device and software, it is important to reiterate that this is not the only viable implementation, as there are cases where it would be better to delegate intensive analysis algorithms to stronger computing hardware, or storage functionality to higher capacity servers.

As demonstrated through the examination of this use case, the performed retrofit can be properly explained through the proposed modules, which allow for an easier understanding of the purpose of each of the added elements in the machine's retrofit. The proposed modules should be then able to deliver a better understanding of the different options in terms of what can be achieved through a machine's smart retrofitting, as well as providing a better understanding of the fundamental requirements of each, hopefully allowing for an easier retrofit development and hardware selection process.

CHAPTER 4

INDUSTRY 4.0 LEARNING PLATFORM

This chapter introduces the learning platform developed through the work of this thesis. The retrofit architecture proposed in the previous chapter is used to design the implementation of this platform, which aims to aid in the learning of Industry 4.0 (I4.0) technologies, particularly of Industrial Internet of Things, as well as showcasing the use of the proposed architecture through the development of a small scale IoT system. For this chapter, a summary of the problem will be first presented, as well as the context in which the learning platform came to be. Following this, the design process and implementation of the first iteration of this platform will be presented, showcasing the use of the proposed architecture. Finally, the last section will cover the weaknesses found through the exposition of the developed platform, as well as the measures taken to solve these and the effects of these changes.

The GA-AIM project

Many challenges arise due to Industry 4.0 being an emerging technology, both from the side of companies and future workers. On one hand we have the employers, SMEs may not aware of the potential benefits of I4.0 technologies or the risks of not integrating themselves into this new form of manufacturing. Additionally, for those that are aware of the potential gains, they may see these state-of-the-art technologies as something left for the “Big Leagues” and not something a small business can or should be able to handle. This creates a false sense of fear from the potential complexity and extreme costs that smart systems may involve. While this may have been true in the beginning of the smart manufacturing era, the advances of technology that have happened since then have severely lowered both the cost and difficulty barriers that Industry 4.0 may have had before. On the other hand, students are not aware of the technologies involved in I4.0 and thus not aware of the potential jobs and skills that may be required to extract value of these new paradigms. The duality of these two issues are as follows: SMEs are faced with a lack of I4.0 capable workers, and future workers are faced with a lack in demand for I4.0 technology experts.

The Georgia Artificial Intelligence in Manufacturing project (GA-AIM) was created with the purpose of helping alleviate these issues. This EDA funded regional challenge aims to expose SMEs to the capabilities and opportunities that Industry 4.0 technologies can offer, while on the other side bringing awareness to students and the workforce, particularly in rural communities, about career opportunities that come with this new shift in industry, as well as introducing them to these new technologies through learning platforms.

The first phase of the project, and the one presented in this chapter, revolved around the exposure of I4.0 technologies. This would be achieved through the design and development of physical demonstrations of these technologies, which would be used through different events as well as in the GA-AIM Mobile Studio, to hold several of these physical demonstrations across the state of Georgia. To concretize the scope of each demo, I4.0 technologies were divided into 6 “families”: Computer Vision, Additive Manufacturing, Industrial Internet of Things (IIoT), Augmented & Virtual Reality (AR/VR), Robotics and Natural Language Processing (NLP). Each of these families would then get its own physical demo, denominated “Vignettes”, which should provide an overview of the respective technology, as well as providing an idea of its potential uses and value. This chapter will only cover the design and construction of the IIoT physical demonstration, however most of the Vignettes had a similar design and construction process.

The intent of the IIoT Vignette is to allow manufacturers and students alike to begin understanding concepts of IoT and the value that can be obtained in manufacturing from the interconnection of different systems and data points. The design of the Vignette's system should be on the simpler side, as to not overwhelm its audience while also showcasing that value can be extracted, even from very small use cases. To aid in the construction of this Vignette, the retrofit architecture proposed in the previous chapter is used, which was designed with the intention of being a first step into IoT systems and as such its implementation would fit well on the intended smaller use scale. The use of the proposed architecture should provide guidance through the design process of the Vignette's systems and, by using it on the construction of this physical demonstration, it will be possible to showcase to manufacturers both the proposed architecture and a potential implementation of it.

The first iteration of the Vignette

The first step was to select and deploy an appropriate IoT platform. While there are several fully fleshed out industry-ready platforms, an important constraint is that the chosen platform must be easily accessible, even for students. This means that any IoT software that is locked behind a hefty paywall or on a subscription model is immediately no longer an option. Another consideration is that the platform to be chosen should be capable of handling all the functional requirements defined in the proposed system architecture. As such, the chosen platform should be able to provide a user interface, store historical data and allow for the creation of simple automations and data analysis algorithms. To further emphasize the accessibility of the system to be deployed, the platform should have a low knowledge requirement to begin integrating automations and algorithms within it. Some of the platforms found, although more complete in terms of functionality, were more complex and slower to learn and/or did not have sufficient accompanying documentation. With all these considerations in mind, *Home Assistant* was chosen as the IoT platform for the IIot Vignette. Albeit Home Assistant is primarily intended to be used for smart home applications, the functionality between an IoT smart home application and an IIoT smart factory system is nearly the same. While Industrial IoT platforms come with higher security, rate of data transfer and generally higher robustness, they both accomplish the same purpose of collecting data from varied sources, keeping a historical record of said data, and enabling automation through the connection of various devices through the same unified platform. Although Home Assistant would not be recommended as an industrial scale IIoT system, it works without issues on smaller scales and could even be used for small benchmarking projects or as a testbed for measuring the benefits of IoT on bigger systems, especially before jumping into more reliable but expensive software. As was seen on the use case presented on the previous chapter, Home Assistant has the ability to handle all the requirements of an IoT platform established on the architecture. It also comes with the secondary benefit from the fact it is an open-source platform that has been around since 2013. Due to the high popularity of Smart Home applications and the customizability of Home Assistant, it has gathered a rather large number of both users and developers. Therefore, not only have many solutions for integrating different devices been created by its userbase, but also all of these are open to the public as well, enabling the addition of a variety of external applications. This also means that a high number of problems or challenges that a Home Assistant user may face may already have a solution provided by another developer if searched for it, sometimes either through add-ons to the platform or documentation.

Once we decided on our IoT platform, a choice had to be made regarding the hardware that would host it. Conveniently a perk of Home Assistant is the ability to run it in a variety of hardware, ranging from Windows or Linux directly, as a Virtual Machine or any x86-64 machine. The computing unit to be chosen had to be able to facilitate connectivity to itself, either through Wi-Fi or direct Ethernet connection, to facilitate the implementation of the system's service layer. This computing unit also required the ability to boot directly into Home Assistant, in order to simplify the booting of the whole Vignette, and should be ideally economical as to be viable for SMEs. Which is why the obvious option of a laptop was not possible. A Raspberry Pi was initially considered; however this idea was soon dropped for two main reasons. First, while a Raspberry Pi could technically host and run a Home Assistant instance, its low processing power runs the risk of overheating as well as potential data storage issues should too much data be accumulated, especially since it is not trivial to connect additional external memory drives to it. The second issue was related to the perceived negative optics that a deployed Raspberry Pi would generate for industry adopters. Because of the accessibility of these microprocessors both economically and in terms of complexity, or rather lack thereof, they have become popular as an entry point to electronics. Unfortunately, due to this an industry-deployed Raspberry Pi may give out a more "toy-like" impression as it may oversell on the simplicity of the system. Therefore, another alternative was searched for that could have more processing power and perceived as more robust and "Industry-ready", while still remaining economically affordable. This led us to use a ZimaBoard, shown in Figure 15, as our main piece of hardware, advertised as a "Single Board Server" it works essentially as a Quad-Core micro-computer, which has enough processing power to handle any data processing that we might implement later in the scope of the Vignettes, and does not have a cost much higher than the average Raspberry Pi, especially as the latter has been suffering inventory shortages due to resale scalpers. It is also possible to connect an external SSD memory through a SATA cable to the ZimaBoard, which solves the storage problem as well.

With the IoT platform up and running, the next step was to properly define the example to be displayed on the Vignette, as well as the modules that would showcase this example. As the Vignette does not exactly include a machine to be retrofitted, only Independent sensing modules and Intrusive sensing and control can realistically be introduced. While actuation was considered as a showcase component it was ultimately deemed too risky, as it introduces pinching or crushing hazards which are not suitable for situations where the Vignette would be showcased to students. As such, only Independent sensing modules remained as the possible implementations. These would then present the value of device interconnectivity, data collection, data history, and simple automations. For the actual implementation of these different modules, three of them were composed of a combination of one 1kg Load Cells for weight sensing and one HX711 A/D weight converter to interpret the electrical values of the load cell into actual numbers, where all of these modules use an ESP32 for the necessary communication with the IoT platform through Wi-Fi. To facilitate this connection to Home Assistant, an add-on called ESPHome was used, which facilitates the programming and connection of ESP-type microcontrollers. A DHT11 humidity and

Figure 15: ZimaBoard single board server. Source: [2]

temperature sensor was implemented as a fourth module, where the same ESP32 was used for communication, as well as the interpretation of this sensor's data. Another module that used the ESP32 for interpretation and communication included a 24GHz mmWave sensor which possessed heartbeat, motion and breathing rate sensing capabilities. Finally, two more modules were introduced in the form of S31 SONOFF smart plugs, which are conveniently capable of directly connecting into the IoT platform, due to using an ESP8266 microcontroller which was reprogrammed to function in the same manner as the mentioned ESP32. These smart plugs could then perform all functional requirements, from data collection to communication of this information, thus fulfilling the requirements of the entire module in a single device. A summary of these introduced modules can be seen in Figure 16.

A physical station needed to be built to hold everything together. For this a custom designed table was constructed for each Vignette in a shape similar of an assembly station, with dimensions specifically designed to fit through the average door, as well as compact enough to be easily transported by truck, while having enough space to hold every component of the respective

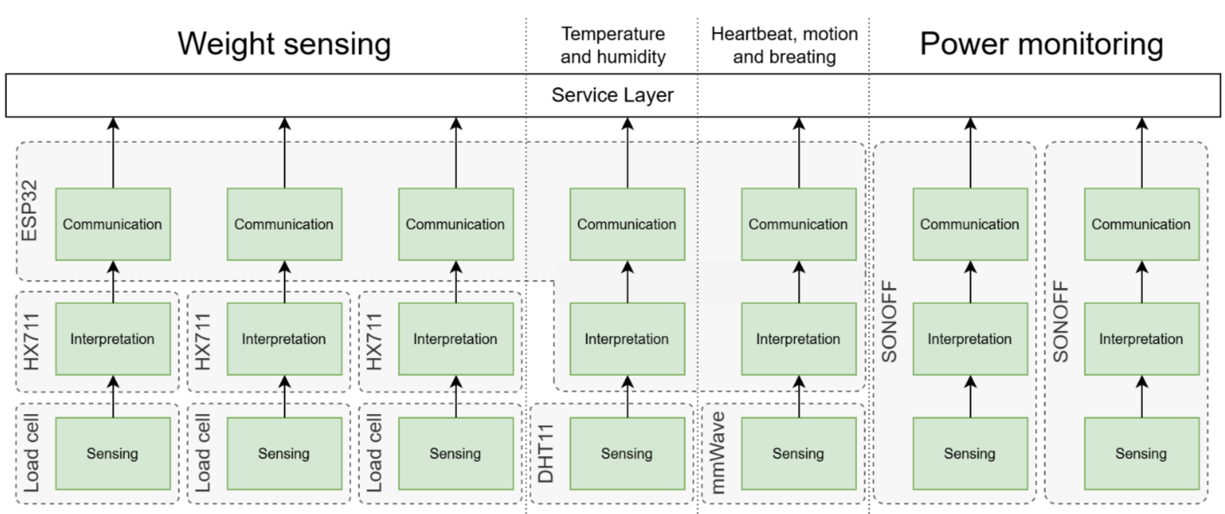

Figure 16: Summary of Vignette's introduced modules.

Vignette. This table was outfitted with a cabinet to store any loose components during transportation, as well as some closed off space to secure hardware that was not meant to be exposed. The table was also outfitted with a Flat screen monitor to easily display the relevant contents of each Vignette. For the IoT Vignette, the ZimaBoard was fixed inside the closed off space, and the TV would be connected to it to display Home Assistant’s Dashboards.

Aside from these mentioned modules, and to add some form of interaction beyond the sensors and the Home Assistant’s dashboard, a button box and a 3 light LED tower were also introduced into the Vignette. For the connection of the LED Tower a different microcontroller was needed, as it required 12V to function while ESPs only functioned within 5V. For this, an Arduino OPTA was used instead, specifically the X00002 model. This specific model of Arduino reassembles a PLC, giving it a more industrial-ready look as well as conveying to manufacturers that may interact with the Vignette the visual representation of an IoT system integrated with PLCs. This Arduino comes with an Ethernet port which makes for an easier connection to the IoT

Figure 17: Circuit box holding the ESP32 and Arduino OPTA, with the mmWave sensor fixated at the top left.

platform. This specific model works in the voltages range of 12 to 24 volts, as well as providing four NO Relays along the usual Input/Output (I/O) analog pins, which would simplify the functionality of the LED tower. The LED tower was then connected to the relays of the Arduino and fixed to the side of the Vignette, while the Button Box wired to the Arduino's I/O pins. The Arduino was then programmed to connect to Home Assistant using the MQTT. Both the ESP32 and the Arduino OPTA were secured inside a circuit box, which itself was then fixed into the Vignette's structure (*Figure 17*). In the case of the other components, 3D printing was used to create custom fixtures and casings that would facilitate securing them on the Vignette. A custom case was made for the DHT11 and mmWave sensors, where the latter was then screwed on the circuit box in such a way that the sensor is pointing to the front of the Vignette. Custom fixtures were created for the Load cells (*Figure 18*), both to hold them into the Vignette on one side and to be able to hang standard plastic bins commonly found in manufacturing onto the loadcell. Printed casings were also created for the HX711 A/D converters in order to fix them next to their respective Load Cells. Finally, the button box was left loosely mounted on the Vignette with enough cable length to be easily moved around the table for easier access to these controls.

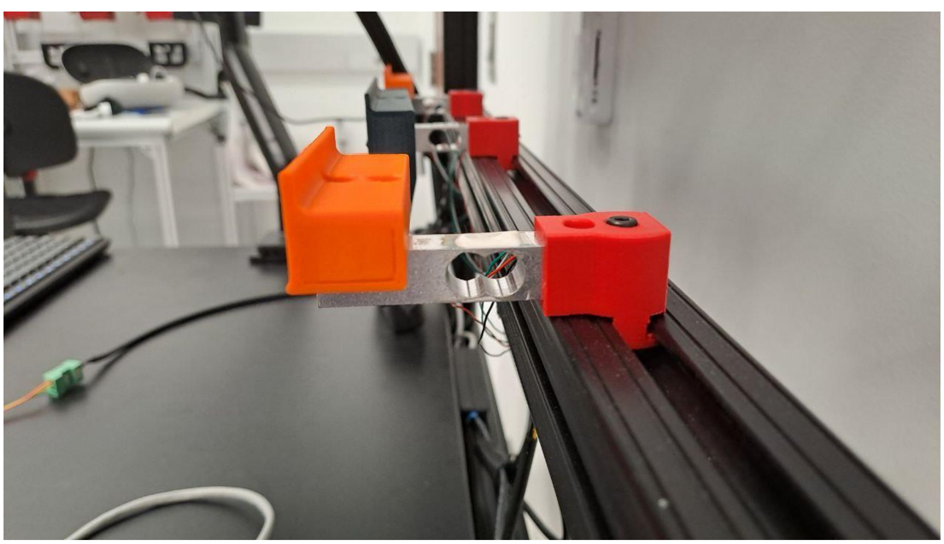

Figure 18: Load cells with custom 3D printed fixtures.

While initially it was intended for Home Assistant to fulfills the automation and data processing capabilities of the system, they were very limited in what they can do. Because of this, additional software was searched for in order to fill this role. Between the considerations taken on this search, the main requirements for this software were that it must be able to be easily integrated with the Home Assistant platform, and it should provide a simplified toolset that a user without prior programming skill could easily pick up. For this, Node-Red was found to be a very suitable platform to integrate into the Vignette. This low-code development tool is intended to aid in the creation of IoT systems through its visual block-based programming, which removes the programming language barrier and allows non-computer scientists to be able to develop data flows and automations just through their logical thinking and problem-solving skills. Node-Red was then used as the main "programming" platform, where a calibration system was made for the Load Cells, as well as some simple automations between the resulting values of the Button box and the LED tower to show as examples. Finally, to provide better access to the IoT platform as well as the Node-Red flows a tablet was mounted to the side of the Vignette, which would allow direct

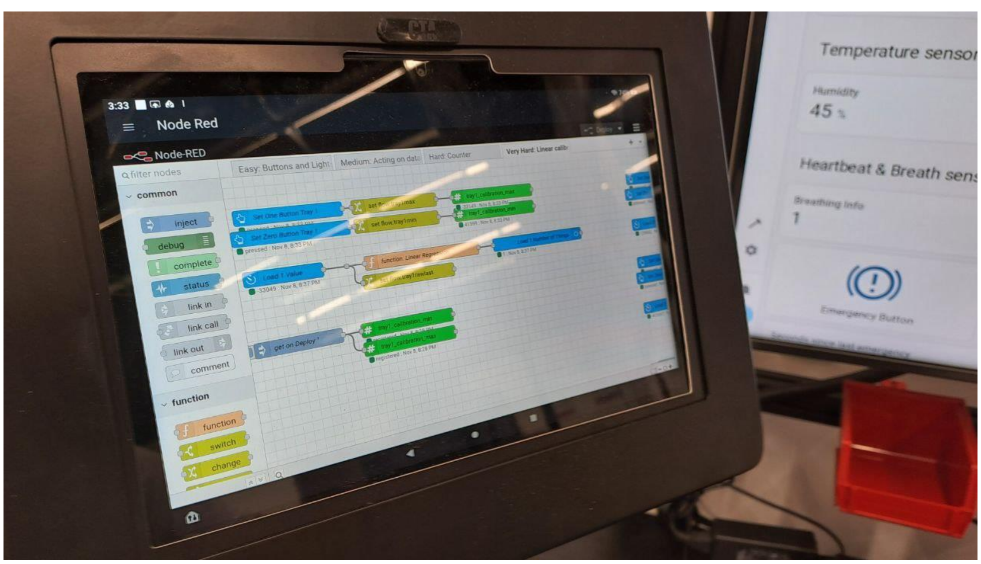

Figure 19: Node-RED access through the side-mounted tablet.

interaction with Node-Red without interfering with the display of the main dashboard from the TV (*Figure 19*).

The main example shown on the Vignette would consist of the 3 storage bins (*Figure 20*), commonly found on assembly lines, being held up by the Load cells. These bins made it possible to showcase the value of data collection from very simple sensors and the amount of information that can be extrapolated from this data. For example, from the calibrated weight measurements of each bin it is possible to know the quantity of objects on each one of them. Additionally due to having historical data of current and past values, it is then possible to extrapolate new information to be able to now have knowledge on inventory count, production speeds, detecting assembly errors, incorrect assembly order, and real-time notifications to other parts of the facility alerting of low part count. From this example, it is then possible to follow up the same idea with the rest of the sensors, such as knowing machine uptime/downtime from the smart plugs, or correlating product quality with the environment's temperature from the DHT11 sensor. The LED tower

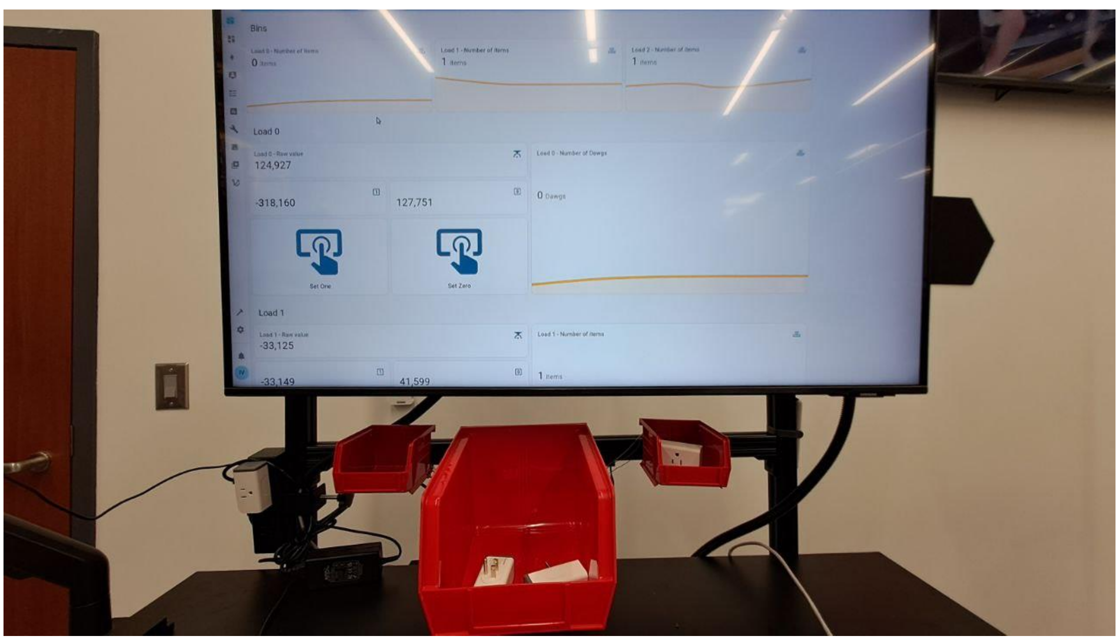

Figure 20: Plastic bins used as the main example and their calibration dashboard.

alongside the Button box can be used as a very basic example of what an interconnected system can be, as the same input from a button that triggers a light can also be from a more advanced automation triggered by one of the integrated data sources. Node-Red was also meant to display the availability of simple programming tools for automations and IoT interconnectivity, as through this platform it was no longer necessary to hire a highly skilled computer engineer to begin working on IoT systems, however, still leaving space for deeper programming through specialized JavaScript nodes. Through the side-mounted tablet it was possible to interact with the Node-Red platform, being able to see examples of simple automations, as well as being capable of constructing new ones. The resulting IoT Vignette can be seen in Figure 21, which would serve as a baseline for future iterations.

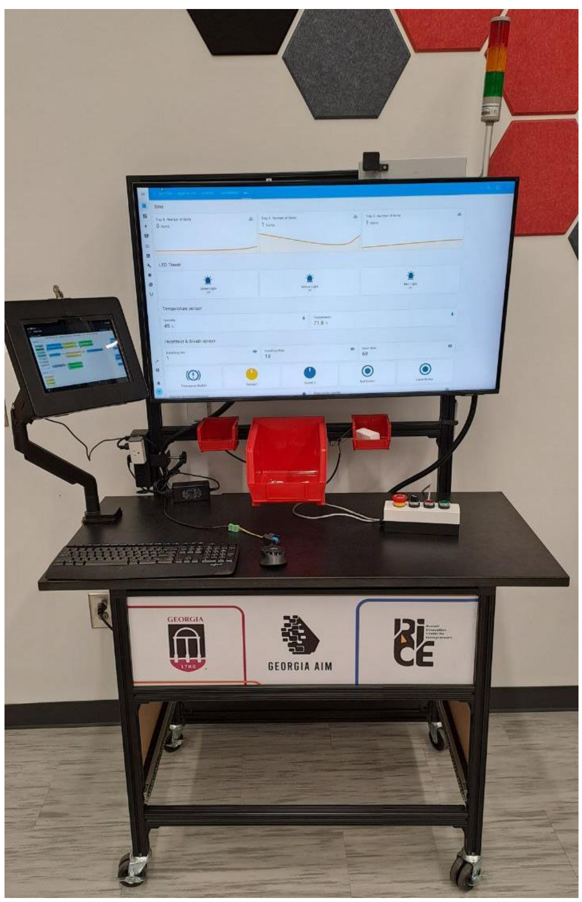

Figure 21: Completed first version of the IoT Vignette.

The second iteration of the Vignette

After the construction of the first set of Vignettes were completed, they were exposed to SMEs, Large Industrial Companies, and students through participation in community events where the Vignettes were displayed, as well as through visits to the laboratory. Through these expositions, the value of IoT technologies was explained to the corresponding audiences, including the showcase of the proposed architecture and its implementation through the Vignette for the case of manufacturers. The Vignettes were successful in attracting the attention of manufacturers and the workforce alike, and insights regarding the strengths and, more importantly, weaknesses of each Vignette were obtained. Regarding the IoT Vignette, the first weakness found was related to part of the Load sensor wiring, particularly the HX711 A/D converters. These were not secured enough, both in terms of the custom case they were being held, as well as the wiring from them to the microcontroller, which often caused the Load sensors to give wrong readings or none at all. For this, improvements were made to the HX711 cases, so they were better fixed to the Vignette's structure, where the new design merged these cases with their respective Load cell's fixture into a single piece. To improve on the wiring, some 3D printed cases were also designed which would prevent the wires to bend excessively, as well as making the connection to the A/D converters more "tight fitted", This change made the Load sensors less prone to malfunctioning due to lose connections.

Another weakness detected was the general functionality of the mmWave sensor. While this sensor is capable of obtaining accurate heart rate, motion, and breathing rate readings, it is meant to be used in medical monitoring applications that involve only one observed person at a time. As such, the values that this sensor would generate would be almost always incorrect, due to multiple people being in front of the Vignette during demonstrations. Therefore, this sensing module was not integrated into the second and following iterations, as its measurements were not providing enough difference to warrant an alternative.

Finally, one of the biggest weaknesses found was regarding the interaction with the Vignette itself. While manufacturers would often be attracted to all Vignettes equally, they could envision the application of the presented technologies on their own systems. However, it was hard for the IIoT Vignette to catch the interest of younger audience. Ultimately, the idea and main contribution of IIoT may fall more in the technical side, and the presented ideas were not as interesting to students, whose attention tended to be directed more towards the rest of the Vignettes, which applications could be more easily gamified, such as the VR or Visual Recognition Vignettes. For this, the main approach of allowing the use of Node-Red through the side tablet was left as an example rather than the main point of interaction for students. Instead, the focus was shifted towards the Button box, and a more "Gamified" dashboard was created, shown in Figure 22, that would emphasize the interactions between the available controls, the IoT platform and the

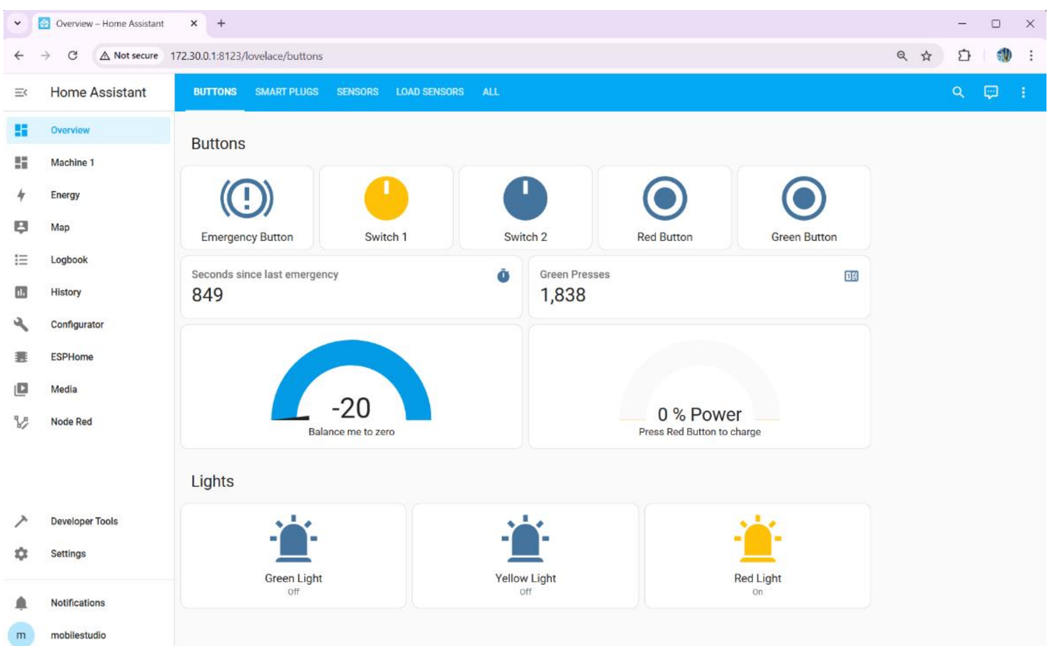

Figure 22: "Gamified" dashboard.

LED tower through some simple games, like pressing one of the buttons to “charge” a gauge indicator or balancing a meter with the available switch. This was done on a secondary view, so it would be possible to switch back to the more technical display when presenting the Vignette to manufacturers and more technical audiences.

All of these changes quickly showed their results in the demonstrations that followed. Thanks to the changes made regarding the wiring of the load cells, malfunctions were severely reduced, as well as making the connection and disconnection of the cables easier to perform. While presenting breathing rate and motion detection was generally interesting, it often led to slight disappointment when the measurements were not actually changing when audiences attempted to do so, and the removal of this sensor allowed for a less cluttered dashboard. As for younger audiences, the gamified dashboard proved to be successful in capturing more the attention of students, as the immediate feedback and clear objectives would more often attract the curiosity of

Figure 23: Final iteration of the IoT Vignette, located inside the GA-AIM mobile studio.

some. However, due to the more technical nature of the Vignette, their interest still tended to fall more into the other demos. Nonetheless, the Vignette reached a more mature stage that addressed a lot of the found weaknesses. The Vignette was later replicated, this time with a better looking exterior and special wheels that allow the Vignette to be fixed in place (*Figure 23*). This final Vignette was then sent to the GA-AIM Mobile Studio, where it will travel across the state of Georgia to demonstrate the capabilities of Industrial Internet of Things.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

As the next incoming step in industry, it is crucial for manufacturers to begin adopting Industry 4.0 technologies and practices. Not embracing these new paradigms in the current, rapidly evolving industrial landscape is becoming an increasingly dangerous option as companies will struggle to keep up with the competition or even the entire market. As SMEs may struggle to incorporate themselves into Industry 4.0, the work performed in this thesis seeks to aid them by providing guidance on an alternative to begin incorporating these new technologies, as well as raising awareness of the potential of Industry 4.0 both to manufacturers and future workers alike, as well as dispelling the misconception that these paradigms are only meant for larger manufacturers. As such, this thesis presents two main contributions to the Industry 4.0 space, described in the sections bellow.

Smart retrofit architecture with a comprehensive taxonomy

A literature review was first performed to understand the current state-of-the-art of smart retrofitting, a means of introduction to Industry 4.0 that is rapidly gaining traction. Through this review, a wide collection of examples of retrofit were compiled and categorized depending on their contents, which made the identification of a gap easier. With this categorization, it was possible to visualize how the integration of smart control is not covered well enough, as most of the literature is focused on monitoring and sensing capabilities, thus missing on half the potential value that smart retrofitting can offer. Separately, it was noted how in the current literature, particularly in smart retrofit architectures, a differentiation between possible implementations of sensing and control components was not considered or thoroughly described, despite a few methodologies explicitly stating that considering the current capabilities of the equipment to retrofit is a crucial step, which influences the elements used in the retrofit process.

To tackle these found gaps, a smart retrofit architecture is presented, which expands on previous literature by considering both the addition of sensing and control capabilities. This allows the proposed architecture to present a more complete visualization of the structure and requirements of a retrofit, as previous architectures would only focus on smart monitoring of machine parameters. The architecture focuses on providing SMEs their first step towards a smart factory and as such, it is simpler in nature compared to the average architecture. It does, however, enable space on its implementation to be further expanded upon, as it presents a base that can be expanded into more complex and advanced IoT systems.

The proposed architecture, through the introduction of a comprehensive taxonomy, makes a differentiation between different types of sensing and control modules that are possible in introduce in a legacy machine through retrofitting, and how they differ from one another by presenting the general functional composition of each and the context in which each should be applied. As not all sensing and control components are equal, this differentiation should enable manufacturers to obtain a more clear and comprehensive understanding of smart retrofitting and the different elements involved in its process.

Industry 4.0 learning platform

To address the existing misconceptions and further alleviate the knowledge gaps about Industry 4.0, as well as showcase the proposed architecture, a I4.0 teaching platform is constructed. While in the respective project multiple physical demonstrations, denominated Vignettes, were constructed, only the Industrial Internet of Things (IIoT) Vignette is presented. This Vignette's presented IoT system was designed around the smart retrofit architecture presented on this thesis, which allowed for an easier selection of sensing module components as well as the design of the system as a whole, culminating on a small scale IoT system intended to show the potential of these technologies as well as the value of the retrofit architecture through one possible implementation of it. Through the constructed Vignette, both manufacturers and students can obtain a better understanding of what is involved in an IIoT platform, and the potential capabilities these enable. For manufacturers, this demonstration allows them to start thinking more clearly about IIoT applications and how they can obtain value from them by applying these technologies to their own systems and environments, even for smaller use cases. It also aims to dispel the misconception that IoT applications present high complexity and economic entry barriers that only advanced companies can get access to, as this is no longer the case thanks to nowadays technologies being considerably more accessible than their predecessors, as well as the existence of alternatives that are not high cost "enterprise" platforms and software. For students, these demonstrations allow them to expand their understanding of Industry 4.0 technologies, bringing awareness on career opportunities within this field. By directly engaging with the practical applications of these technologies, students can envision potential job roles that leverage Industry 4.0 advancements, which they may not have previously considered. The Vignettes presented on this thesis hope to then generate a double-sided effect on Industry 4.0 careers. On one side, as manufacturers start seeing the value of Industry 4.0 technologies, they may begin requiring capable engineers knowledgeable in the works and implementation of these technologies. At the same time, by raising students' awareness on these career opportunities, more are likely to follow a career path that would ultimately make them experts in Industry 4.0 and its technologies. It is hoped that the Vignettes constructed may be ultimately generating both I4.0 jobs from the side of manufacturers giving future engineers a higher range of career options, while at the same time generating more I4.0-able engineers capable of fulfilling the needs of these manufacturers, allowing them to remain competitive in the industry.

The entire design and construction process of the teaching platform was presented in detail, hoping that it would serve as an example for researchers who intend to create their own physical demonstrations. By presenting the entire design process, as well as the reasoning behind modifications between iterations, this thesis intends to give a better understanding of the considerations to be aware of at the moment of designing an Industry 4.0 demonstration piece, as well as the potential reception of these by different audiences.

Future work

As for the next steps, it is left as future work the proper implementation of the proposed architecture on a legacy machine. A complete implementation should be carried out, attempting to use all different types of the modules proposed, with the intention to fully validate the structure definition of each module as well as quantifying the difficulty and value that each brings through their implementation. In order to carry out a proper validation, the search for a legacy device or machine that would allow the implementation of all modules is required. As such, the equipment to be retrofitted should be able to provide information about some of its attributes for Adaptative and Replacement sensing modules to be implemented, while still leaving opportunities for new parameters to be monitored through Independent and Intrusive modules. The selected machine should also enable the control of its parameters in such a way that all forms of control modules can be implemented.

A specific and comprehensive methodology should also be defined for the presented architecture, which should describe the entire process on how a manufacturer would carry out its implementation, including pre-implementation steps such as design, economic considerations and problem definition, all the way to pos-implementation validation.

Regarding the learning platform, the first step of the GA-AIM project revolved mainly around the exposure of Industry 4.0 technologies. As the developed Vignettes focused more on presenting the general idea of what each technology entails as well as bringing awareness to their potential value through limited time interactions that focus more on expositions, it was not put much emphasis on a more long-term direct use of these physical demos by their respective audience. This is not to say the Vignettes do not fulfill their purpose, as they were mostly intended to be used as presentation pieces to a relatively large number of viewers at a time, or through quick overview sessions that would occur on the GA-AIM trailer where these Vignettes would travel the state. As such, the audience would not be able to deeply interact with each demonstration piece. The next stage of the project, and second version of the Vignettes, should then focus on this missing interaction, which would enable a deeper understanding of each technology through a more hands-on experience of them.

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