I-AM: Interface for Additive Manufacturing

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Abstract: The shift of the computational paradigm to a model where there is a multiplicity of computational devices capable of feeling and acting on the environment allied to the digital transformation of manufacturing processes, with an increasing real-virtual fusion, are two of the pillars of the ongoing industrial revolution industry coined as Industry 4.0.

In the context of new manufacturing environments, the development interfaces that are usable, intelligible, interactive and easy-to-implement and deploy across multiple device is a major aspiration to be achieved.

This paper describes the design process of an interface, supported by web standards, adapted for additive manufacturing appliances. This interface aims to allow the monitoring of the production parameters, providing the operator with all the information related to the manufacturing process and the equipment and materials involved. Beyond providing an effective tool to monitor and control of the real manufacturing process, it also allows to virtually simulate the process, thus enabling optimization and anticipation of possible issues.

The adopted user-centered design methodology is described, as well as the proposed architecture. Details are presented on the developed prototypes, the users studies, and about the information collected from users for the requirements elicitation process and from the tests. The interface was developed through several iterations and was evaluated very positively by the users (operators) using established usability assessment instruments and methods.

In the near future it is intended to generalize the approach and architecture to move towards a framework dedicated to the design and implementation of universal interfaces for industrial environments.

1 INTRODUCTION

In recent years there have been lively technological developments, and thus the integration of new technological trends has become natural in any area or sector that benefits from them. Emerging paradigms and technologies such as pervasive computing, autonomous agents, augmented reality, virtual reality, among others, tend to be exploited and integrated in all sectors of the industry.

There is a sustained motivation to increasingly venture on new technology solutions since the expected earnings are huge and the changes are fast. Human-Machine Interfaces (HMIs) for manufacturing process control are no different from other areas and can greatly benefit from the integration of various technologies.

HMIs are used on a daily basis for a variety of purposes, such as in: cars - to provide driver information about the trip, motor parameters, and extras such as air conditioning or radio; medical equipment - to provide information about the patient and to allow some action by the patient's condition; in the industry - to provide information about a manufacturing process and to allow control thereon.

In the industrial context different manufacturing processes have different needs from the control and automation point of view. One of the main objectives of HMIs in industrial contexts is to provide correct information to the operator and to enable it to assist in the normal operation of the processes or in situations of failure (Hollifield et al., 2008).

A well-designed HMI can lead to large benefits, for example in the case reported in (Errington et al., 2005), where the redesign of an HMI resulted in an increase of more than 5 times the number of anticipated fault situations and an increase of 37% in success rate

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in the treatment of malfunctions.

The work reported here arises from an innovative project that aims to investigate the process of additive manufacturing in an industrial environment using thermoplastic materials for high temperature and resistance applications, a process that has very specific needs regarding the control of the equipment and process monitoring.

Additive Manufacturing (AM), also known as Addition of Material, is a manufacturing process whereby a product can be directly manufactured from a 3D model, allowing the production of a very wide range of forms. The techniques of manufacture by addition of material, in counterpoint with more traditional processes of subtraction, have several advantages. It is the process used in most 3D printing devices.

This work aimed to develop an HMI, based on web technologies, customized for an additive manufacturing equipment. The HMI shall allow previewing, monitoring and manipulation of its parameters by providing the operator with a tool capable of providing in real time all the information concerning the manufacturing process as well as the equipment itself and shall allow the control through functions specifically designed for that purpose.

2 RELATED WORK

A main goal of this work is to devise an easy to develop and easy to deploy interface. The system should be able to integrate easily, being able to convey information from/to the myriad of computational devices on an industrial plant. With this goal in mind, standard web technologies became a rational choice due the cross platform / media support for the interfaces, the large support of tools and languages and the easy integration via services or APIs on top of reliable and available internet protocols.

The following text on this section describes some of the most relevant examples found in the literature regarding the use of web technologies for the implementation of HMIs in industrial processes.

A case study, described by Kacur et al. (Kačur et al., 2013), a PLC (Programmable Logic Controller) was used as a web server and allowed to remotely monitor a physical process. By taking advantage of the capabilities of web technologies, monitoring can be done remotely, anywhere on the planet, provided they have access to the internet. In this case, two physical processes were used for remote control: steel coil winding and coal gasification, in which both temperature values were monitored.

Another noticeable implementation of a web-based system for control and automation was presented by Bermudez-Ortega et al. (Bermudez-Ortega et al., 2016). In this case, a system was developed based on web technologies for remote control of PLCs from a control laboratory through a browser. The system consists of a Beckhoff manufacturer's PLC with Twincat software, which allowed running control experiments in a laboratory. As a webserver they used Node.JS which has an implementation that allows connectivity to Twincat and on the frontend of web application with a dedicated library : Easy Javascript Simulations (EjsS).

Another work that is relevant to the subject and that relates to the previous case is described by Li and Zhang (Li and Zhang, 2011) where a system is described to carry out remote control experiments in a PLC. The developed system included a pneumatic manipulator as control object, connected to the PLC (Siemens model S7-224 PLC). It contained a network card and was ethernet-connected to a server with Windows 2000 operating system and STEP7-Micro / WIN32 software installed. This software is also from the Siemens manufacturer and serves for the purpose of developing automation projects. The server in turn was connected to a network hub that allowed remote access by clients on the internal network and on the internet.

A Final example is the Eiger software (Markforged, 2018) providing remarkable features as:

- Access through any device with a browser;
- Import of 3D models / drawings to be printed;
- Print layers preview;
- Able to edit some properties such as dimensions, positioning, material, etc.
- Real-time print parameter monitoring;
- Store and preview previously printed parts;
- 3D and 2D part display;

3 PROPOSED ARCHITECTURE

3.1 Architecture

The proposed general architecture follows a multi-tier architectural model. In the particular case we identify 5 fundamental layers.

Sensing/Actuation Layer
Composed by all the apparatus that compose the additive manufacturing appliance, including sensors and actuators;

Connectivity Layer
Implementing the communications protocols and network infrastructure (HTTP, MQTT, sockets, etc.);

Data Integration Layer
This layer responsibility is concerned with data integration from several sources, persistence and data processing (e.g. time series)

Application Layer
The application layer implements the main logic and data access and processing. Exposes data access and functionality via RESTful services. Also enables subscription to real time services using web sockets that enable two way communication between the application and presentation layer;

Presentation Layer
This layer comprises the front-end modules and applications, intended to be executed by a web browser. Web standard client side technologies such as HTML5, CSS and JavaScript are the supporting technologies, although front end frameworks and libraries can be integrated. Presentation is intended to be cross platform and responsive to several devices specific characteristics (size, colors, etc.).

In our specific instance of the proposed architecture, the interface is fetched by a web browser that loads all the resources needed to start the HMI. In addition to HTML (structure and content) the loaded web page incorporates by reference CSS (presentation) and Javascript / Ember.js (communication, interaction, and behavior) documents. Ember.js was the front-end framework selected for creating web interfaces using Javascript.

Real time services are subscribed using Socket.IO library which enables real-time, bidirectional and event-based communication between the browser and the server.

The web server was implemented in Node.js and making use of the express.js frameworks and the ADS.js module. The latter enables communication with automation software via TCP/IP.

At the integration layer we opted to incorporate the Twincat automation solution from Beckhoff manufacturer, which enables you to develop automation solutions as well as communicate with hardware devices that are connected to the system, such as motor drives, PLCs (Programmable Logic Controller or Programmable Logic Controller) , input/output channels, etc. This software has a modular architecture that allows to deal with each module (consisting of software and possibly hardware device) as a stand-alone device. The messages between the modules are made

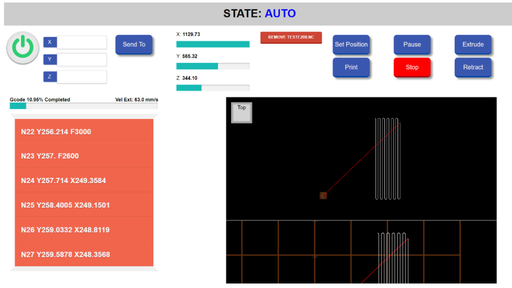

Figure 1: First Interface Prototype.

possible through an ADS (Automation Device Specification) interface that each module has and through the ”ADS Router” in the software that manages and can identify the recipients of the messages. This in practice means that when a remote message arrives, the ”ADS Router” can identify which module / device this message is addressed to.

Finally, at the sensing/actuator layer there are several different types of devices that can control and monitor the physical process, such as servos, temperature and pressure sensing devices, etc.

3.2 First Prototype

In order to validate the proposed architecture and technologies, a first functional prototype was implemented, although not in the final equipment, but in a similar equipment in terms of functionality and characteristics.

The developed prototype allowed to assess possible issues from the implementation and to validate the architecture and the considered for the final system in a real equipment, thus giving us unidealized information of its behavior, forms of communication, and integration issues. It also allowed us to show a first approximation to the reality that would be put into practice in the development of the final system. Without hard concerns about usability or requirements responding to user needs, the main focus of the prototype was to develop a system using a set of selected technologies, as well as to analyze its behavior.

This prototype has a set of functions that allow to control and monitor the process equipment and parameters (see Figure 1), such as monitoring the state of the machine (it can vary between on / off, pause, auto or manual), set the axes to a certain position, send a GCode program to the machine to interpret and execute, pause the equipment, abort the execution of a GCode program, view the GCode lines that are being executed in real time, track position and view the 2D and 3D models drawings (Figure 2).

As conclusion, we confirmed that the set of selected technologies was suitable for the development

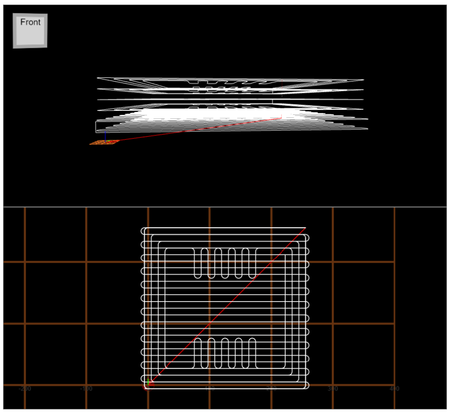

Figure 2: 2D and 3D views of the part being manufactured.

and was used as a reference in the development of the final system.

4 DESIGN OF THE FINAL HMI

4.1 Requirements Elicitation

Requirements elicitation is a crucial phase in the life cycle of each project because an erroneous, incomplete or non-existent requirement usually means serious design problems.

The main objectives of the requirements analysis can be summarized in understanding the problem and identifying the needs of the project and, as a result of the analysis, the definition of a set of requirements as specifications to be implemented, describing the behaviors, properties and the expected attributes that reflect the needs of stakeholders in the project (Ferreira, 2010, p.25). A survey of requirements was carried out with a group of HMI users (see Table 1) that were categorized into three large groups, "Informative", "Functional", and " Complementary".

4.2 Interface Prototype

The next step was to develop a first version of the HMI. The strategy was to develop a mockup that manifest the list of requirements collected from users.

The development of mockups facilitates the understanding of the requirements between all the parties involved, presenting concepts and functionalities of the software. There are several approaches to develop mockups, that is, they may be low fidelity, with no screen interaction, but they allow for quick adjustments or changes depending on feedback collected, as well as complex and interactive mockups that more closely represent the software to be developed , but whose counterpart is the fact that the necessary changes or adjustments are more time-consuming to make.

Table 1: Requirements from the operators.

Function	Details	Category
View Axis	Axis X Axis Y Axis Z Axis B Axis C	Informative
View Speeds	Operation Polymer Extrusion Fiber Extrusion	Informative
View Temperatures (current / target)	Chamber Chiller Table / Platform Extruder Motors	Informative
Control Heating System (set / on / off)	Chamber Table / Platform Extruder	Functional
Control Ventilation (set / on / off)	Chamber Table / Platform Extruder	Functional
Set Operation Mode	Automatic Manual MDI mode	Functional
GCode Program Execution	Import Start Pause Stop General Homing Axis Homing	Functional
GCode Manual Commands	Execute Command Pause Stop	Functional
Set Configuration Parameters	Operation Speed Polymer Extrusion Fiber Extrusion	Functional
History	View Log	Informative
Manual Control (On / Off)	Global Heating Ventilation Motors	Functional
Illumination (On / Off)	Chamber	Complementary

The approach followed was to, in the first phase, create mockups that visually had a representation as close as possible to the final HMI, but which were static. A web tool specializing in the creation of static mockups was used (https://moqups.com/).

The design of the first mockups was intended to conduct an observation and analysis on how the information would be organized and made available to the users in the interface, as well as all to check the fullness of the functionality available to the user. To this end, it was a crucial to discuss with the potential users of the interface operators of the AM equipment in order to understand the priorities in the organization of information and functionalities.

From that discussion, it resulted the first drawing of the mockup illustrated in Figure 3, where it can be observed that in the upper area of the screen there are three groups of information that is being updated in real time, relative to the position of the axes, the operating speeds and temperatures measured at several places.

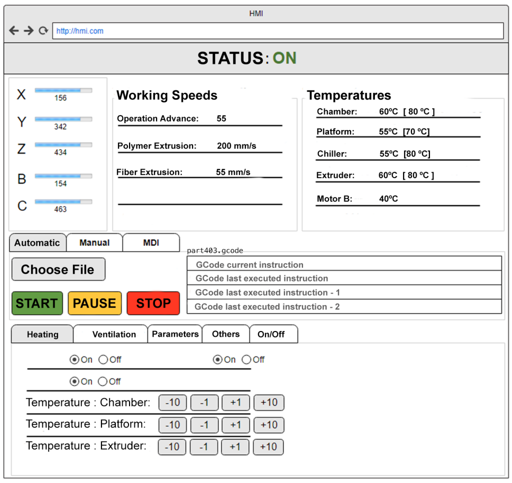

Figure 3: First static HMI prototype.

This was indicated as the most critical information set and consequently should be placed to enable a quick understanding for the user. Below there are user interaction zones, namely the Automatic, Manual and MDI modes.

In the Automatic mode it is allowed to execute and control the execution of a G code file, in Manual mode it is allowed to control and operate each axis manually and individually and in the MDI mode it is allowed to execute a G code command.

Finally, in the lower part of the screen it can be seen a set of tabs that allow to control some parameters related to the additive manufacturing process and also to the equipment itself. The first tab: Heating, allows you to control parameters related to the heating system of the equipment, such as heating the chamber, the platform (tray) or the extruder, as well as simply making variations in the temperatures of the same. The Ventilation tab allows you to control the air supply of the camera. The Parameters tab allows you to adjust the feed speeds, polymer extrusion and fiber extrusion. The Other tab allows you to run a table adjustment function and control camera lighting. The last tab allows you to turn off equipment components such as motors, the heating system, the chamber heating and all equipment.

After the creation of the first static version of the models, a second version was created. This version allowed interactivity, that is, it was possible to navigate between screens and tabs of the HMI, in order to simulate the execution of all the tasks. Also note that these respected the size of the touch screen that will be used in the actual additive manufacturing equipment and were created using a web tool (https://proto.io/) that allowed exporting a prototype in HTML, making it possible the execution of the same in the browser and the consequent navigation between screens. An example of this model can be seen in Figure 4.

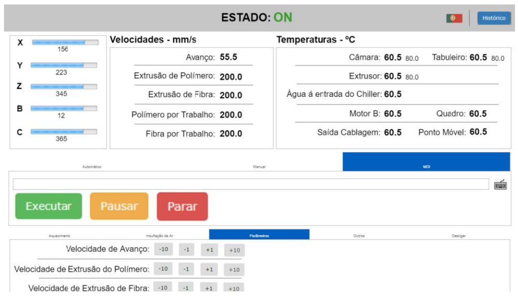

Figure 4: HMI - Fully Interactive Mockup.

4.3 Interface Assessment

Since the interface is the most visible part of the whole system and enables the interaction between operators and the additive manufacturing equipment, it has become fundamental to carry out an evaluation of the interface as well as its usability.

Usability tests are processes that aim to evaluate the ease of use of a product (system, interface, etc.), preferably with the participation of groups of potential users, allowing to improve and bring constructive criticism about its usability. In an ideal scenario, the test participants will be real users and will perform real tasks, creating a scenario very similar to the reality that the product will be subject to when it is launched. The test results will be obtained from the observation and measurement of the interaction between the participants and the interface (Afonso et al., 2013).

In order to perform the usability tests, two strategies were used to evaluate the system, together with a group of four users and the functional model executed on the device's touch screen. Considering that the solution to be developed would be for a specific equipment, that is, oriented to Additive Manufacturing, it became more difficult to select users with sufficient knowledge to perform usability tests. However, according to several studies ((Virzi, 1992), (Sauro, 2010), (Nielsen, 2000) and (Molich, 2010)) a group of four to five users may be sufficient to obtain value results and cover approximately 80-90% of existing usability problems.

The first evaluation strategy was based on the System Usability Scale (SUS) (Brooke, 1996) survey, which allows us to measure the usability of a system through a set of ten questions, and where responses are recorded on a Likert scale and should ranging from 1 (Strongly Disagree) to 5 (Strongly Agree) (Brooke, 1995). This tool allows to evaluate a wide range of products or services and has the

Table 2: SUS Survey Results.

Item	User 1	User 2	User 3	User 4
I think that I would like to use this system frequently	4	4	4	5
I found the system unnecessarily complex	1	1	1	1
I thought the system was easy to use	5	4	5	4
I think that I would need the support of a technical person to be able to use this system	3	2	2	2
I found the various functions in this system were well integrated	5	3	4	4
I thought there was too much inconsistency in this system	1	1	1	1
I would imagine that most people would learn to use this system very quickly	5	4	5	4
I found the system very cumbersome to use	1	1	1	1
I felt very confident using the system	5	5	4	5
I needed to learn a lot of things before I could get going with this system	2	1	1	1

SUS Score = 88,125

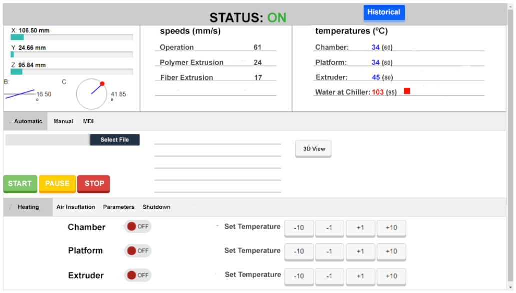

Figure 5: Home Screen of the Final HMI Design.

main advantages of being able to easily differentiate between usable and non-usable systems, to be quite easy to apply and to compare since it is widely used (Brooke, 2013).

In the table 2 the results of the SUS are made available, per question and per operator, and a calculation method specific to the tool is used to calculate the ”SUS Score” per user. used the arithmetic mean of all calculated ”SUS Score”. The final result was 88,125 in a maximum of 100, which indicates a high degree of user satisfaction about the usability of the system.

Notice that, complimentary to the SUS survey, we have used observation instruments and open questionnaires that allowed us to gather additional information about specific issues that operators pointed out that could be improved or corrected in subsequent iterations of the HMI design.

4.4 Final Design

The developed system is made available to the user through a web interface, which is executable through a browser. In addition to this layer of graphical interface, the system also has a backend layer developed using NodeJS technology and a document database, RethinkDB, which in turn are connected to the Twincat automation solution . Thus, the initial screen made available to the user is that of Figure 5.

As it can be seen, the interface can be divided into three main groups of use. The upper group contains process control information, that is, it allows the user to monitor in real time the position of the axes,

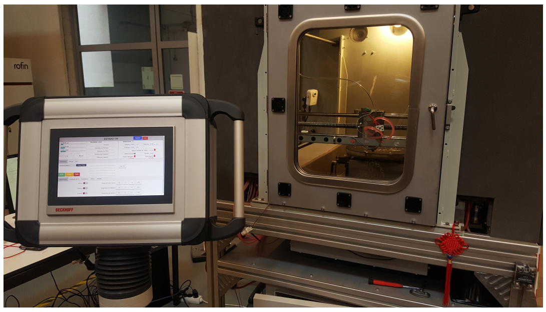

Figure 6: Working version of the I-AM HMI.

speeds and temperatures. The position of the axes is made available in millimeters and is accompanied by a graphic object representing the axis. In the case of X, Y and Z axes, the graphic object is a progress bar for each. The B axis, which in the actual equipment corresponds to the inclination of the tray where the printing takes place, is represented by a fixed gray horizontal bar and a blue (dynamic) bar that demonstrates the inclination of the table (as if the tray were seen in profile), corresponding to a certain angle in degrees celsius. Finally, axis C, which in real equipment corresponds to the rotation of the tray on itself, is represented by a circumference and a red dot with a blue line (dynamic) from the center of the circumference for viewing the rotation angle (as if the board was viewed from above). The system is also log a set of parameters and displays them in the form of time series. The working version of the developed HMI alongside the 3D printer used in this work is depicted in Figure 6

5 RESULTS

The developed system basically consists of a web interface supported by a backend layer that, in turn, establishes and manages the communication with the automation layer, and as such, it has become essential to close the cycle of this work to carry out tests to the developed HMI which is connected to the final additive manufacturing equipment.

These tests were possible to run with the group of four users who participated in the interface validation inquiries, however, since part printing has a cost to the material that is used, only one part can be printed. In the remaining tests the same procedure was performed with the only difference that although the axes of the equipment made the same movements, the pieces were not printed and the remaining data were simulated. This difference was explicit through an attribute in the content of the G code and therefore, in the perspective of the HMI the functionality

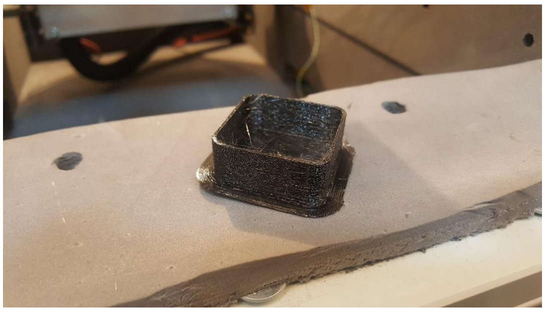

Figure 7: Sample part manufactured during the user tests.

would be exactly the same because it only guaranteed the upload of the file selected by the user and gave the order to the controller to begin its execution.

Since the equipment is not yet finished from an automation point of view, some of its functionality is not yet implemented.

After the tests were carried out, a new SUS survey was made to the users in order to obtain new feedback about the usability of the HMI. The final result was 89,375 in a maximum of 100, which indicates a high degree of satisfaction in the usability of the system. This value, compared to the value of the evaluations made to the models, was increased, since the result had been 88,125. These results indicate that, in general, users are satisfied with the developed HMI and that it met their expectations. More relevant than the quantitative assessment, the issues pointed out by the operators were improved or corrected in the final version of the HMI.

During the tests with the equipment que HMI was used to control the manufacturing of sample pieces as the illustrated in Figure 7

6 CONCLUSIONS

The work carried out allowed to verify that, although there are already some approaches similar to the proposal presented here, there is still a great margin of evolution in order to take advantage of all the existing potential in the technological areas and direct it to areas of applicability in the industry, especially if consider the area of Additive Manufacturing.

The methodology used involved users throughout the process. In a first phase, requirements were created that allowed the creation of visual mockups and obtaining first user feedback through surveys, including usability studies, which in turn validated the proposed solution and ensured in advance that necessary adjustments were recorded. Based on the results, the final solution was developed, and tests were carried out on the actual equipment that resulted in the printing of a part using the Additive Manufacturing as the manufacturing process.

The development methodology of the interface, centered on the operator needs, with validation and evaluation by means of prototypes and user tests, regarding its usability, proved to be fundamental to reach the aimed set of objectives. The final solution proved to fit the users needs. The outcome of users tests were a usability assessment close to the ”excellent” according to the evaluation tool used (Bangor et al., 2009). These results allowed us to validate the usefulness and usability of the developed solution.

As future work, and in addition to the implementation of the features that are listed as requirements but which have not yet been developed due to lack of instrumentation or development in the project automation layer, the integration of an Augmented Reality module with in order to visualize the part to be printed in three dimensions and also to obtain information on the process of printing it in real time, in order to prove the feasibility and above all the considerable value that this technology can contribute to industrial processes.

An avenue to future developments is to generalize the proposed architecture towards a framework enabling the development of web based, cross-platform, interactive and responsive interfaces for industrial processes / appliances.

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