Constraints and Challenges in Designing Applications for Industry 4.0: A Functional Approach

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Abstract: The Industry 4.0 concept relies on the integration of its composing elements using modern tools. These modern industrial plants must consider concepts like the Internet of Things, Cyber-Physical Systems and Smart Devices. The main features involved in these architectures are the local control, machine-to-machine information exchange, and human-to-machine interface through virtualization. The integration of these elements to create a connected environment presents a challenge to developers and engineers. In this text, we perform a theoretical analysis of the main constraints and challenges in designing and implementing novel applications using digital twins, robots, wearable devices, and other control interfaces. To evaluate the theoretical approach, we performed a series of tests in prototype environments.

1 INTRODUCTION

Industrial environments are evolving to Cyber-Physical Production Systems (CPPS) through the concepts of Industry 4.0 and the Internet of Things (IoT) (Vogel-Heuser and Hess, 2016). Applications in this context allow researchers to do engineering steps towards the comprehension of the concepts related to this topic (Zezulka et al., 2016). This kind of environment bases on network connections, decentralization and virtualization, allowing the human-machine interaction, as well as machine-to-machine communication (Brettel et al., 2014).

Robots and Smart Actuators have an extensive role in Industry 4.0, as instruments to automate multiple industrial processes. They are tools that offer safety, flexibility and the possibility of collaboration with other devices in modern environments (Bahrin et al., 2016). Thus, they are not only a replacement for humans performing repetitive tasks but also collaborative components linked by smart sensors and human-to-machine interfaces.

Many times, industrial processes present hazards to the involved workers (Saleh and Cummings, 2011; Shaikh et al., 2018). Within this topic, the prospect of operating and controlling industrial processes away from their hazards is a possible solution for this matter. Therefore, another important topic is human interaction through data virtualization and digitalization.

All this interaction requires a network-based environment in which the devices can communicate with each other and generate insights and decisions. Thus, this integration uses the paradigm of the Internet of Things (IoT) as a basis for the development of novel applications. The IoT is a modern paradigm in which devices communicate through network connections, especially using wireless technologies (Hozdić, 2015).

As mentioned, multiple connections compose an Industry 4.0 application environment. Furthermore, the virtualization aspect is relevant to create this kind of system. Also, the integration of elements such as robots and smart sensors have a significant role in industrial applications. Finally, this appliance must have elements that allow machine-to-machine communication and human-to-machine interfaces.

Although there is a comprehension from the importance of Industry 4.0 and its elements, the literature lacks discussions of functional constraints for designing such applications. Furthermore, the literature lacks on works that test these constraints in pro-

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totype environments. Thus, in this work, we provide both a theoretical and practical analysis of the main constraints and challenges of developing applications based on elements of Industry 4.0. As these are the minimal conditions for the design of appliances, it configures this as a functional approach. Hence, the main objective of this work is:

- Establish the theoretical main functional constraints and challenges in the development of Industry 4.0 applications and test them in controlled prototype environments;

At first, we organize and understand what are the main constraints in the design of Industry 4.0 applications through a theoretical approach, discussed in Section 2. We analyze the elements which compose these systems, as well as their single constraints and integration challenges. Furthermore, we created prototype environments in which we test some of these constraints to create model applications and perform tests, presented in Section 3. Finally, we discussed the results in Section 4.

2 THEORETICAL ANALYSIS

In this section, we introduce the theoretical view of the aspects covered in this work. Our objective here is to establish the main functional constraints and challenges concerning the design of novel applications for Industry 4.0 from a theoretical approach. Our further tests will validate the restrictions gathered in this survey.

2.1 Industry 4.0 and the IoT

Lasi et al. (Lasi et al., 2014) present the most modern industrial paradigm as the fourth industrial revolution, henceforth called "Industry 4.0". In this new paradigm, industrial plants will require decentralized, modular and efficient manufacturing units. Saldivar et al. (Saldivar et al., 2015) presents some of the main design principles regarding Industry 4.0:

- Interoperability;
- Virtualization;
- Decentralization;
- Real-Time Capability;
- Service Orientation;
- Modularity;

There are some key concepts and technologies to enhance the functioning of these systems, such as Big Data, Machine Learning, and IoT. According to Atzori et al. (Atzori et al., 2010), the Internet of Things (IoT) is a novel paradigm in modern telecommunication. The main techniques to enhance communication between devices are wireless network protocols. Taneja and Davy (Taneja and Davy, 2017) enforce that a typical IoT application bears several modules running together. Beyond smartphones, tablets and personal computers, novel computer-based devices can also compose these networks. Some examples of IoT devices are:

- Robots (Ashokkumar and Thirumurugan, 2018);
- Gloves (Köseoglu et al., 2018; Farahani et al., 2018);
- Helmets (Roja and Srihari, 2018);
- Smart Sensors and Cameras (Ibañez et al., 2018; Jang et al., 2018);

Each module can combine in multiple ways to build and integrate several IoT appliances. This feature is enforced by the modularity of the device network, as stated previously.

2.2 Constraints and Requirements for Industry 4.0 Applications

The works found in the literature do not present a formal approach to the basic functional constraints and requirements for the Industry 4.0 application design process. Thus, in this section, we create a theoretical basis for the main restraints for designing novel solutions.

Initially, we look at the constraints from the ground theoretical perceptions from Industry 4.0. As presented previously, the main concepts around this topic are the Cyber-Physical Systems (CPS) (Vogel-Heuser and Hess, 2016) and the Internet of Things (IoT) (Hozdić, 2015). Therefore, we formalize the constraints combining three main sources: The main restraints of CPS, the main requirements from the IoT and the Industry 4.0 design principles (Saldivar et al., 2015).

At first, we evaluate the Cyber-Physical Systems. Abad et al. (Abad et al., 2016) enforce that these systems must remain fully operational throughout the task execution time. This constraint creates a need for software safety protocols to observe soft and hard real-time requirements. Furthermore, this requires hardware robustness and reliability, which is a basic embedded systems constraint (Hansen, 2017). These restraints represent a reliability aspect in the produced data, which is hardware- and software-dependant. Xie et al. (Xie et al., 2018) reinforce the reliability as a constraint for CPSs, and its direct relation with real-time requirements.

Also, we analyze the Internet of Things' main constraints. Samie et al. (Samie et al., 2016) enforce that the Internet of Things goal is the ubiquity of network-based decentralized devices. As much as information is the most important value, the network communication capability is the main constraint in developing IoT applications (Gravalos et al., 2018). Tuyishmere et al. (Tuyishimire et al., 2016) state that Wireless Sensor Networks are the main theoretical base for IoT applications. From these applications, we learn that these networking constraints affect the data reliability.

Therefore, we present two main issues as the most important constraints in the design of Industry 4.0 applications:

- **Software and Hardware Reliability.** As a CPS, the application must present reliable hardware and software elements to provide the environment to develop the proposal;
- **Networking and Communication.** As an IoT application, the devices must provide services with minimal quality restraints to enable fully operational applications in the context of Industry 4.0 with data reliability.

From the design principles presented by Saldivar et al. (Saldivar et al., 2015), the reliability constraint from the CPS analysis serves mostly the interoperability, real-time capability, and modularity of the proposed application. The networking constraint affects, for the most part, the interoperability, virtualization, decentralization and service orientation aspects.

3 PROTOTYPE ENVIRONMENTS

In the previous section, we introduced the main constraints, challenges, and elements employed in the creation of advanced network-integrated environments based on the IoT and CPS concepts. In this section, we present prototype environments based on Industry 4.0, created to experiment and validate the gathered information.

As stated, Industry 4.0 applications have two main constraints: Software and Hardware Reliability and Networking and Communication. Through this conjecture, we created two different environmental tests to validate both these constraints.

3.1 First Environment - Digital Twin Wearable-based Teleoperation

The first prototype environment evaluates the Hardware and Software reliability aspect. In our proposed appliance, we use a digital twin virtual environment and tactile feedback from a data glove as Human-Robot Communication interfaces. Figure 1 displays the proposed environmental architecture.

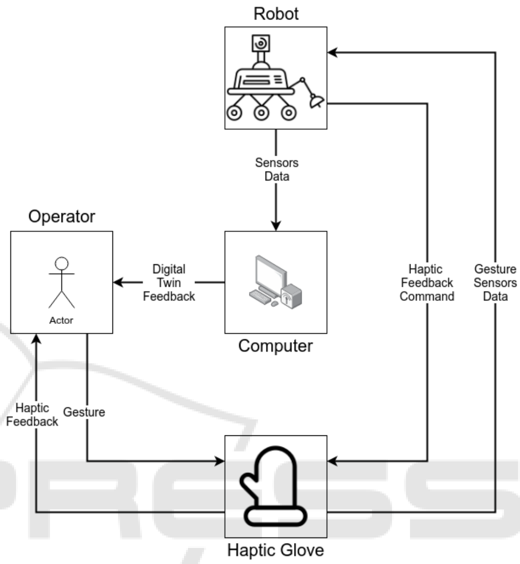

Figure 1: IoT-based operation environment architecture.

As stated before, the operator receives information from the robot through the digital twin application and the tactile feedback from the glove. He uses the haptic glove as a communication interface with the system. The glove embedded computer node actively sends the gesture sensors information to the robot for interpretation and acting. It produces haptic feedback using an embedded vibration motor.

In this appliance, the robot receives the fingers data and turns it into a hand signal command. There are three main basic hand signs. If the user keeps his hand open, the robot should stay stopped. If the hand is closed, the robot should travel forwards at a controlled speed. Finally, there's another special sign to make the robot travel backward, with only the two first fingers open. Figure 2 displays these hand signs.

The robot receives the information from the glove, interprets the gesture and acts accordingly, sending the position encoders and obstacle detection sensors data to the digital twin application. In case the robot detects an obstacle, it sends a signal to the digital twin application and the haptic glove to generate a feedback response. Finally, the computer application tries

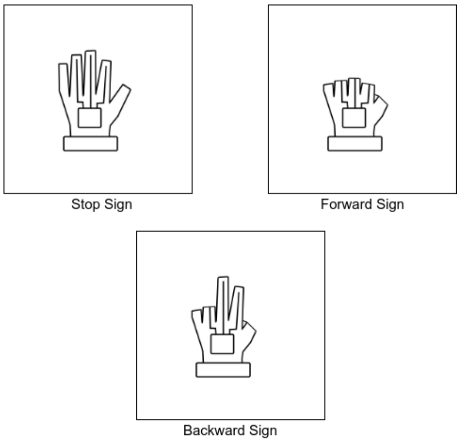

Figure 2: Robot Control Hand Signs.

to reproduce the robot condition from its transmitted sensor data.

The communication means used by these prototypes is a Wireless Local Area Network. The applications running on each device send and receive data using UDP protocols to avoid delays in the data stream.

3.1.1 Validation Test

In order to test and validate the proposed architecture using the presented prototypes, we arranged a setting containing elements to examine the system proposed features. With this environment, we tested the precision of the digital twin.

For the digital twin validation, we proposed a test to compare the longitudinal distance from the robot against the reproduction in the virtual environment. Figure 3 illustrates the test set.

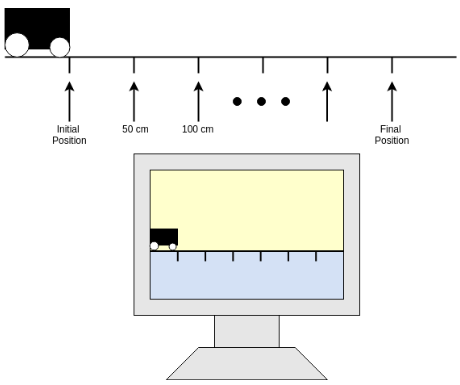

Figure 3: Digital Twin Validation Test Illustration.

To evaluate the reproduction of the digital twin environment, we obtained values of real distances and the correspondent value on the digital twin environment for various measures. In an ideal circumstance, the regression function obtained from these points should approximate from a function as the represented on equation 1, where $d_{vi}(d_r)$ is the ideal value of the robot position in the virtual representation as a function of the actual real position value d_r.

$$d_{vi}(d_r) = d_r \quad (1)$$

From the point cloud obtained from the tests, we applied a linear regression model to represent the same function with the actual obtained values. This function is represented in equation 2, where $d_v(d_r)$ is the value obtained from the linear regression of the scatter plot, represented as a function of the real position value d_r.

$$d_v(d_r) = \alpha.d_r + \beta \quad (2)$$

Where α and β are the regression parameters. The next step is to evaluate the quality of this function. Thus, we represent the error function between the ideal and the obtained functions. This $E(d_r)$ function is represented in the equation 3.

$$E(d_r) = d_v(d_r) - d_{vi}(d_r)$$
$$E(d_r) = \alpha.d_r + \beta - d_r$$

$$E(d_r) = (\alpha - 1).d_r + \beta \quad (3)$$

In this equation, the term $\alpha - 1$ represents the angular coefficient error, which represents how good is the position measurement. Also, the angular coefficient error indicates the percentage error of the representation when the offset is corrected. The β term represents the offset error, which is a calibration term.

3.2 First Environment - Validation Test Results

In this test, we needed to obtain the data that will correlate the distances of the digital twin and the real distances. Therefore, we manually measured the robot's traveled distance and compared it to the value obtained using the embedded encoder sensor.

We have measured these values 40 times, using distances from 50 to 200 cm. From this data, we applied the method described in Section 3.1.1 to obtain the $\alpha - 1$ and *beta* values that represent the quality factors of this representation. Figure 4 displays the results obtained from this test.

In Figure 4, the red line represents the ideal relation, represented by the $d_{vi}(d_r) = d_r$ function. From the obtained points, represented as black spots in the figure, we have obtained the line that represents the actual behavior of the system given its real data. The

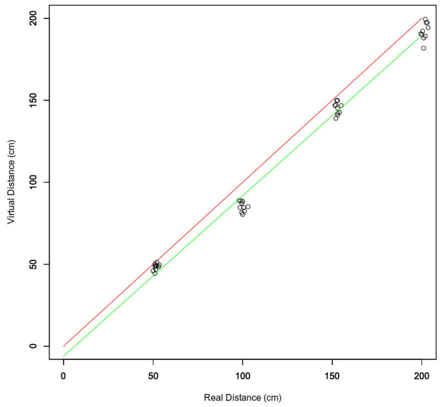

Figure 4: Validation Test Results.

green line displays the function that represents this behavior, represented by the equation:

$$d_v(d_r) = 0.977.d_r - 6.01$$

The resulting angular coefficient is $\alpha = 0.977$ and the linear coefficient is $\beta = -6.008$. The angular error factor is $\alpha - 1 = -0.022$. These results indicate that the behavior of the virtual environment based on the provided sensor data has a percentage error of approximately -2.3%. Also, there's an approximate offset of 6.01 cm, which can be easily solved by adding a bias to the obtained sensor value.

3.3 Second Environment - Digital Twin Inspection of Autonomous Robot Routine

The second prototype environment is designed to evaluate the Network and Communication constraint. Through this architecture, we expect to assess the real-time constraints of this system. For this task, the robot performed an autonomous routine through the ground, providing the sensor information through network queries as an IoT node.

To test the network capability, multiple devices persistently query the embedded sensors data. For this matter, they must open the connection, retrieve the data and close the connection. The robot connection node accepts one request at a time. As part of the prototype environment, the devices generate a reproduction of the device position in a grid.

The robot runs two threads. One of them controls its movements and data acquisition. The second one controls the network connections. The devices will have an active 50 ms sleep time, and then persistently attempt to acquire the data from the sensor. To understand how the network affects the quality of the provided data, we tested the time required for each device to complete the following cycle:

1. Establish connection with the node;
2. Acquire data;
3. Produce digital twin frame;
4. Sleep (50ms);

The evaluation of the real-time constraint in the network environment requires a test formalization. We consider this scenario as a soft real-time system, as the deadline violation decreases the quality of the provided information without catastrophic consequences. Thus, we designed this experiment strictly as a Quality-of-Service (QoS) test, based on other similar analyses in the context of Wireless Sensor Networks and IoT (Silva and Oliveira, 2019; Boukerche and Samarah, 2008; Silva et al., 2019). In the existing perspectives, the examination considers one or multiple devices consuming data from multiple sensors. Thus, we created a proper formalization for a scenario with various devices consuming data from a single node.

At first, we evaluate the time as discrete intervals, as the set $T = t_i, i = 0, 1, 2, 3, \ldots$, following the rule that $t_{i+1} - t_i = \theta$, where θ is a constant sampling time. The soft real-time deadline will be represented by ϕ, where $\phi = k.\theta, k \in \mathbb{N}^*$. In other words, the deadline is represented as an integer number of sampling time intervals. Given this start point, we establish the following definitions:

Definition 1. Let $D = d_i$ be the finite set of devices consuming the data from the IoT node, where $i \in \mathbb{N}$;

Definition 2. Let $E = e_i$ be the finite set of events that each device performs, where $i \in \mathbb{N}$;

Definition 3. Let $L = l_{d,e}$ be the length of time interval that the device d takes to perform an event e, where $d \in D$ and $e \in E$;

Definition 4. Let $P = p_i$ be the set of patterns of events to be observed in the devices, where $p_i = E_i$, $E_i \subset E$ and $i \in \mathbb{N}$;

Definition 5. Let $O = o_i$ be the finite set of observations of a certain pattern $p_i \in P$ on the devices, where $p_i = E_i$, $E_i \subset E$ and $i \in \mathbb{N}$;

The equation that represents the elapsed time λ to observe a certain pattern $p_i \in P$ is:

$$\lambda_{p_i} = \sum l_{d,e_k} | \forall e_k \in E_i, E_i = p_i \quad (4)$$

Given the equation above, let $\hat{O}$ be a subset of O, where $\lambda_{p_i} \leq \phi$, $\forall o_i \in \hat{O}$. Finally, given the sets O and $\hat{O}$:

Definition 6. Let N be the number of elements on the subset O;

Definition 7. Let N_h be the number of elements on the subset $\hat{O}$

The quality factor Q_f will be represented by the following equation:

$$Q_f = \frac{N_h}{N}(.100\%) \quad (5)$$

In other words, the quality factor observes how many times the devices perform a pattern of events without violating its soft real-time constraint. As presented before, all devices will try to acquire the data and process it in parallel and asynchronously. Figure 5 represents how this test works.

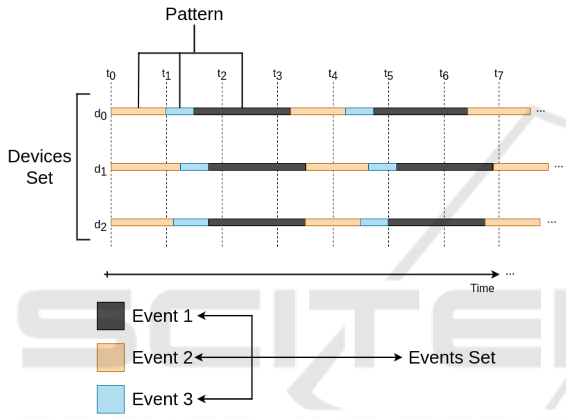

Figure 5: Illustration of the Observed Test Variables.

In this test, we experiment on how increasing the number of querying devices affects the network quality factor.

3.4 Second Environment - Validation Test Results

In the previous subsection, we demonstrated how to evaluate the quality of a soft real-time constraint in the context of a distributed IoT architecture. For this matter, we evaluate and quantify how increasing the number of devices consuming data affects the quality factor of the soft real-time system, following the notation created. In this section, we present the organization and results of the employed tests.

At first, we established the following set of events to evaluate:

- **e1:** Establish connection with the IoT node;
- **e2:** Acquire the node sensor data;
- **e3:** Process data and generate the frame of the digital twin;
- **e4:** Sleep and idle time.

For testing aspects, we divided our time slots into intervals of $\theta = 10ms$. Furthermore, we established a soft real-time deadline of $\phi = 10.\theta = 100ms$. We tested this aspect for a system having from one to seven devices as clients. These clients operate asynchronously, and must persistently query the IoT device to acquire the sensors data. We used various sets of devices, containing from one to seven clients. The time length observations from the events were recorded by each client.

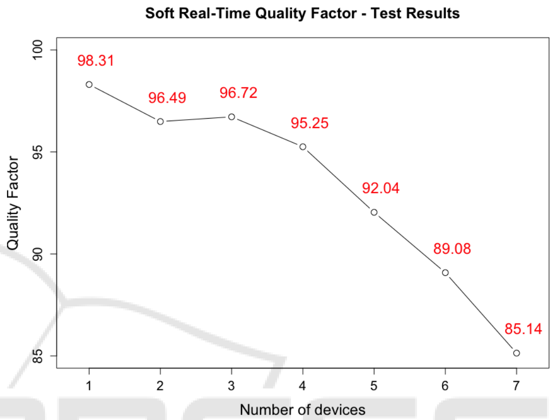

Figure 6: Results of the Soft Real-Time Quality Factor Test.

From the quality test value, the expected behavior is a loss of quality due to concurrency in the soft real-time constraint. Figure 6 displays the results of the test for each number of client devices. Typically, there is a quality factor loss of 1% to 4% for each extra client consuming the data. From qualitative analysis, this quality loss reflects in the real-time precision in the digital twin during the execution.

In further investigation, we also examined how each step contributed to quality loss. For this matter, we analyzed the average period length for each described event. From the data logs, we observed that the main impairment in quality comes in the first phase, which is the connection establishment. This happens as the network concurrency increases and the device answers one connection at a time.

4 DISCUSSION

In this work, we presented the main concepts, constraints, and challenges in designing Industry 4.0 applications. To understand how these constraints apply to design applications, we developed two different architectures to simulate modern network-integrated environments based on IoT and CPS concepts. From those, it was able to test the two main aspects identified in the theoretical analysis: Software and Hardware reliability, and Networking and Communication.

The first proposed architecture is a robot and digital twin virtual environment, with a data glove as a Human-Robot Communication interface with tactile feedback. For this matter, we created a local appliance based on prototypes and providing a digital twin virtual feedback environment.

Our validation test set consisted of comparing real distances and their correspondence on the digital twin environment for different measurements. The result obtained for the digital twin shows that although its percentage error of approximately -2.2% and an approximate offset of 6.01 cm.

This simulation displays relevant aspects that can happen in the environment of an Industry 4.0, regarding the uncertainties of the representation of digital twins and possible uncertainty sources. With this appliance, it was able to observe many uncertainty sources, vital for designing an Industry 4.0 application. Network traffic, sensor uncertainty, mechanical flaws, hardware limitations, and configurations add difficulties to the implementation of such an environment.

Nevertheless, the test allowed us to understand how capable did the appliance perform all the proposed tasks with adequate approximation. Therefore, these tests are suitable tools to validate the proposed architecture with the challenges of the element's reliability. Finally, it also helps to indicate possible problems associated with the communication of the nodes, such as network traffic and latency, which were analyzed in the following tests.

The second proposed environment uses the evolution of the robot used in the previous section. However, the objective of this test is not to define the quality of the data produced by the hardware, but the influence of the network requests overload in the soft real-time requirements. For this matter, we proposed a test which interprets this constraint as a Quality-of-Service issue.

The results of our test display that there is an expected quality loss of 2% to 4% for each extra node persistently consuming data from the device. At first, only 1.69% of the requests violated the soft-real time constraint with only one consuming device. When running the same process with seven consuming devices, the real-time constraint violation ratio increased to 14.76%. Moreover, our further analysis displays that networking overload is responsible for this loss. This result indicates how the overload of network requests in this environment impairs the real-time constraints in distributed IoT networks in the Industry 4.0.

In the papers found in the literature, no author formalized the main functional constraints for the Industry 4.0 design process. Thus, we proposed two main restrictions based on the ground concepts of these applications. Our tests in the prototype environments display how the main constraints identified in the theoretical analysis affect a designed application.

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