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A Predictive Simulation and Optimization Architecture based on a Knowledge Engineering User Interface to Support Operator 4.0

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Abstract: The Real-Time Monitoring and Performance Management suite tool, known as UIL (User Interface Layer), was developed in the FASTEN project, a R&D initiative financed by the innovation and research program H2020 within a bilateral Europe-Brazil call. UIL was conceived and deployed in the IIoT architecture of the project. The goal was to provide a user-centered assistance to the human operator for both decision-responsibility and control loop, in a continuously updating information fashion, related to system's state. In order to have experimental results, a qualitative assessment was conducted in an industrial environment. The architecture proposed was based on the adoption of a Knowledge Engineering User Interface to support Operator 4.0. Our empirical experiments point out to a successful set of results.

Keywords: Intelligent manufacturing systems, IIoT architectures, Human operator support, Real-Time Monitoring, Industry 4.0.

1. INTRODUCTION

Intelligent Manufacturing Systems (IMS) have become an interesting area of research for manufacturers with highly complex and customisable products, to allow them to be flexible enough to easily adapt to environment (Stadnicka et al. (2019)). In this context, the rising complexity of industrial systems has evidenced the need to carefully take into account the human factor during design and operation of IMS, especially to address human errors and material failures during operation (Pacaux-Lemoine et al. (2017). As pointed out by Trentesaux and Millot (2016), a critical point in IMS design is to assume a human operator will be there to handle unexpected situations, being at the same time coordinated, efficient and rapid, i.e. being 'magic human', while, as Slatter et al. (1989) put in, the operator can be seen as a source of unpredictability and hazardous situations. The objective of this paper is to present a successful proposal and experimentation of an architecture of predictive simulation and optimization based on a knowledge engineering user interface to support an Operator 4.0.

This paper deals with the experiments in an industrial use case of IMS design and implementation based on human-machine cooperation principles. The approach has been evaluated by practitioners through real experiments in the context of the European-Brasilian funded research project FASTEN (www.fastenmanufacturing.eu). Section 2 presents the state of the art of human-centered IMS design relevant to this paper, section 3 presents the solution adopted by FASTEN project and Section 4 presents the use case-based experimentation and evaluation performed.

2. RELATED WORKS

In order to gain a deeper understanding of our research work, some previous research works on the topic are here presented. The idea is to highlight the results and consequently possible future development.

2.1 Techno-centered IMS design

Research activities in management have recently studied hierarchical planning in systems interacting with individual decision processes in terms of distributed decision-making (see, as an example, Schneeweiss (2012)). More in general (Hermann et al. (2016)), design principles in Industry 4.0 include decentralized decision-making, on the basis of interconnection of objects and people. Research in manufacturing has devised manufacturing control systems provided with autonomy and adaptation capabilities, by means of the distribution of decision capabilities to artificial entities, e.g. holons. The work of Derigent et al. (2020) describes the main holon properties as autonomous

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and decentralized decision support systems: adaptability, learning with big data analytics, process virtualization via simulation/optimization during decision, real-time capabilities, interoperability and connectivity via cooperation. Holonic architectures therefore focus on cooperation among systems, rather than with the human. More in general, IMS researchers mostly consider the operator as supervisor (Gaham et al. (2015)). According to (Pacaux-Lemoine et al. (2017)), even if industrial designers perceive the above as a 'human in the loop' approach, it can be interpreted more as a way to keep the human in the 'decision/responsibility loop' but not in the control loop". This is why Trentesaux and Millot (2016) have called such a human operator a "magic human", able to supervise the system and reply to decision requests with perfect decisions. This design approach can be defined 'techno-centered", characterized by priority to technical issues. The main problems of the above mentioned 'magic human' approach to IMS design, have been identified by Trentesaux and Millot (2016) as follows:

- *human can be the devil*, as a source of mistakes or over-reactions;
- *human can be the hero*, by devising unexpected and innovative behaviour, which can save the day or spoil the operations;
- *human can be powerless witness*, who cannot observe and control a poorly-designed system;
- *human is legally and socially accountable*;
- *levels of automation must be adaptive*, and must evolve according to events and human competencies;
- *diversity, repeatability of decision and actions must be considered*, to avoid lack of interest or stress and fatigue.

2.2 Human-centered approach to IMS

Several authors reached to go beyond the 'magic human' problem taking into account human factors in design. According to Jensen (2002), three main approaches have been proposed: the classical approach, which incorporates criteria to predict working conditions and validate task requirements; the socio-technical approach, which considers the manufacturing system composed by two sub-systems that must be jointly optimized, the sub-technical system and sub-social system; the human-centred approach, aiming at driving the design towards reinforcing the human capabilities in the system, e.g. enhancing collaboration and knowledge.

In the stream of human-centered approach, Peruzzini and Pellicciari (2017) have adopted cyber-physical systems and pervasive technologies (sensors, virtual commissioning) to engineer and prototype a context-aware manufacturing system able to adapt their behaviour according to defined adaptive rules and the actual working conditions, workers' tasks and physical and cognitive abilities. Dantan et al. (2019) have studied the behavioural interactions between the workers and manufacturing system, with a function-behaviour-structure model to consider human factors during design: these interactions are modeled and simulated to assess the system design using specific indicators.

Frazzon et al. (2020), to go beyond the traditional periodic planning and control decision-making, have considered human limitations by proposing the development of support systems for distributed decision-making and digital integrated manufacturing under a socio-cyber-physical systems perspective, supported by simulation-optimization-analytics methods, with a technology-based approach to digital operations along manufacturing networks.

2.3 Proposal of Human-centered approach to IMS design

Along this reasoning, Pacaux-Lemoine et al. (2017), to allow proper integration of humans in IMS design, have proposed a human-centered approach to IMS design (see figure 1), based on Human-Machine Cooperation to engineer and evaluate systems, processes and their interaction with humans, on the basis of two aspects. The first aspect focuses in information exchanges due to different interactions: i) interactions occur between human and system at three time-bound levels: operational, in the short term, directly related to command and task execution; tactical, in the medium term, to achieve intermediate objectives by task triggering and re-planning and, at strategic level, to achieve long term goals by planning tasks and intermediate objectives; ii) cooperation occurs with exchange of information between human and the control system at each of the three levels, and decisions and requests are exchanged within the same agent between different levels, such as Human at strategic level feeds decisions about overall goals and receives requests about KPIs to be provided to the human and when. As an example, an automatized production line assembles products of different types according to a specific schedule along a certain time horizon, and its performance is measured in terms of delays with reference to due dates. At strategic level the human sets an additional goal related to energy consumption minimization. At tactical level, human and the production line interfere as production line aims at producing according to the schedule while minimizing delays, while human might decide to postpone the production of a specific product type or to group production of same type products to minimize set-up times. Cooperation occurs when human and production line produce a common plan able to take into account both delay and energy consumption minimization. At operational level, the human might decide to switch off one of the machines of the line. A second important aspect is related to integration of mutual observation, with focus on the behavioural model of the 'other' agent, which allows on the one hand, to provide the cooperating agent a way to forecast the other agent behaviour and performance further to its own actions/decisions and, on the other hand, to spot any unreliable behaviour of the other agents.

These principles have been applied to IMS using Artificial Self-Organizing systems (ASO), in which an assistance system was design to support cooperation between ASO and humans: experiments were conducted to evaluate the systems in improving performance of Human-Machine Systems. How to assess the impact of cooperation principles in Human-Machine systems is relevant for the work of this paper: the following subsection is dedicated to this.

2.4 Human-Machine systems cooperation principles

The term "agent" is used in literature in a general sense to define a decisional entity, e.g a human or an intelligent control system, or a Decision Support System. "Two agents

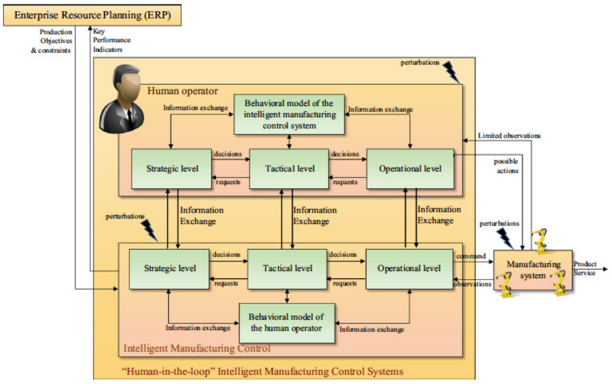
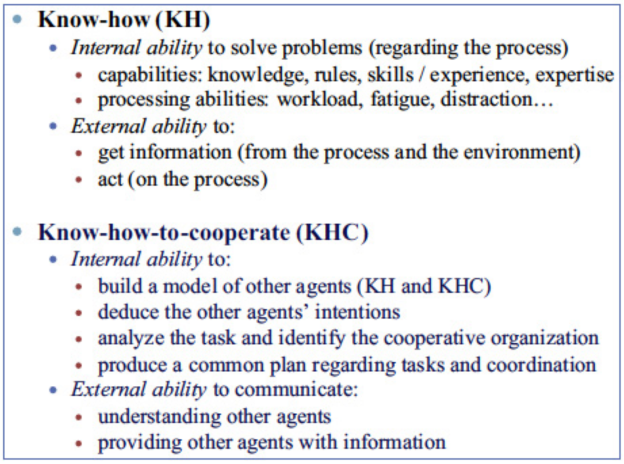


Fig. 1. Human-centered IMS design approach (Pacaux-Lemoine et al. (2017))



- **Know-how (KH)**
  - *Internal ability* to solve problems (regarding the process)
    - capabilities: knowledge, rules, skills / experience, expertise
    - processing abilities: workload, fatigue, distraction…
  - *External ability* to:
    - get information (from the process and the environment)
    - act (on the process)
- **Know-how-to-cooperate (KHC)**
  - *Internal ability* to:
    - build a model of other agents (KH and KHC)
    - deduce the other agents' intentions
    - analyze the task and identify the cooperative organization
    - produce a common plan regarding tasks and coordination
  - *External ability* to communicate:
    - understanding other agents
    - providing other agents with information

Fig. 2. Model of cooperative agent (Pacaux-Lemoine et al. (2017))

are in a situation of cooperation if (a) each strives to reach goals while interfering with the others' goals (at least regarding resources or procedures), and (b) they try to manage such interference to make the other's activities easier" Lemoine et al. (1996). Cooperative agents, while interacting and involved in controlling the same IMS process, perform both individual and cooperative tasks: the abilities involved can respectively be called "know-how" and "know-how-to-cooperate" Millot and Lemoine (1998), see figure 2.

3. FASTEN IIOT ARCHITECTURE

FASTEN project has adopted an Industrial IoT (IIoT) architecture integrating a Digital Twin of the system and a discrete-event simulator to support real-time decisions. The adopted approach is then based on vertical integration of real-time information, from the physical resources (IIoT end-points) of a production line, to the IoT Platform which collects the real-time status of the resources, up to the simulation model which uses the IoT platform data to feed the Decision Support model. Finally the Decision Support System involves a computational activity to provide decision suggestions. More in detail, figure 3 describes the adopted architecture which involves the following layers: i) Data Sources (the physical resources); ii) Integration Layer (IIoT platform); iii) the Optimization-Simulation layer (which includes both simulation and operation research capabilities for real time optimization; iv) Prediction layer, with data-analytics functionalities and, finally v) the User Interfaces Layer which allows interaction of the Operator with all other layers except the Data Sources. This architecture is aligned with the framework described in Frazzon et al. (2020), described in previous section, which builds upon the combination of the capabilities of simulation, optimization and data analytics to cope with the operational data level reacting to conditions that vary in real-time.

architecture.png architecture.bb

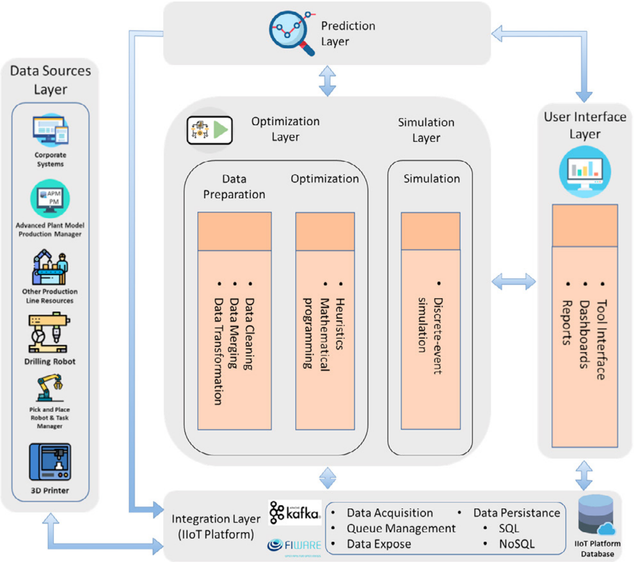


Fig. 3. FASTEN Predictive Simulation and Optimization architecture

4. EXPERIMENTAL ENVIRONMENT AND RESULTS

Proposed system has been validated in an industrial scenario, on the scope of the aforementioned H2020 FASTEN project, and is supporting human operations in the logistics warehouse and in the assembly line of an aircraft manufacturing plant of Embraer. Within this facility, two interesting scenarios have been considered:

- Pick and Place Robot (PPR): A kitting order is created by the company's management execution system (MES) and sent to the Advanced Plant Model (APM), a Digital Twin of the logistics warehouse. The order is translated into an action plan that is provided to the Production Manager (PM) component, responsible for activating and monitoring the programmed tasks: the parts are picked from an automated warehouse system and placed inside bins over its output tray; then, the robot is programmed to move to the output tray and to pick the ordered parts; finally, these are placed in a kitting box over the robot's platform and transported to a specific area in the assembly line. Two cases occur: parts are known by the robot's controlling software or, new parts can be recognised by its perception system.
- Wing Assembly Line (WAL): A wing assembly line, made up by operators and workstations, must be balanced in terms of allocations of tasks maximizing

the productivity both at the beginning of the shift and when changes and disturbances occur. An “Holistic Simulator-Optimizer tool” proposes the allocation of resources and tasks to resources in the workstations, to cope with the objectives of the production plan.

FASTEN project has adopted a requirement-driven engineering method able to take into account the complexity of the use case and to elicit user expectations and needs.

4.1 FASTEN User Interface layer (UIL): interactions with Operator

As described in section 3, the FASTEN project designed and developed an IIoT platform able to support human-machine cooperation; the platform deals with three main blocks, with reference to Figure 3: i) at tactical level, with the Prediction Layer; at tactical level again, with the Optimization-Simulation Layer; at operational level, with the Data Sources layer, with regards to the monitoring of the real-time position of the robots. To clarify the difference between operational control level and tactical control level, we define the former as task execution (with main agent the Process) and possible disturbances left to the Operator, physically interacting with the Process, the low level ones, which require quick intervention and do not affect the medium term performance; the latter level relates to task planning (main agent is the System supporting the Operator), with possible disturbances the medium level ones, with relevant impact on the performance of the Process.

Scenario 1: Pick and Place robot The FASTEN PPR is a collaborative mobile manipulator composed by an AGV, capable of efficiently moving the robot inside the plant, and by a Universal Robots UR10 collaborative manipulator. The robot is equipped with two laser scanners which provides the required safety features for collaborative operation and the autonomous feature for an efficient localization and navigation system. Moreover, the robot is equipped with a 3D camera providing inputs for for the perception skill, and a 2-finger gripper, providing input for the grasping.

The robot programming has been developed following a modular approach. Each capability of the robot is described in isolation, following a skill-based robot programming approach, as detailed by Arrais et al. (2019). The orchestration of the skills is provided by a module entitled Task Manager, developed as a Python application running in the Robot Operating System (ROS) (Quigley et al. (2009)). As previously mentioned in Section 4, the FASTEN PPR software stack, entitled Open Scalable Production System (OSPS), includes also the APM and the PM. The OSPS provides not only the necessary semantic and geometric information for the digital representation of the plant (the digital twin) inside the APM (Toscano et al. (2017)), but also the necessary vertical and horizontal integration features, to allow proper inter-operability between FASTEN systems, existing industrial equipment, and high-level enterprise software (Arrais et al. (2020)).

Fig. 4. Industrial Dashboard for the Pick and Place Robot

At all times, the robot must be aware of its surroundings, being collaborative with human operators sharing the same logistic environment, by dynamically updating its position and reporting inconsistencies on its internal digital twin representation, that are then propagated to the APM (Arrais et al. (2017)). Furthermore, the robotic system responds to a set of production orders issued by the PM, which, in combination with the APM, provides an intuitive web-based interface that can be used by Embraer logistic personnel to monitor, in real-time, the ongoing state of the digital twin representation (Toscano et al. (2017)), but also supervise and control the operational status of the FASTEN PPR with its main parameters (See Fig. 4).

Scenario 2: Wing Assembly Line Here the context is the Wing Assembly Line (WAL); in this case the UIL allows the Operator to access a set of functionalities, such as: i) control the Optimization-Simulation layer execution and access previous executions and obtained results; ii) visualize, in real-time, the execution and results of the Prediction layer, and control the analytic models in it; iii) visualize, in real-time dashboards, data coming from the Data Sources layer (sensors and devices) through the Integration Layer (IIoT platform). All this information allow an overall monitoring of the production processes. The Optimization-Simulation layer contains the Holistic Simulator-Optimizer Tool which, combining a set of simulation and optimization techniques, proposes the best allocation of resources and tasks for each workstation considering: i) existing production plan; ii) operations; iii) availability of resources; iv) work-in-progress. These decisions are tested using a simulation model. This model comprises the main logic and behavior of the real system, allowing to predict the expected performance of the system. The Predictive layer uses machine learning techniques to predict the remaining useful life of robotic resources; the purpose is to reduce the number of corrective maintenance and relative downtime. UIL is here composed by a set of dashboards which display data and results coming from the other layers, provide data trends from sensors and devices in real-time fashion way , provide a wide view of the system behavior to the Operator. These dashboards allow the Operator to to properly manage the plant using the optimization and prediction capabilities of FASTEN system. Furthermore, the UIL provides insights about the system's operational status (e.g. performance KPIs, bottlenecks, underused or under-performed resources, expected date to complete the production schedule) and potential failures, such as in Fig. 5.

4.2 User Assessment: methodology

Objective of the assessment is to get information and lessons learnt from users during the experiments performed in the project. The methodology adopted in this

Alarms Description

93000: Parada de emergência

9510217: Superaquecimento do gabinete eletrico. Verifique se o ar condicionado esta funcionando e contacte a manutencão.

9700142: Erro no movimento do spindle.

Index	Date	Message
2	2019-11-18 15:16:49	There is evidence on robot conditions indicating chance to have Probe problem on the next 12 hours. Inspection and Cleaning action needed!
2	2019-11-18 15:16:49	There is evidence on robot conditions indicating chance to have Probe problem on the next 12 hours. Inspection and Cleaning action needed!

Fig. 5. Drilling robot alarms dashboard

work has been inspired by the one developed by Pacaux-Lemoine et al. (2017): accordingly, we define the following terms: the Operator is the human in charge of manage and control the Process under investigation, while the System is the cyber-physical system in support of the Operator.
On the basis of the cited cooperative model by Pacaux-Lemoine et al. (2017), see figure 2, a questionnaire has been developed in order to reply to the following research questions, from the Operator viewpoint:
Operator Know-How:

(1) Which capacity has the Operator to manage and control the System and Process with non-cooperative actions, including solving problems and address disturbances.
(2) Which capacity has the Operator to interact with the System and/or the Process.

Operator Know-How-to-Cooperate:

(1) Which capacity has the Operator to reach its goals while minimizing interferences with the Process.
(2) Which capacity has the Operator to exchange information with the System/Process.

The approach adopted for the user assessment of the IT solutions deployed in EMBRAER can be framed into the context of qualitative research, focusing more on human phenomena and less on quantitative data, with an interpretive focus on providing sense on how the IT solutions support users in their interaction with the system and the process under intervention. The questionnaire developed and submitted to the EMBRAER practitioners, aims at showing how the interaction of the Operator with the System and the Process has been supported in terms of Operator capability to control the process i) with non-cooperative actions (that is, when there is no interference on shared resources between the actors) and ii) cooperative actions (in which the Operator commands resources shared with the System or the Process, with the aim of minimizing interference by means of a common plan). Questionnaires were developed together with EMBRAER, with the support of a business analyst, along the schema presented in Fig. 2, asking to the evaluators to reply to open-ended questions by using a Likert scale, to add an explanation of the grade assigned, suggestions on how to improve the system, in case of less-than-favorable evaluation score, and to list the most relevant disturbances (internal and external) for each scenario.

4.3 Assessment results and discussion

The developed questionnaires have been submitted to the company's managers and practitioners, completed with examples of compilation. The PPR and WAL scenarios have been evaluated respectively by one and two EMBRAER evaluators.

Scenario 1: Pick and Place robot The PPR scenario is an operational level scenario, in which the System focus is task execution and process control. The evaluator agrees about the important role of the 3D visualization tool, which, by superimposing real-time information on the actual image of the plant, allows both having a clear understanding of the state of the system and, interestingly, how to to deal with internal problems, e.g. failures, or external, such as interference with human hindering robot movements. The majority of the questions received a favorable response, anyway the evaluator highlighted possible improvements especially in terms of cooperation, such as i) by equipping the moving robots with Light systems and HMI devices; ii) by suggesting to have the robots provide information to the humans sharing the area about their future movement paths or which parts they are carrying; iii) enhancing the information provided by the UIL about failures of the robot and the automatic warehouses, especially if robot activities (namely 'skills') need to be stopped.

Scenario 2: Wing Assembly Line As the WAL balancing is a tactical level scenario, which means planning the application of tasks (to be executed at operational level) and possible updates of the plan, the main focus is using the System's simulation-optimization capabilities to devise balanced planning and new task allocations. In this context, the System support must, on the one hand, provide timely and feasible plans and, on the other hand, enable the Operator to ensure a thorough and precise replication of the Process and its constraints, and easily devise alternative plans by setting up the relevant parameters for Holistic tool runs.
From the first perspective, that we might identify as non-cooperative actions, the Operator needs timely identification of optimal plans, including all the needed KPI to evaluate alternatives, and the evaluators agree that the System in general performs with a sufficient level, in a timely manner: the whole process of generating a new plan, does not take longer than one hour and includes all the relevant Production Kpis. Anyway, some improvements are highlighted by the evaluators: i) the System should check incorrect data entry before simulation; ii) more active support from the system when feeding data into the Holistic tool would be desirable; iii) training should be provided to the users especially on the Holistic tool process (identify needed data, loading them, manage the tool and understanding the outputs.
From the second perspective, that is enabling operator to ensure a thorough replication of the system process, which we can identify as 'cooperative activities', such as the one helping the Operator to build a behavioral model of the System and Process. Evaluators have evidenced the following improvements: i) System should minimize the limitations in replicating the Process, e.g. allowing management of maintenance tasks and relevant KPIS, stations changes, new WAL layouts; ii) if the computer used to run the Holistic tool does not meet the minimum requirements, an estimation of the simulation run time should be provided; iii) the Holistic tool should provide an

user guide; iv) the Holistic tool should provide checkpoints to the user along the simulation process.

5. CONCLUSIONS AND FUTURE WORK

This paper shows two important aspects of the work of FASTEN project. On the one hand, its enhanced user interface design concept which, integrated in the novel IIoT architecture framework, such as the one adopted in the project, effectively supports all the possible user interfaces requirements in terms of monitoring and control the complex autonomous production systems, at both tactical and operational level. On the other hand, the user assessment approach adopted in the project, guided specifically by a human-centered approach, is able to highlight potential improvements, allowing the whole experiment to go beyond the requirement-driven design and development cycle. An interesting recommendation is to carefully design the UIL to show the behavior model of the systems involved, e.g. the future state of the robot or the estimated time and operational cycle of the Holistic tool while processing. As some actions could not be enacted due to the delays caused by the pandemic situation, there are several possible directions of future work, for example questionnaires could be submitted, followed by interviews with EMBRAER practitioners, belonging to different roles. Moreover, the questionnaire analysis could be performed in order to capture insights more thoroughly, by means of content analysis with standard coding techniques (Strauss and Corbin, 1990).

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