Foundations for the implementation of automatic control in a Hybrid Flexible Manufacturing System

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Abstract

This paper describes the main methodological bases to incorporate virtual elements in an existing Flexible Manufacturing System (FMS). This procedure allows building a hybrid system where virtual and real elements co-exist. Present work takes as starting point an existing FMS which is nowadays implanted in the Aerospace Engineering School (ETSIA). Nevertheless, the scope goes far beyond and can be extrapolated to any other FMS, so this is a very useful tool to create virtual laboratories for manufacturing or to expand and analyze the behavior of already existing systems. Virtual devices must reproduce the behavior of their real-homonymous elements so much as it was possible. This includes not only a mechanical way, but also a behavioral way.

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1. Introduction

A Flexible Manufacturing System (FMS) is formed by two or more workstations usually based in Numerical Control Machine Tools, interconnected by an automated logistic subsystem, all of them under a computer control. System flexibility allows to react to changes in manufacturing requirements, whether they are either foreseen or

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unforeseen, adapting its operation to the new conditions. This flexibility makes FMS especially suitable for the manufacturing of small batches.

The FMS got into the industry in the 80’s, although early prototypes and developments, Williamson (1967) or Broscheer (1968), come back from the late 60’s. From the point of view of manufacturing process engineering, the interest of FMS is unquestionable, as evidenced the number related scientific papers collected in Figure 1. The initial growth experienced by the FMS has remained steady as a result of heavy investments required for implementation that is not usually affordable for the small and medium enterprises. A slight decrease in the number of publications in the late 90’s can be appreciated, maintaining it a fairly stable rate in published papers including the term FMS in their titles from then on. It is striking the boom experienced by the published works in 2011, although not directly aimed at the study of the FMS, at least mentioned them in their contents.

This work is based on a real FMS called (CFF-ETSIA). It can be considered as a Flexible Manufacturing Cell (FMC) due to it has the minimum amount of elements to be considered as a FMS. Despite its size, CFF-ETSIA has all the performances required by a FMS and allows the access of students to the learn and research of technologies involved in a FMS operation. It also offers the possibility to perform different tests leading to check the potential of this kind of systems.

The original implementation of the CFF-ETSIA dates from 1995. From then until now, many technologies have undergone substantial changes, so an update of the CFF-ETSIA has been necessary, especially in the part concerning the control and communication subsystems. Present work redefines both subsystems and proposes a modular structure based in newer technologies that allows the addition of new machines or components to the system. Considering that the FMS growth through new equipment represents a significant investment, present work also proposes a new kind of FMS called “hybrid-FMS”. It consists of a system in which both, real and virtual elements created by virtual reality applications, can work together. This approach allows performing a wide variety of tests using the virtual environment before making changes in the real environment. This procedure can save costs and time. Considering the university scope of the CFF-ETSIA, the hybrid status becomes even more interesting since students can work with a FMS minimizing the risks of accidents and their impact.
2. Main elements of the CFF-ETSIA

Main elements of the CFF-ETSIA are shortly described in Table 1 which only shows most relevant elements. For a more detailed knowledge about CFF-ETSIA layout and functioning, other references like Perez-Acal (2007), may be consulted.

| Name                  | Image | Description                                                                                                                                 |
|-----------------------|-------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Lathe Compact 6       | ![Lathe Compact 6](image) | NC lathe designed to produce parts with a maximum diameter of 90 mm and a maximum length of 160 mm. The external control actions are done by the pins of the input/output of a controller Scrobot (C1). |
| Milling machine VMC-100 | ![Milling machine VMC-100](image) | Vertical milling machine designed for carrying small parts until 185x95x200 mm. The external control actions are made by the pin of the input/output of a controller Scrobot (C1). |
| Scrobot Controllers (C1 and C2) | ![Scrobot Controllers (C1 and C2)](image) | Contain ACL commands and programs (Advance Control Language) that let control the robots. In turn, the machine-tools are connected to it through the input/output pins. The controller is operated from a PC via RS232. |
| Scrobot ER-VII        | ![Scrobot ER-VII](image) | Vertically articulated robot whose mission is to supply parts to the workstations and the conveyor belt. The robot is mounted on a linear sliding basis, which grants the robot access to both machine-tools. This robot is operated by a controller Scrobot (C1). |
| Scrobot ER-V          | ![Scrobot ER-V](image) | Vertically articulated robot whose mission is to supply parts to the conveyor belt, relocate parts once they are finished and feed the automatic measuring station. This robot is operated by a controller Scrobot (C2). |
| Computers (Master and dedicated) | ![Computers (Master and dedicated)](image) | Each computer is communicated with a Scrobot controller via RS-232 serial protocol. Through this communication, a computer can execute ACL commands or enable/disable the output pins to execute actions in external control machine-tools. |

Note that it has been mentioned the presence of a conveyor belt and a lineal basis. For practical purposes, they are considered as an additional axis of the robot Scrobot ER-V and VII respectively. In the diagram of Figure 2 is summarized the starting configuration of the CFF-ETSIA.
3. Design of the new control subsystem

Throughout this section a restructured control subsystem of the CFF-ETSIA will be presented and developed. Modularity on the new configuration allows easily isolating and correcting failures or malfunctions. Also, the proposed development allows the incorporation of different control algorithms contained in the bibliography such as those proposed by Yasuda (2011), Prakash (2008) or Lu (2011).

3.1. General Approach

The new configuration proposed in this work starts on assigning a computer to each of the elements of the system. Thus control is achieved by a modular cell and a clearly defined hierarchy can be established. With this approach, the assigned computer to each work station is solely responsible for interacting with its associated machine, controlling all loading and unloading of programs, execution of direct orders and management of possible alarms.

Communication between workstation-computers and the other controlled elements of the system is conducted through new input/output controllers created by the Group HW (2013) manufacturer, incorporating the possibility of communication using TCP/IP.

Each controller has 8 input signal pins and 8 output signal pins that can be routed from an Ethernet network using TCP/IP. Each of the elements of the cell is connected to a controller as shown in Figure 3. In turn, each of the controllers is connected to a router via a network cable. Thus, control of all elements of the FMC can be done from a computer connected to the same router. The basic operation of the controller is that the signals received through the input pin translates messages into TCP/IP protocol and send them via an Ethernet network where the
computer associated with this device receive them. Furthermore, the computer can send messages using the TCP/IP over the local network that are received by the controller and modify the output signals of the device. This change achieves the goal of modularity initially set, as in the starting configuration several elements shared the same controller (controller Scorbot), but now each element is associated with one and only one controller (HW controller). Note that, as just mentioned, the implementation of such controllers implies the need for a router, network cables and at least one computer to send and receive signals from the controller via TCP/IP.

Thus, each real cell module comprises:

- The device or machine (robotic arm, machine-tool, conveyor belt, others...)
- The controller with input/output signals. It is connected to the device via the 8 input and output pins. It is also connected to the router of the cell through a network cable.
- The computer. It is connected to the router of the cell via a network cable or wireless connection.

Besides, having as many computers as there are elements in the CFF-ETSIA, it is necessary the existence of a master computer (Figure 4) to coordinate them all. This computer, to be on the same network as the rest, must also be connected to the router to communicate with each of the modules.

![Figure 3. Modular configuration and the TCP/IP](image)

3.2. Hybrid System

The term "hybrid" is referred to anything that is the product of elements of different nature DRAE (2001). In this case, the difference of nature generating the "hybridization" considers real elements (based on a physical reality) and virtual elements (based on virtual reality) and produces a combined use of both.

Virtual Reality has been widely used in manufacturing systems simulation, Rubio (2005), Sanz-Lobera (2006) or Kadir et al (2011), but it has not been employed in combination with real elements. In this way, Augmented Reality (AR) also combines real and virtual elements in manufacturing simulations, Nee et al (2012), but in AR
real and virtual elements develop actions of different nature and works with elements whose behavior is clearly
different. In a hybrid FMS, real and virtual elements of the same nature co-exist and work together.

The modularity raised to the control of the CFF-ETSIA allows a configuration in which virtual and real
elements can co-exist within the system. In this case, unlike the previously mentioned AR, a real-machine-tools
and virtual machine-tools will perform the same actions and will need the same control and information flow, no
matter if they are real or virtual. This fact can be very useful in analyzing the behavior of the system when new
elements are incorporated. The use of virtual elements allows knowing the settings of the new element behavior. It
also shows how it affects the rest of the elements, and experimentally determines the changes produced in process
parameters such as production time, or occupation levels of machines, everything before acquiring the real
equipment.

The result of applying this approach to the CFF-ETSIA is outlined in Figure 4. As can be seen, virtual and real
elements are at the same level of hierarchy and behave identically, sending and receiving signals from the master
computer in charge of the distribution of tasks in the system. It could be said that the master computer does not
need to know if a cell element is real or virtual, since from the point of view of the operation, it makes no
difference to it. Of course, the control program of each module will actually "know" whether it is a real or a virtual
element. In the first case it will send and receive signals from the appropriate controller, while the in the second
will execute their own routines inside the program itself and will return control signals to the master computer.

![Figure 4. Configuration of control subsystem proposal](image)
3.3. Extending the model

In the future, actual configuration will require slight modifications in order to take into account the nature of the actions performed by each element. For instance, if a robot perform a movement or a handling action, it needs its own movement controller, so this controller will have to be incorporated into the proposed scheme. Despite of this modification, the controller in each module (HW controller) should not disappear since it is necessary to know the state of each element quickly and efficiently. Present work has only been developed to the level corresponding to the controller (virtual and real) leaving for future developments in the implementation of new elements.

4. Software and virtual elements

The new control scheme requires three different kind of computers, or more exactly, three different kinds of software programs. The first one is necessary for the operation of the master computer and the other two are required for both real and virtual elements. Network configuration requires additional software to make the task of the network server. This software may be hosted in any of the control computers or in one not linked to any element and, besides, connected to the network.

4.1. Master Computer software

This program does not need to send or receive signals from any controller, but receives signals from each of the computers in the cell. It is responsible for directing the operations of the entire sequence of the cell: for example, when it receives the signal that a machine-tool has finished a piece and that the door is open, it sends a signal to the robotic arm to pick up the piece and take it to the next location. The user interface of this program is a drop down menu that yields a list of all the control computers connected to the system. When we select one of them, we can see the virtual representation of the associated element.

4.2. Real element software

This program is responsible for receiving the signals from the host computer and transmits them to the appropriate controller, so that in turn it operates the element to which it is connected. It also receives signals from the element through the controller and sends the corresponding signal to the master computer. The graphical interface of the program, shown in Figure 5, consists of a panel in which appears, in addition to the identification data of the element, the current status of each input and output pin of the corresponding HW controller and a representation of the controlled element and the controller itself.
The representation of the element and controller is not strictly necessary for the operation of the program, since both are real elements and therefore they physically exist in the system. They are included in the interface only for reasons of consistency with other system elements and to facilitate the presentation of results. The state of the input and output signals cannot be modified through interaction with the model, since their values correspond to the actual state of an element and are obtained from the signals sent by the host computer and the controller element.

4.3. Virtual element software

The program, whose interface is depicted in Figure 6, is similar in appearance to the interface of the real element described in the preceding paragraph, but internally its structure and operation differ substantially.

In this case there is no actual element associated, therefore the program receives the signals from the master computer, running a series of internal routines that simulate the operation of the virtual element, and these routines return the signals that are sent again to the master computer. The graphical interface displays the input and output pins of the virtual element and a panel with 3D representation of the item. On the 3D panel, the virtual element should behave as the real element would, receiving and sending the same control signals that the item would. In this case, the 3D panel is interactive, and it is possible to interact with the virtual element in a natural and intuitive way.
4.4. Creating virtual elements

As indicated above, virtual elements are a virtual reality representation based on real elements. In the current work, the communication interface between the control elements and the CFF-ETSIA has been established. This means that the level of detail of the model and the internal configuration of the same are independent of their integration within the FMC as long as they meet the connection requirements established by an I/O signals controller. In general, the creation of virtual elements of 3D models starts with the generation of 3D models with the aid of a 3D modeling software. Models created are assembled and exported to virtual development environments. In the examples shown in this paper, 3DVIA Virtools environment by Dassault Systemes (2013) has been used. Virtools allows programming routines and behavioral virtual elements through an intuitive scripting and flowcharts based on the use of blocks (building blocks) with a format similar to that shown in Figure 7.

Figure 6. Interface software element associated with a virtual

Figure 7. Flowcharts and Virtools Scripting
5. Conclusions

The approach presented in this work has enabled the implementation a new control subsystem in the real FMS called CFF-ETSIA. The control subsystem is based on a flexible and modular concept for incorporating updated communication and simulation technologies. The use of TCP/IP controllers allows the control of every signal of any system element through control programs developed for the master computer.

The work also proposes the concept of hybrid system, in which both real and virtual machines and devices work together under common control. This concept is new and extremely useful for manufacturing systems oriented towards teaching and learning, as it is for the CFF-ETSIA. Creating new virtual models will allow the recreation of more complicated systems available today at a reduced cost. In this way, it is possible the analysis of new configurations and the study of their behavior for different production requirements. This allows the knowing of the advantages and disadvantages of an extension or restructuring of a system without having to purchase any item previously.

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