

An Industrial Communication Networks Laboratory for Distributed Automation Systems*

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Industrial communication networks are a difficult subject to teach due to the wide range of standards found in industry for communicating systems and processes. In this article, a new approach is proposed; the methodology allows the student to deal with all the different steps involved in automation systems when the creation of a whole automation pyramid is pursued. This task is achieved in ten 3-hour lab sessions, following a rotating strategy in certain sessions. The course is developed around an almost real application: a simplified 'cookie factory'. Every session is part of the complete automation system, thus, the student builds the whole system step by step, from the sensor/actuator level to the management level including Ethernet connection, Supervisory Control And Data Acquisition (SCADA), and Human-Machine Interfaces (HMI).

INTRODUCTION

INDUSTRIAL COMMUNICATION networks are common in industry nowadays; their use saves a great amount of installation and commissioning time, reduces cost, eases maintenance, and improves integration among different parts of an enterprise. The current trend tends to integrate business, engineering, manufacturing, and management information systems inside the company; this trend is called Computer Integrated Manufacturing (CIM) [1]. The main aim of CIM consists in establishing a methodology for conceiving automation, production, and management systems able to increase quality levels and optimize plant operation [2].

In order to effectively implement these systems, different areas of work must be considered together. Thus, an extensive knowledge of different automation and industrial systems is required, including plant programming (programmable logic controller, PLC, programming and sensor/actuator networks), and use of different industrial networks and software development (PC programming for SCADA systems, database systems, and HMI devices). In most cases, these topics are studied in separate courses and are usually lacking from the industrial point of view, focusing on aspects that are not relevant for industry. It seems appropriate, therefore, to propose a course to analyse the implementation of integrated industrial systems that include all the

different areas of knowledge necessary for their successful design and operation. Moreover, this course must provide the students with a technical view of every system involved in deploying industrial automation systems, analysing their advantages and drawbacks, and completed with a practical hands-on laboratory to put those concepts into practice.

The course covering these topics is called 'Distributed Industrial Systems, DIS' and is taught in the third (and last) year of a bachelor's degree in 'Telecommunications Engineering specialising in Electronics Systems—ITT.SE' at the University of Valencia. A good knowledge of the use of automation systems and distributed automation strategies is important for a degree in electronic systems and allows the student to gain wider experience in their field. However, automation systems are not only related to electronic systems, but involve many different areas related to engineering. Therefore, it may be considered useful to include this in other engineering curricula, particularly in geographic areas where a great number of manufacturing companies are located and there is a demand for specialists in automation systems for proper design of production plants.

This course may be easily applied to other engineering curricula because many of the discussed topics are self-contained and the only prerequisites are those related to PLC programming, general knowledge of PC programming, and some basics for data networks.

The DIS course consists of 30 hours of classroom lectures and 30 hours of laboratory sessions.

* Accepted February 2005.

Approximately 30 students per year register for the course. Regarding ITT.SE, students do not have a strong background in automation systems; the only previous courses which are related to automation are 'Introduction to PLCs', where they learn how to use and program PLCs, and 'Control Systems', where the fundamentals of control systems are studied. In relation to communication networks, they will have studied 'Telematic Systems', where a good basis in network concepts is obtained. Taking into account these considerations, the focus of DIS is the study of the systems used in industrial automation facilities and the whole design of an industrial plant. In other words, the course is more concerned with the knowledge of commercial systems and devices commonly used in industry, rather than the electronic design or the study of network systems. This is an important point because it gives a very practical approach on how to conceive, set up and maintain industrial networks, optimising the resources and achieving an efficient network operation using standard products.

In order to take full advantage of laboratory time, all the concepts involved in the sessions are previously discussed in detail in classroom lectures. The chapters included in the schedule are the following:

- Chapter 1. Introduction to Distributed Industrial Systems.
- Chapter 2. Communication Networks: Topologies and Data Links.
- Chapter 3. Industrial Communication Networks.
- Chapter 4. Industrial Systems based on Programmable Logic Controllers.
- Chapter 5. Industrial PCs.
- Chapter 6. Supervisory Control and Data Acquisition: HMI Systems.
- Chapter 7. Installation, Commissioning and Maintenance of industrial plants and industrial networks.

This paper describes the laboratory sessions of the DIS module. Since a wide range of techniques, technologies and devices exist, laboratory sessions include different schemes of design using various communication systems and controlling different devices. This allows the student to gain a general view on how industrial plants are designed, programmed and integrated. The following sections describe in detail the arrangement of laboratory sessions and how the learning process is implemented.

Other educational approaches for teaching distributed automation and integrated manufacturing have already been proposed. In [3], a CIM system for manufacturing was proposed using a combination of robots, computer numerical control systems (CNC) and artificial intelligence for optimization of the production line. In this case, the main focus was on robot, PLC, and CNC systems, together with manufacturing optimization procedures; description and

programming of fieldbuses, and PC monitorization using SCADA were disregarded. In [4], an educational laboratory based on fieldbuses for automation systems was demonstrated including SCADA software usage and Ethernet monitorization. Although complete implementation of the automation pyramid using Profibus, Ethernet and Asi was proposed, no real application of the systems was shown, even when using all the modules for a single problem or in individual stages. An interesting application was proposed in [5], where an educational system oriented to Web-based distance learning was described. In this case, two PCs were used to connect the web learners to the industrial system using different PC cards (Profibus, serial, imaging boards), as well as connecting several automation devices to the profibus network (PLC, sensors, actuators), robots to the serial link, and machine vision to the imaging boards. This approach allowed the students to program and control the proposed manufacturing system, but no specific application was proposed in the paper.

OBJECTIVES

Upon completion of this course, the student will have studied the basis of industrial networked systems and related technologies, which allow the design of a networked automation system, from simple automation processes to a whole factory (from shop-floor to management). Furthermore, the student should be able to propose solutions for every kind of control, supervision, and data exchange strategies that a company may require. During the course, the student will become familiar with the basic hardware and software elements and systems used in industrial plants as well as their advantages and drawbacks depending on the intended application (manufacturing, process automation, chemical environments, etc.).

In order to accomplish this objective, it is very important to provide the student with a broad set of laboratory sessions where different elements, normally found in factories, are used. Thus, in each session they install and program an automation subsystem to make it function properly, but always keeping in mind how it fits within the whole factory system. The laboratory sessions cover sensor/actuator networks, PLCs, several network modules for PLC communication, industrial PC, industrial panels, and different network elements.

The associated learning milestones and how they are achieved in the DIS course are given in Table 1.

Since providing a full view of industrial communication systems inside a factory is the main objective of this laboratory, a holistic approach is followed. The aim of all laboratory sessions is to develop a single, complete industrial application. Obviously, this cannot be achieved in a single session, but the outcome of every session is a small part of the full application. Upon completing

Table 1. Learning milestones to be accomplished by the subject

Learning milestone	Proposed task where milestone is achieved	Work to be done
Different industrial networks knowledge	Lab sessions	Several networks commissioning
HMI operation and integration into networks	Lab Sessions	Programming touch panels and SCADA systems
Network configuration and commissioning	Lab sessions and study of theory classes	PLC programming for network operation
Network functions and modes	Lab sessions	Effective communication among network nodes
Data networks and control networks inside a factory	Individual work project	Network type selection based on the application
Industrial networks design	Individual work project	Conception of a complete networked factory
Computer Integrated Manufacturing plant design	All parts of the subject	Conception of a complete networked factory

the course, the student will have worked on all the steps of a real industrial application. This retains the interest of the students in the sessions because they can see how a complex application is being built, allowing them to feel that they can actually design real factory systems from the conception point.

DESCRIPTION OF THE PROPOSED LABORATORY

The aforementioned objectives of the DIS course could be easily achieved if a large amount of time and money were available, i.e., having one seat prepared to perform every different desired function, including all the specific parts and always ready to perform the same application. However, since this type of system is very expensive due to the high price of industrial systems and the wide variety of devices required, this is a feasible option only if there is a large cohort of students so that the usage time is high. The real situation, in most cases, is that resources dedicated to this course are not enough to replicate equipment in all seats. Therefore, resources need to be shared and the laboratory organized in such a way that students can learn all the concepts and use networks appropriately, whilst maintaining a relatively low budget. A rotating strategy is applied in this case.

For this laboratory, the proposal consists of ten 3-hour sessions. If we divide the sessions according to the educational objectives, we have three main blocks:

1. Review of PLC programming and advanced PLC functions. This block requires two sessions where essential information on PLC programming is given. These sessions allow students to acquire the same level of knowledge independently of their origin, since not all will have the same background.
2. Industrial network programming. There are three sessions dedicated to installation and programming of industrial networks. The first

session deals with an ASi network, the second with a multi-master Profibus network, and finally, installation of a master-slave Profibus network. There is one additional session combined with HMI system design, which also makes use of an Industrial Ethernet network.

3. HMI system design. The last four sessions consist of SCADA and operator panel programming. The first session is an introduction to the SCADA software, while subsequent sessions allow the student to program a PC-based SCADA system, a PLC based touch panel, and a SCADA monitoring system of a Profibus network through Ethernet.

Some of the sessions would require more than three hours if all the work were to be done by the student. In these cases, the students are provided with some parts of the work, especially PLC programming, so that they can focus on the core objectives without spending a lot of time on basic PLC programming.

For this laboratory, the available devices are the following:

- Two Siemens PLCs 314IFM [6] with a Profibus card CP342-5 [7].
- One Siemens PLC 314IFM with an ASi card CP343-2 [8], an ASi power supply and an ASi slave with four inputs and four outputs.
- One Siemens PLC 314IFM with a Profibus card CP342-5 and an Ethernet card CP 343-1 IT [9].
- One Siemens PLC 314IFM with a Profibus card CP342-5 and a Micromaster MM420 servodriver with Profibus connection connected to an AC 0.75 kW motor [10].
- One touch panel Siemens TP170A with 5.7' monochrome screen [11].
- Five PCs for PLC, touch panel and SCADA programming.

The software needed to program all the systems is:

- Siemens STEP7 v5.1 [12].
- Siemens ProTool v6.0 [13].
- Siemens WinCC v6.0 SCADA environment (design and runtime modules) [14].

This laboratory has five seats available and a reduced number of students in every session (ten students maximum, two students per seat).

THE APPLICATION

In order to achieve the required goals for the laboratory sessions, a complete industrial project is proposed. The idea is to create a simplified 'cookie factory' in such a way that each session deals with a small part of it. Thus, when the student completes all the sessions, the whole production line has been developed. Let us briefly describe the system.

The whole factory is intended for ubiquitous production control, monitoring, and management through Ethernet, but also controllable within the production plant. We want to control all the processes, from the selection of the cookie recipe to their packaging. This scheme was inspired in a real cookie factory. Some simplifications were introduced in order to prevent the system being over-complex. The simplifications did not alter the main layout of the factory and consisted of reducing factors such as the number of ingredients and the number of inputs/outputs for some sensors and actuators (not compulsory for the process), while altering other small details that would have increased the development time in the laboratory. Briefly, the processes to be carried out are:

1. Mixture of ingredients and kneading. We can control the type of cookie we want to make at any moment (selectable among three varieties of cookie: coconut, whole grain, and chocolate) whose recipe is fixed. There is a tank where, depending on the type of cookie, different percentages of ingredients are introduced for mixing and kneading. There are four main ingredients: flour, water, sugar, and one that depends on the type of cookie. Each ingredient

- is introduced into the tank through an electrovalve, which is opened for a period of time proportional to the quantity of ingredient required according to the recipe's indications.
2. Once the ingredients are mixed appropriately and the mixture is ready, it is poured onto the conveyor belt in small portions of pastry corresponding to one cookie per portion.
3. Marking and shaping. Before the cookies are baked, they are marked with the name brand and a mold is applied so that the desired shape is obtained for every kind of cookie.
4. Baking. The cookies are introduced into an oven where they are baked at a certain temperature. The conveyor belt does not stop during the process. The oven temperature is set according to the recipe but is monitored and an alarm must be activated if the temperature is out of limits (plus or minus 15°C from the set point).
5. Packaging. Once the cookies are ready, they are stacked up and packaged into units of 25 cookies. The packaging system is able to package the cookies 'on the fly' without stopping the conveyor belt. It is able to discard broken cookies and must count all the packaged and broken cookies in order to get a production quality index.

The speed of the conveyor belt is also controlled with a motor that changes speed according to the recipe. The driver controlling the motor also checks the current consumption in order to stop the system if a large peak in consumption is detected (this would mean that a jam has occurred somewhere along the line).

Apart from the production procedure, the system must check for warning signals such as low levels in the ingredient tanks, presence of persons or objects in the marking machine, over/under temperature, packaging system failure, etc. A touch panel is also included in the plant in order

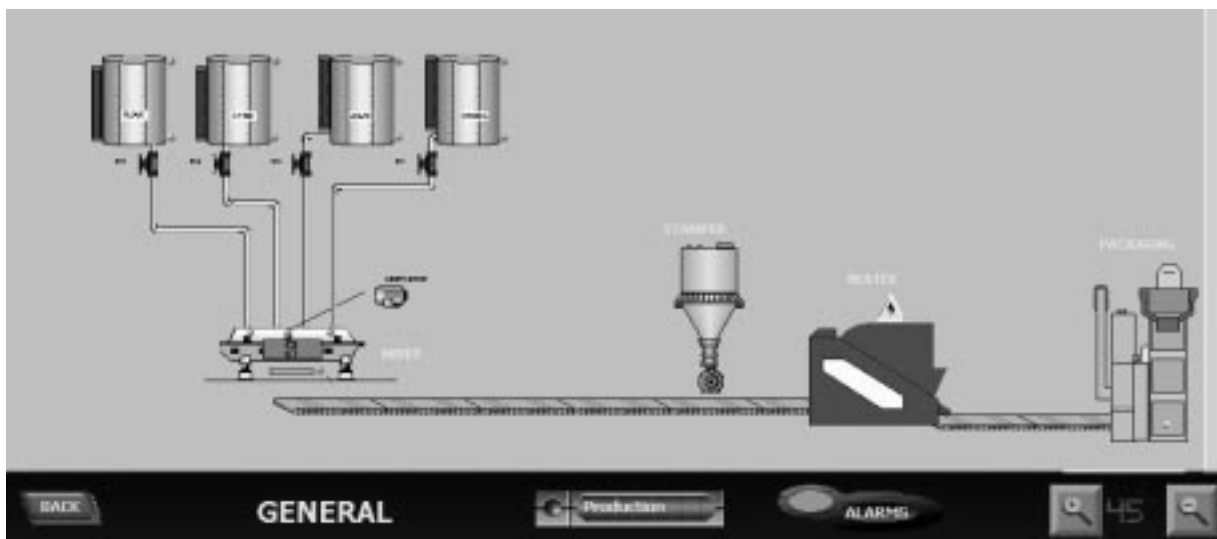


Fig. 1. General view of the production plant.

to be able to control the system from the factory floor. Figure 1 shows the SCADA image of the whole process.

THE DESIGN OF THE PLANT AND PLC PROGRAMMING

According to the processes carried out in the plant, the tasks are distributed among several PLCs connected with a Profibus network for information exchange. The student must program the PLC using STEP7 software and AWL programming. The assignment is the following:

PLC 1. This PLC is responsible for mixing and kneading and is also the Master of the network. The tasks to be performed include programming and reading of local and remote inputs and outputs, timers, and data handling in order to store the settings of the recipe and the rest of variables of the whole process. This PLC contains a Profibus Network card to read/write data from the other elements in the Profibus Network (PLC2, PLC3, motor driver); it also contains an Ethernet network card for remote connection of the SCADA software, and a touch panel for operating the controls in the field. This PLC must control 7 digital local inputs and 10 digital local outputs, and also has to store information in 20 data blocks for all the data that must be transmitted to/received from the other PLCs and the monitorization system (SCADA), both via Ethernet and local panel system (HMI).

PLC 2. Marking and shaping. According to the selected recipe, this PLC controls an ASi network that senses/activates the digital inputs and outputs of the marking and shaping machine. The programming is carried out during one session, where the student learns how to use an ASi network and how to read/write parameters from the ASi. Using direct inputs and outputs, this PLC also controls the temperature of the oven; PLC2 also includes a Profibus card to communicate with the rest of the plant, linking the ASi network with the Profibus Network in order to control the ASi remotely. This PLC must control 2 digital local inputs, 1 analog local input, 2 digital local outputs, 3 digital ASi inputs and 4 digital ASi outputs, and includes 7 data blocks which incorporate the Profibus servodriver motor control.

PLC 3. This PLC controls the packaging line and quality control. The programming of the system is complex due to the large amount of inputs (seven) and outputs (four digital and two analog), but does not involve too many communications (only some exchange of information with the Master PLC through the Profibus network).

The speed of the conveyor belt is controlled by a servodriver directly connected to the Profibus network as a slave controlled by the PLC 2. Figure 2 shows the design of the distributed control structure.

Since many different tasks are involved in the design of the system, the proposed schedule for the

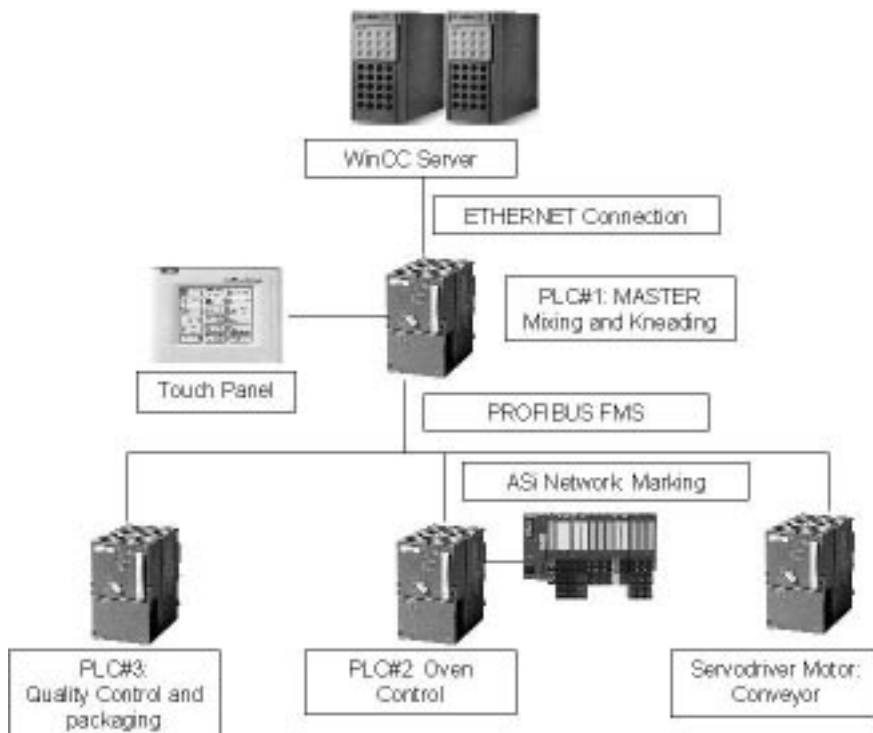


Fig. 2. Network structure of the proposed factory.

laboratory sessions is as follows (10 sessions of three hours duration each):

- Session 1. Introduction and review. The cookie production plant is introduced but no programming is included. Small exercises are proposed in order to refresh PLC programming concepts and software environment (Siemens STEP7)
- Session 2. PLC 1 is programmed and configured in readiness for network communications.
- Session 3. PLC 2 is programmed, the ASi network is introduced.
- Session 4. PLC 3 is programmed; advanced PLC programming concepts are involved.
- Session 5. Profibus Communication among PLCs is introduced (multimaster). The student communicates all three PLCs using basic communication functions for an FDL link.
- Session 6. Profibus communications in Master-Slave mode is introduced. PLC 1 communicates with the servodriver.
- Session 7. Operator panel programming. The ProTool software is introduced and the TP170A touch panel is programmed to show information about the plant.
- Session 8. SCADA programming I. The WinCC software is introduced and the student learns the basics of WinCC: variable declaration (local and remote), picture handling, drawing, etc.
- Session 9. SCADA programming II. The student learns how to use animations, user-access control, graphical charts of production information, etc.
- Session 10. Ethernet communication. The student learns how to work with an Ethernet card for PLC, basic programming of this card (configuration, sending, and receiving data) and SCADA communication through Ethernet for information display between a remote PC and the production plant.

Sessions 1 to 6 are intended to show all the aspects regarding the hardware installation and programming of an industrial system. Sessions 1, 2 and 4 are purely oriented to PLC programming. However, due to the relationship with further network communication, indications about location of data are given beforehand in the student session guides. Session 3 introduces the student to industrial networks; an ASi network is used due to its simplicity, thus being a good starting point. Sessions 5 and 6 deal with Profibus DP, showing its different working modes. As Profibus DP is largely used, it is important to focus on all the aspects involved in the proper usage of this network. Students must install the network (cabling and connecting it), configure the system, and communicate several PLCs and a slave device (servodriver) using the specific functions oriented to Profibus communication included in the STEP7 software. Sessions 7, 8, and 9 are oriented to HMI programming (this point will be dealt with in the next section). Finally, session 10 is dedicated to Ethernet communication, showing the students

how to remotely access the production plant from the SCADA software.

According to the learning objectives, Sessions 1 and 2 belong to the first objective, Sessions 3 to 6 to the second, and 7 to 10 to the third. This distribution allows a rotary approach in certain sessions. Sessions 1 and 2 are performed at the same time by all the groups because no special material is needed, only one PLC per seat. Sessions 3 to 6 are rotational because every session makes use of special devices and there is no overlap of teaching content. Thus, every group performs a different application, except in some cases where the material is replicated (as in Session 3). Session 7 is not rotational; once all the groups have finished the previous rotary scheme, they enter the HMI programming section, which provides a general introduction to Sessions 8 to 10. These sessions are also rotational.

HUMAN MACHINE INTERFACES (HMI)

Apart from programming, installation, and commissioning of the PLC and networks involved in the system, one important aim of these laboratory sessions is the learning of industrial HMI, its usage and programming. Two HMI devices are used, an operator panel (touch panel) and a SCADA system running on a PC. Each interface has its own development software.

The student starts with the easiest software (Siemens ProTool v6.0), learning how to program operator panel interfaces in a similar way to the SCADA programming for PC. In this case, a TP170A touch panel with Windows CE 3.0 operating system is used. The panel is easily programmed from a PC via an RS232 port and is connected to the PLC via the MPI port, making it possible to test and reprogram the panel in the standalone mode.

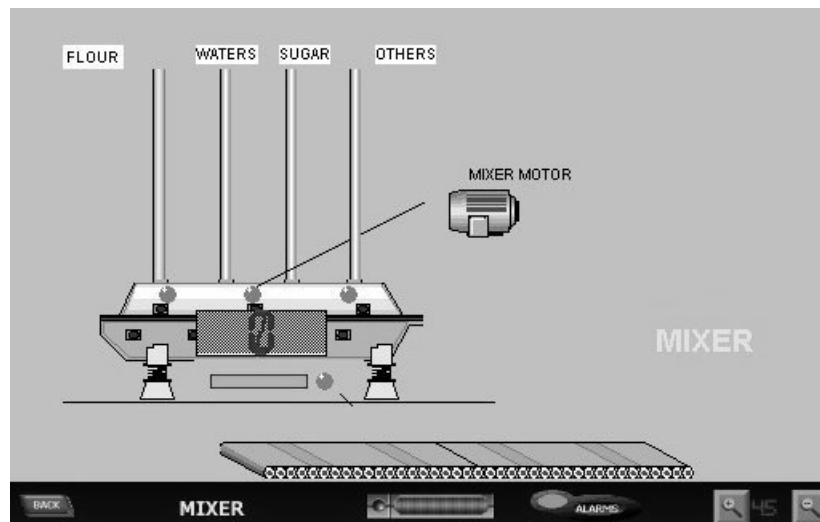
Siemens ProTool serves as an introduction to the Siemens WinCC SCADA software. Both software packages have many common points and, in many cases, the programming procedure is the same. Thus, the student can learn the basics of WinCC faster and can readily start to develop the proposed application.

With regard to HMI learning objectives, the student must achieve the following goals:

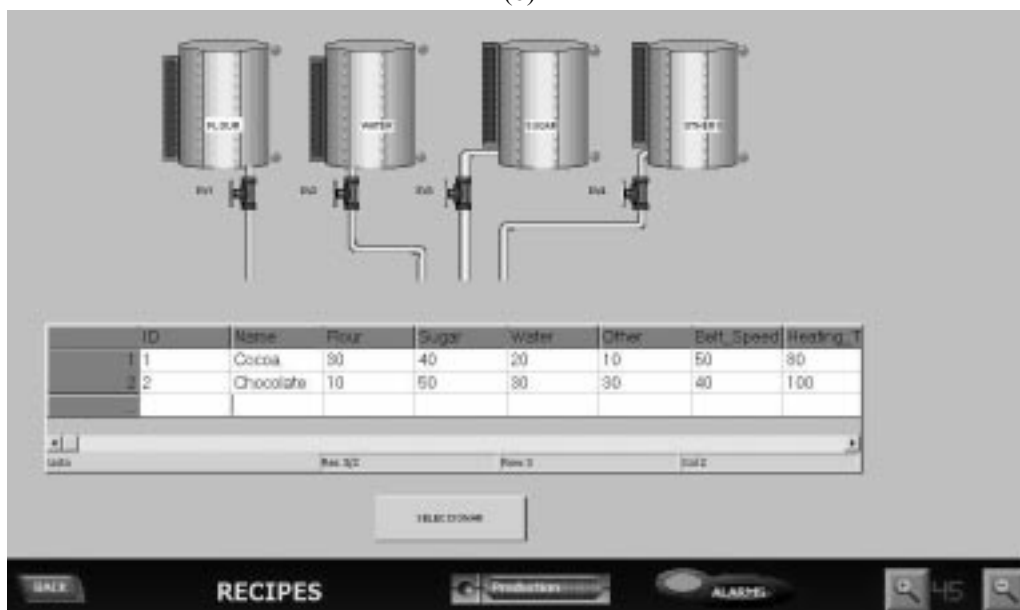
- Communicate with a PLC, obtaining data from it. This PLC collects data from the other PLCs in the Profibus network so that different information from the entire network is obtained.
- Associate graphical objects and actions to data changes in any monitored value from PLCs.
- Create and design a coherent and friendly user interface, including a common menu bar, buttons, navigation options, etc.
- Create animations able to show what is happening in the production plant according to the real operation.



(a)



(b)



(c)

Fig. 3. SCADA snapshots: Main screen, recipes, and mixer.

- Create user access levels and user logging options, so that different actions are permitted depending on the user.
- Create an alarm view and alarm events to show any possible problem that may occur in the monitored system.

The aforementioned points allow the student to become familiar with the design of HMI systems and to be able to design and program these systems which are widely used in industry. In order to achieve the goal of learning HMI systems, the design of the following screens is proposed:

- A main menu screen where all the options and actions are accessible (Fig. 3a).
- A general view screen where the main actions in every process are displayed (Fig. 3b).
- A particular view for every individual process: five screens regarding the mixing and kneading, baking, marking, packaging, and recipe selection (Fig. 3c).

RESULTS

The DIS course and its corresponding laboratory have been running for two years. The time schedule has been slightly modified depending on the year in order to adapt to the students' previous knowledge, but in general, the proposed laboratory sessions are well suited to the whole laboratory time.

After completion of the course, the students are proficient in the field of industrial buses and are able to design a complete manufacturing system using Profibus and ASi industrial buses, PLCs, HMIs, and Ethernet. A brief questionnaire has been distributed among the students in order to assess their degree of satisfaction with the course. Results show that students are quite satisfied with the laboratory because they are able to build up a whole system from its conception. This approach helps the student to learn not only how to design automation systems, but also the small details which need to be taken into account for the real installation of an industrial plant (cable connections, connectors, power distribution, bus addressing, network configuration, software programming, communications software, etc.). On the other hand, students find an additional

difficulty in the usage of different software and devices, not having enough time to get used to it, which means that additional time is needed for learning of devices, and then, use them in the specific problem.

For easy access to information about the DIS subject, a web page is offered to the students (<http://gpds.uv.es/sid>); they can download the documents prior to attendance at the laboratory, and read papers and application notes about implementation of automation systems or manuals referring to the devices used in the course of the sessions. In some cases, the documentation guides the students through the configuration process to ease the procedure.

Using this approach, a significant financial saving is obtained, given the high price of automation components. If a full laboratory were equipped with 5 seats, including all the components, the price of the laboratory equipment would be around \$40,000. However, at a cost of \$12,000, we have been able to do the same practical sessions, saving 70% of the initial cost.

CONCLUSIONS

In summary, we can state that the proposed laboratory provides an interesting pedagogical approach to industrial automation, especially in the field of distributed automation systems. The laboratory sessions are oriented in an incremental way, so that all the sessions contribute to the same application by configuring and programming a different part of the final system during a single session. When the students complete the laboratory sessions, they are familiar with all the topics involved in a plant automation process.

In order for laboratory sessions to be successful, it is essential to provide strong theoretical support in parallel classroom lectures by introducing the different concepts involved (software, hardware, different bus networks, multiple connections, standards, etc.).

This procedure leads to an efficient learning process when limited time and equipment exist, allowing the coverage of a wide range of applications in a reduced time (30 hours for all the laboratory sessions) and with a reduced amount of equipment.

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