

# Complementary usage of real and virtual manufacturing systems for safe PLC training

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**Abstract:** Physical models mimicking industrial plants and relevant control issues are usually considered the most interesting targets for effective PLC (Programmable Logic Controller) training. However, they introduce safety problems. Filtering bad commands from the PLC is double interesting in this scenario: it guarantees safety and guides trainees by supplying explanations when a command is filtered. However, devising the appropriate filters can be hard for complex systems. Simulation is the single safe solution in advanced PLC training. While synthetic systems are traditionally viewed as a second-class solution in PLC training, modern computer game technologies are enabling realistic and interactive virtual environments, from where a “de facto” effective and exciting training environment comes very naturally. And filters can be relaxed in virtual environments as they only intend to help trainees in finding out their mistakes whenever a (virtual) accident happens. The paper details the design and usage of filters in PLC training. The aim is to demonstrate the benefits of the complementary usage of real and virtual target systems in PLC training, which were assessed and validated with different skilled students.

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## 1. INTRODUCTION

The purpose of hands-on courses in Automation is the transfer of knowledge (i.e. theories) and know-how (i.e. applications of knowledge) to students. The know-how must be adapted to industrial world requirements (Marange *et al.*, 2006, 2007, 2008a, 2008b) (Bellmunt *et al.*, 2006). Thus, it is important for the student to face “real” systems involving “real” problems. This is why physical models mimicking relevant manufacturing plants (composed of many and different sensors and actuators) and their associated control problems are usually considered the most interesting targets for effective PLC (Programmable Logic Controller) training. However, the use of these devices raises several problems; namely safety. Indeed, an error in the design of the control-command program can cause injuries to trainees and damages to equipments. Synthetic systems are naturally safe but are also usually viewed as a second-class solution in PLC training. Yet, modern computer game technologies are enabling realistic and interactive virtual environments, from where a “de facto” effective and exciting training environment comes very naturally.

The paper demonstrates the benefits of the complementary usage of real and virtual target systems in PLC training. Central to the paper is the design and usage of filters controlling bad commands from the PLC. This approach presents two advantages: it guarantees safety when real systems are used and guides trainees by supplying

explanations every time a command is filtered. Filters’ formal design can be relaxed in virtual environments as they only intend to help trainees in finding out their mistakes whenever a (virtual) accident happens.

The first part of the paper deals with PLC training from theory to practice. The pros and cons of real and simulated target systems are briefly surveyed. The second part of the paper details the use of real systems. We propose an approach based on the design of a filter, composed of logical constraints, placed on the PLC, and formally checked to guarantee the safety and to supply explanations. However this approach forbids the trainee to see the consequences of the errors and can be difficult to implement for large and complex systems. Simulation is the simplest safe solution in advanced PLC training. This is why the third part of the paper shows the benefits of virtual systems like ITS PLC Professional Edition. This software is based on video game technologies and offers five realistic and interactive virtual scenarios. In this case, the filter is only used to supply explanations when a safety constraint is violated. This approach has been tested and validated with students. It offers new possibilities for remote labs and shows the complementary usage of real and virtual manufacturing systems for PLC training.

## 2. PLC TRAINING: FROM THEORY TO PRACTICE

Automatic control courses, as all technical courses in the broad sense, require the transfer of knowledge and know-how

to students. In the case of Discrete Event System (DES) education, the knowledge is characterized by the study, at different levels, of the state automata, combinatory, and sequential logics, statecharts, Petri nets, GRAPhe Fonctionnel de Commande Etapes Transitions (GRAF CET, IEC 60848), and SFC. The level of knowledge depends on the educational grade, varying from discovery to specialization. Know-how concerns, for instance, the installation and the programming of PLC by means of a software compliant to a standard, e.g., IEC 61131-3. The acquisition of this technical knowhow requires a practical work in specialized and expensive labs, including PLC and simplified manufacturing systems, which are a replica on a reduced scale of a real system found in the industry. These facilities are expensive, must be maintained by specialized personnel, and are not generally in free access for safety reasons.

An alternative is to use some plant simulation models. Yet, most fail to mimic well enough the most important scenarios and control problems of real plants. Anyway, real and simulated plants (Riera *et al.*, 1999, 2009) allow students to test their own control solutions, which are supported by PLCs and software patterns similar those they are expected to develop over their professional lifetime (cf. figure 1).

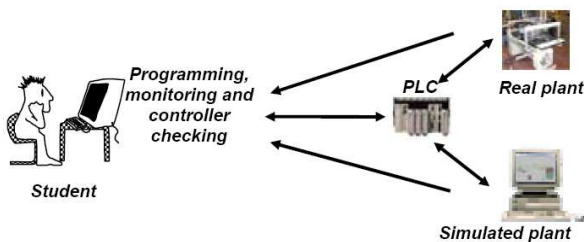


Fig. 1. Use of real or simulated plants for PLC training

### 3. REAL TARGET SYSTEMS

PLC training on reduced scale real plants designed with industrial components it is obviously that very interesting. Most of these physical models are reproductions of manufacturing plants and mimic relevant control problems. Additional safety devices are added to avoid the accidents. Hence, students can use them as they would in their professional activity. On the other hand, small scale plants are very expensive and require maintenance by qualified people. They are also exposed to hard trial by learners who make errors during the design and the programming stages of the control solutions. That causes failures that make plants unavailable for a certain time. The practical training with real plants requires a lot of experiences, competences and time from trainers. When PLC and real plant are used, controller program must be validated at least from the point of view of safety before being implemented in the PLC. Designing tools for checking PLC program quality becomes thus a must. The paper presents an original approach to guarantee the safety by the mean of a filter placed in the PLC.

#### 3.1 Principle of control validation by filter

Figure 2 shows the principle of the filter and its design stage. It is placed into the PLC and it only authorizes validated outputs. The filter is composed of a set of Boolean equations, called safety constraints, which have to be true all the time, in order to avoid the plant to reach forbidden states. It is important to note that these constraints are valid whatever the specifications. That means that safety constraints have to be defined only once. The filter is necessarily designed by an expert. As seen, its main objective is to protect the target system from control errors performed by control designers.

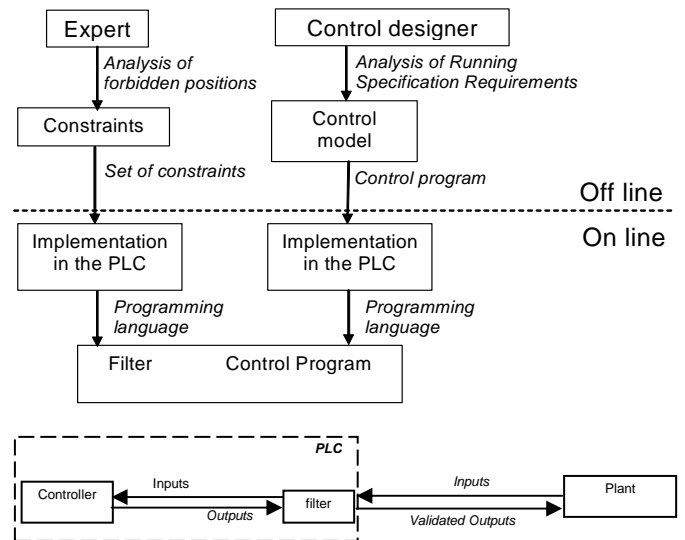


Fig. 2. Control Filter principle

Safety constraints definition is based on a functional, structural and dysfunctional analysis. The structural analysis defines independent subsets of actuators called *EIPE* and Manufactured Parts called *MaP* which interact all together. The functional/dysfunctional analysis defines the dangerous (i.e. forbidden) situations for the plant, according to the instrumentation (sensors) that have to be strictly avoided through the filter. In the proposed approach, only the interactions between *EIPE* and *MaP* are studied. That avoids combinatory explosion and is adapted to large systems.

Figure 3 presents a sub system which is a part of the packaging equipment called PRODUCTIS used at Reims University, to illustrate the concept. Two pneumatic cylinders controlled by 5/2 air valves (AV, RE, DE, MO) share the same zone. The sensors are *a*, *b* for the horizontal cylinder and *h*, *d* for the vertical cylinder. Therefore, 2 *EIPE* interact all together. There is a risk of collision between the 2 cylinders. Figure 3 indicates the corresponding allowed and forbidden positions. One can note that forbidden positions are not allowed whatever the control specifications may be. Knowing forbidden system states, it is not obvious to define safety constraints through the “sensor-actuators” states, and that for 2 reasons. Firstly, constraints have to avoid a forbidden position and not to measure it. Secondly, manufacturing system observability through binary sensors is low. Hence, it can be necessary to design system estimators. The best solution in this case is to use behavioural plant models. However, they are difficult to get. Our approach to

solve this problem is different, pragmatic and formal. We propose to the expert a framework based on a classification of various types of safety constraints. The human expert is still responsible for the constraints definition based on this framework. However, to guarantee the system safety, the sufficiency of the proposed set of constraints will be formally checked.

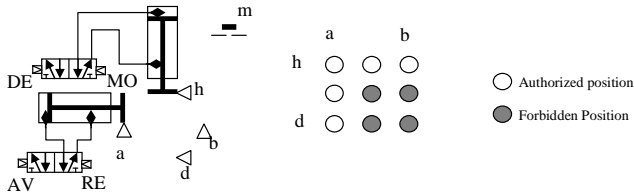


Fig. 3. Two cylinders sharing a common zone

### 3.2 Filter Robustness Verification

We have noticed previously how it is important to check constraints designed by expert in order to insure the manufacturing system safety. The challenge is to answer to the following question: are we sure that constraints are sufficient to avoid dangerous (forbidden) positions of EIPE and MaP? The methodology to check the constraints sufficiency is presented in figure 4. Constraints and formal properties are obtained from the set of forbidden positions for a new interaction. In order to check the set of constraints, the principle consists of modelling the behaviour of EIPE involved in the interaction, the PLC running, the maximum permissive controller and the filter. If properties are checked, that means that forbidden positions cannot be reached whatever the control.

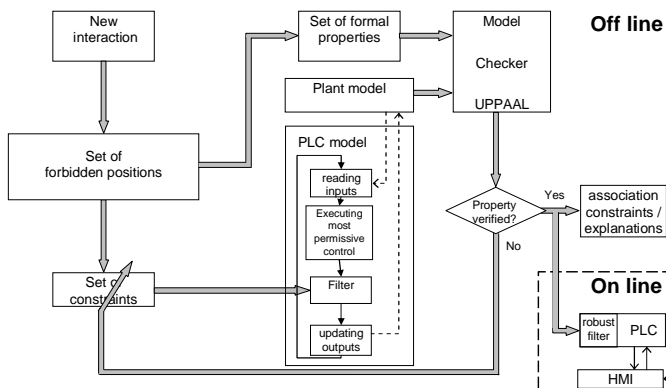


Fig. 4. Method to check the constraints

We use UPPAAL (Behrmann *et al.*, 2002) as model-checker. UPPAAL is a free integrated tool environment for modelling, validation and verification of real-time systems modelled as networks of timed automata, extended with data types (bounded integers, arrays, etc.). The originality of the method is to check, with the constraints and whatever the control, that the plant will never be in a forbidden state. We do not check a particular control linked to specific specification. In other words, through the model-checker, we verify that there isn't at least one path (or trace) dealing to forbidden positions. If it

is not the case, that means the set of constraints is not sufficient and the set has to be modified by changing or adding new constraints.

In the example of the 2 cylinders, let us consider the 3 following safety constraints represented by simple logical equations:

$$AV \wedge DE = 0 \quad \uparrow AV \wedge /h = 0 \quad \uparrow DE \wedge /a = 0 \quad (1)$$

«  $\uparrow x$  » is a rising edge of the logical signal  $x$ , «  $\downarrow x$  » is a falling edge of the logical signal  $x$ , «  $/$  » is the logical operator “not”, «  $\wedge$  » is the AND logical operator and «  $\vee$  » is the OR logical operator.

In this example, the 3 equations (1), (2), (3) are not sufficient to avoid a collision between the 2 cylinders whatever the control. Indeed, for instance the GRAFCET (Diez *et al.*, 2006) specification proposed figure 5 will involve a collision and however the 3 proposed constraints are all the time respected.

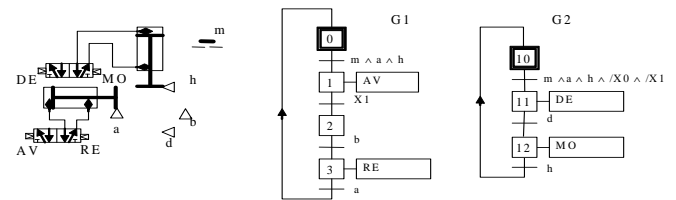


Fig. 5. Example of unsafe control

Indeed, when the step 2 becomes active, the horizontal cylinder is moving but the logic level of the sensor  $a$  is still true. So, step 11 becomes active and the vertical cylinder is moving. Consequently, there will be a collision although the 3 constraints are respected.

Using this approach, it is possible to show that the 3 constraints initially proposed for the 2 cylinders example are not sufficient to guarantee safety whatever the control. It is necessary to add constraints like the 2 following:

$$\downarrow AV \wedge a = 0 \quad \downarrow DE \wedge h = 0 \quad (2)$$

In this case, with the 3 previous constraints, it is formally checked that they are sufficient to guarantee the safety whatever the control. One can note that there are other solutions. For instance, the 2 following constraints can be used instead constraints (2):

$$\downarrow AV \wedge /b = 0 \quad \downarrow DE \wedge /d = 0 \quad (3)$$

After be checked, the set of constraints can be easily programmed into the PLC. In addition, each constraint is a very interesting source of explanation. Firstly, the Boolean equation explains why the constraint becomes violated. Secondly, it is also possible to find a path showing how a constraint can be not respected. For that, one has to build a subset containing all the constraints minus the constraint that you want to explain. Of course, the formal property will not be checked and the diagnosis trace, by giving a valuable path to reach a forbidden position, is a possible explanation. The formal verification by model-checker is based on the

definition of several properties and the use of different models representing the system which are not presented in this paper. Reader can find further information in (Marangé *et al.*, 2008c). We have implemented and tested this solution with success on different real systems. In the case of the PRODUCTIS system (64 Inputs, 46 Outputs), 89 constraints have been defined to formally guarantee the safety. With this approach, the PRODUCTIS has been used successfully by learners with different level of knowledge and know-how, from novices to experts (Marange *et al.*, 2007). It is important to note that this safety approach has also interesting applications in maintenance.

As seen, the filter avoids bad consequences on the real system. However, it is well known that students learn a lot from the errors they can do. In addition, the proposed approach applied to large or complex systems can involve a lot of constraints which could be not compatible with the capacity of the PLC. The use of simulation and virtual systems make it possible to solve some of the mentioned problems but cannot replace completely a real plant.

#### 4. VIRTUAL TARGET SYSTEMS

The main differences between a virtual and a traditionally simulated target system are (Riera *et al.*, 1999): a realistic rendering of the layout, the functions and the behaviour of the system with a respect the real time dynamics.

Researchers from FEUP (Portugal) and Reims University (France) have been designed and used simulated systems for more than 10 years. The utility and usability of prototypes have been shown through questionnaires directed to students and teachers. Advantages and inconveniences of simulated systems are summed up hereafter (Riera *et al.*, 2009).

- Some of the systems were simple prototypes and not commercial grade solutions making them hard to use. They were too naive when compared to real industrial systems. The interface between the software and the external controller (PLC) was established through OPC using a SCADA as a gateway. This type of interface had a slow response time which proved to be inefficient.

- Solutions based on a specific interfacing hardware driving industrial standard logic signals (0, 24VDC), like those proposed by A. Magalhães, FEUP, allows for the usage of any PLC. In addition, students are required to wire the PLC to real I/O. This is very educational and establishes a physical border between the controlling and the controlled system.

- Simulation of sensors and actuators failures proposed by B. Riera, Reims University, increases the possibilities of applications and enables powerful scenarios to test the controller.

- 3D and sound rendering in simulations designed by B. Riera 10 years ago are still very appreciated by students and offer a better perception of the structure and functions of the system. However, the rendering is today very far from the possibilities offered by CAD/CAM and PLM softwares.

Research activities in order to design 3D virtual systems have been conducted since 2005 (Vigario *et al.*, 2006) (Magalhães *et al.*, 2005) in order to design 3D virtual systems. These works are at the origin of the software ITS PLC Professional Edition and the Portuguese company Real Games. A scientific and technical partnership between Real Games, FEUP and Reims University exists today.

#### 4.1 ITS PLC Professional Edition

ITS PLC is a simulation software package aimed at control systems education and training. It uses the latest computing technologies from the video game industry, which include real-time 3D graphics, physics and sound. This simulation software offers five virtual plants that are based on common real industrial plants, thus offering convincing virtual training scenarios and real world control challenges. The goal is to make the five virtual systems work correctly by using an external PLC running the control software developed by the trainee. Therefore, each virtual system includes virtual sensors and actuators so that its actual state can be sensed and controlled by the PLC. The interface between these systems and the PLC is supported by an USB DAQ board with 32 isolated I/O channels that allows it to be wired to any type of PLC of any brand. The Plug and Play USB DAQ board is a very flexible solution as it makes possible to use this software with workstations, laptops and even notebooks. ITS PLC is powered by three modern and key technologies: a graphics engine (integrating a sound engine), a physics engine and an instrumentation engine (Vigário *et al.*, 2006). The graphics engine processes real-time 3D graphics and sound. The physics engine computes Newtonian physics models. The instrumentation engine simulates virtual sensors and actuators and manages the data exchange between these and the DAQ board.

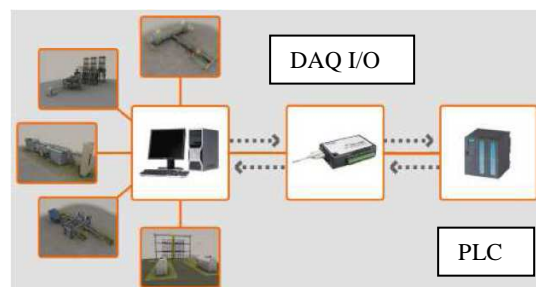


Fig. 6. ITS PLC working principle

ITS PLC uses a proprietary graphics engine. Its most notable features are batched rendering, material system, scene graph culling, GUI system and custom content pipeline processors for models, GUI skins and collision shapes. The physics simulation is done by the third-party Newton Game Dynamics physics engine. It is a robust and stable physics engine that proved to efficiently simulate complex industrial machinery. The instrumentation engine is an original concept and is composed of a sensing layer and a communication layer. The sensing layer offers several generic behavioural models of sensors and actuators. The communication layer manages the data-exchange between the virtual sensors and

actuators and the DAQ board. The five virtual systems included in ITS PLC can be partially or fully controlled, thus offering multilevel control challenges that can range from the very simple to the extremely complex. The five plants consist of sorting, batching, palletizer, pick & place and automatic warehouse applications and are organized by their expected difficulty level. The goal of the sorting system is to transport cases from an entry bay to two exit elevators, sorting them by height. The batching system simulates a process of paint mixing. The objective is to mix three primary colors (red, green and blue) in order to obtain a desired color. The goal of the third system is to palletize cases up to three layers using a high-level palletizer. The challenge in the pick & place system is to place parts inside boxes using a three axes incremental manipulator. In the last system the objective is to transport, store and retrieve boxes from a rack.

All these plants can be controlled manually (by the user) or automatically. When controlling the system in manual mode the user can try the controllable parts of the system, allowing for a complete understanding of system goals and parts operations. When in automatic mode, the external PLC is the system controller. A major feature of ITS PLC is its run-time “interactivity”. Interactivity allows users to cause malfunctions and jams in the virtual plants. This is done, on one hand, by introducing open or short circuit failures on virtual sensors and actuators and, on the other hand, by adding, removing or jamming objects during the simulation. Figure 7 shows an example of interactivity; a carton box is “stolen” from a pallet while transported by a conveyor. More than increasing the realism of the simulation, “interactivity” is the key feature of ITS PLC making virtual plants to mimic (unreliable) real plants. This allows for new and valuable challenges in PLC training and education and makes ITS PLC an effective and attractive training software package.



Fig. 7. Interactivity example

#### 4.2 Application to an automated warehouse

This system simulates an automatic warehouse (cf. figure 8), where the objective is to transport, store and retrieve boxes from a ten columns, five rows rack. The automatic warehouse also includes a transelevator, an entry bay and an exit bay. Two automatic monorails bringing boxes in and out interface the warehouse to an imaginary world. As in real systems, the boxes are handled by telescopic forks. The fifty cells of the rack are encoded as a six bits word, facilitating the positioning commands of the transelevator.

For this system, functional, structural and dysfunctional analyses lead to five possible failures involving forbidden positions (called DP) of actuators or boxes.

The five DP are the following. DP1: movement of the transelevator when the forks are not in a correct position. DP2: transfer of a box from the automatic entry monorail to the transelevator where a box is already located. DP3: transfer of a box from the transelevator to the automatic monorail where a box is already located. DP4: movement of the forks when transelevator is moving. DP5: transfer of a box in a cell where a box is already located. In order to design and formally check the constraints, the system has been considerably simplified only one axis of movement for the transelevator and only one cell with one entry bay and one exit bay were considered.

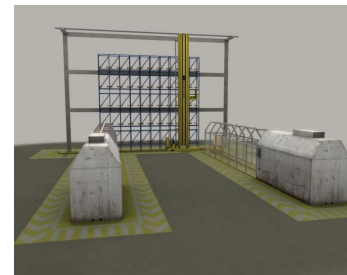


Fig. 8. Virtual automatic warehouse

With this simplified system, the set of constraints must avoid the following situations:

- forbidden positions for the transelevator and the forks,
- the possibility to have several boxes in a cell,
- the possibility to have several boxes on the transelevator.

Sixteen constraints have been defined and formally checked. One of the main interests of this approach is the explanatory power of the constraints. In addition, as previously noticed, the model checker can be used to find a path in the control involving a bad position of the actuators or the boxes. 75 constraints for the whole system have been implemented in PL7-PRO in a TSX Premium (Schneider PLC). This system has been successfully tested by master students during practical trainings in 2008. Even if a safety constraint is disregarded, the output is sent to the virtual system. Students can see the consequences of a bad control on the simulated manufacturing system. Today, at Reims Champagne-Ardenne University, there is one PLC available for self training. This system can also be integrated in a remote lab (Lunt *et al.*, 2000) (Colace *et al.*, 2004), allowing students training without being present where the PLC is located.

## 5. CONCLUSIONS

The paper has discussed the usage of real and virtual target systems in safe PLC training. It departed from the notion that physical devices combining industrial machine parts, sensors and actuators are usually considered the most interesting targets for effective PLC programming training, but these

introduce safety problems; on the other hand, synthetic systems are inherently safe but fail to mimic well enough the most important scenarios and control problems of real plants. Thus, physical and virtual target systems seem to be distinct and distant solutions in PLC training, neither of which completely satisfactory. A filtering device prohibiting a PLC from sending unsafe commands to the controlled system is an interesting way of guarantying equipment and trainee's safety when PLC programming education is conducted on physical targets. These filters, based on logical constraints and formally verified with a model checker, were discussed in this paper. Some conclusions came up: apart from guarantee safety, filters are interesting as they may guide trainees by supplying explanations every time an output signal is filtered; yet, devising the appropriate filters for complex systems can be hard. As such, conducting effective and safe PLC programming education on real machine parts, sensors and actuators is indeed possible in small plants. However, safe training on medium or large plants requires a different solution: simulation. Synthetic systems are traditionally viewed as a second-class solution in PLC programming training. Yet, modern video game technologies are enabling realistic and interactive virtual environments from where a "de facto" effective and exciting training environment comes naturally. The ITS PLC Professional Edition software package is a good – probably the best – available solution in this subject. It was surveyed in the paper concluding of its high quality: on one hand, realistic graphics, physics and sound, immersing users in a convincing 3D world; on the other, fully interactive emulation of attractive and very common plants coping everyday problems and challenges found in most industrial environments, including machinery, sensors and actuators failures. Filters may complement the benefits of virtual plant by helping trainees to find out their mistakes every time a (virtual) accident happens. However, since in virtual systems filters are no longer safety driven (and thus no longer require a complete fault coverage or formal development and test), they just can be tailored to serve different helping level to different skilled trainees. The last part of the paper concerned the application and validation of both (real and virtual) educational approaches in different training programs. The main conclusion is that PLC training on physical and virtual targets is now becoming complementary solutions, both safe and increasingly satisfactory.

#### ACKNOWLEDGEMENT

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