# HOME I/O and FACTORY I/O: a virtual house and a virtual plant for control education

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***Abstract:*** This paper deals with the presentation and the use of 2 dynamic 3D simulators, which can be considered as serious games, for control education. The first software, named HOME I/O, is the result of a R&D project partially founded by the French Ministry of National Education in order to design a virtual house adapted to control and STEM (Science, Technology, Engineering and Mathematics) education, and usable from middle schools to Universities. This 3-year R&D project (2011-2014) is a fruitful collaboration between CReSTIC lab from the University of Reims Champagne-Ardenne (URCA) and Real Games, a Portuguese company. The main idea has been to bring a virtual house into the classroom, adapted to learners and teachers and suitable for control and STEM interdisciplinary education. In this paper, 2 examples of teaching application used at URCA to initiate students about feed-back control and sequential logic are proposed. The second software is FACTORY I/O developed by Real Games. It enables to build a virtual plant and to bring it into the classroom. An application of virtual commissioning of a real laboratory ball transportation process used at Chalmers University (Sweden) is presented. An equivalent system has been designed with FACTORY I/O. Hence, it becomes possible for students to test their controller without any risk before applying it on the real system, with a methodology matching Industry 4.0 framework.

***Keywords****:* control education, virtual systems, PLC, serious games.

## 1. INTRODUCTION

With rapid technological change in industry around the world, it is likely that specific skills demanded in the future will differ from those required in the past. Learning (and teaching) industrial control and automation is a hard task for many reasons (William 2005). For instance, and just to mention a few, it deals with complex problems requiring a multidisciplinary knowledge, spanning from mathematics and physics to computer science and logic programming while including sensors, actuators and electrical and mechanical drives engineering. Bridging theory and practice, a major requirement in industrial control and automation training, means that learners have to master a considerable number of functional features and operating procedures of the supporting equipment, most of which differ a lot from a manufacturer to another. Virtual systems can be a great tool to perform this task (Magalhães et al. 2011). Virtual systems are graphical computer simulations of dynamic systems, which are driven by peripheral controlling devices which can be simulated or real. The major expected benefit is to allow users to watch and assess the impact of the developed applications as they would in a similar real system, but at reduced costs and without any risk of injury to users or damage to machines. The use of technology and video games technologies (rendered graphics and sound, interactivity, attractiveness) is seen as a way to promote "situation awareness," student motivation and thus foster their learning. Hence, video games can be a great tool, really adapted to control and STEM education (Mayo, 2009) (Arango et al., 2008) (Riera et al., 2009). The use of video games technologies can transform the simulation into an immersive and entertaining experience where the teacher remains in control of the lesson plan (i.e. the game design).

In our case, serious games are considered primarily as a digital tool that the teacher will be able to use as part of his/her own teaching scenarios, thus promoting multiple uses. However, the gameplay must approach the standards of video games. This approach of serious game is quite original because it does not withdraw the teacher from the education loop. He or she is the game master.

Design digital tools promoting investigative approach and allowing the teacher to imagine and implement multiple problem situations has been the vision that led to the development of HOME I/O and FACTORY I/O by Real Games with a collaboration of the CReSTIC laboratory of Reims University since 2008.

The paper is organized as follows. The first section deals with a presentation of HOME I/O. The second section presents 2 pedagogical applications of HOME I/O performed at Reims University. The first one concerns feed-back control and the second an initiation to combinatorial and sequential systems. The third part of the paper deals with FACTORY I/O. The last part of the paper deals with an example of use case of FACTORY I/O. A real sorting balls laboratory used at Chalmers University (Sweden) has been modelled with

FACTORY I/O, enabling students to test their controller with an equivalent simulated system. This approach of “pedagogical virtual commissioning” seems very powerful and opens a large range of teaching applications adapted to the Industry 4.0 requirements.

## 2. HOME I/O: A VIRTUAL HOUSE FOR CONTROL AND STEM EDUCATION

HOME I/O is the result of a 3-year R&D project “DOMUS” (2011-2014) partially founded by the French Ministry of National Education, between CReSTIC lab from the University of Reims Champagne-Ardenne and Real Games, a Portuguese company (Riera et al., 2016). HOME I/O is real time simulation software (Fig. 1) of a smart house and its surrounding environment, designed to cover a wide range of curriculum targets within Control, Science, Technology, Engineering and Math (Gonzalez and Kuenzi, 2012) (Corlu et al., 2014), from middle schools to Universities. The idea to simulate a house was to offer to kids, students and learners a system from the today life that they can use to raise awareness about energy efficiency, change behaviors and learn about new technologies. By giving the possibility to modify the environment and the level of automation, it becomes possible to have one numeric tool usable from middle schools to Universities.

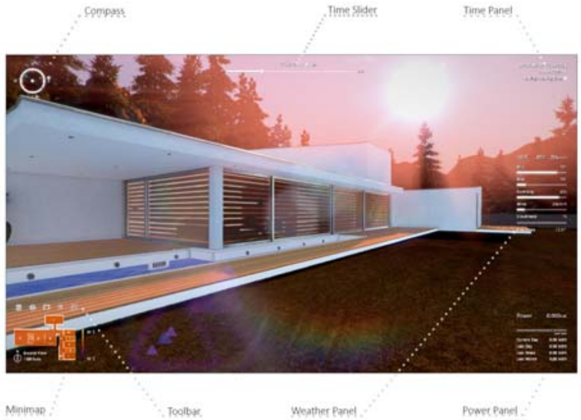


Fig. 1. HOME I/O head-up display

This virtual house, like a video game in first person (FPS, first person shooter), is a place of discovery and experimentation for STEM fields, that it is not possible for obvious reasons of cost, space and feasibility of owning in schools. HOME I/O is a realistic modern virtual house (Fig. 2).

Fig. 2. HOME I/O kid room

The virtual house is also adapted to high school and Universities. In middle school, it is important for the software to be autonomous and does not have to require other applications to be used. However, for high schools and Universities, the house could rather be seen as a source of data that can be interfaced with third party devices and software (LabView, Matlab...) or hardware (microcontrollers, programmable logic controllers, Arduino, Raspberry Pi...). The idea was therefore to provide an educational tool contributing to the continuity of STEM education, from middle schools to Universities.

A house cannot be seen and studied independently of its external environment. Indeed, home automation scenarios necessarily take into account geographical and weather elements. This vision also enables multiphysics technology to link automatic control with other scientific disciplines (mathematics, physical sciences, life sciences …). HOME I/O allows locating the house anywhere on the earth, and the sun's position (and thus the lighting) will be realistic in accordance with the date, time and location. Similarly, it is possible to change the weather conditions (wind speed and direction, cloud cover, humidity and minimum and maximum temperatures for one day). Environmental parameters play on the temperature and brightness inside the house. A simplified model has been created for real-time simulation of heat transfer. This model includes radiation phenomena, convection and conduction, and takes into account the physical properties of building materials (no modifiable). The exchanges between air masses of different temperatures are also simulated. The model is influenced by the disturbances created by the opening of doors and windows. The temperature of the outside air acts on the temperature of the house (heat transfer and airflow). The wind facilitates the transfer of heat between the house and the outside air. The walls of the house located upwind are more reactive to heat transfer with the outside air. Cloud cover decreases the effects of radiation from the sun and sky. Finally, the moisture changes the dew point, which acts on how the outside air affects the temperature of the house. The goal set with HOME I/O is educational. This means that the house is a "black box", a data source and a place for experiments. Dynamic models in HOME I/O are purely descriptive.

In a house, the physical phenomena have very different dynamics. For example, a garage door or a roller blind can be closed in seconds. However, to achieve the steady state temperature in a room can take several hours. It is therefore essential to be able to speed up the time, which allows HOME I/O. Four simulation speeds are possible; the fastest simulates a 24 hour period in just 17 seconds.

With HOME I/O, it is possible to control lighting, rollers, electric heating, an alarm system for intrusion safety and home safety (fire). Altogether HOME I/O offers 174 interactive objects (lights, switches, inverters, roller blinds, gate, garage door, sirens, motion detectors, lighting, fire detectors, door opening sensor, remote control, radiators , thermostats) that can be used to automate the home or as a source of logical or numerical data (Fig. 3). For example, it is possible to know and monitor power consumption.

All controllable objects can be used in three modes: wired, console or external (Fig. 4). In wired mode, the house is not automated. This is a conventional electrical installation where all devices are wired.

Fig. 3. Interactive objects in HOME I/O

Fig. 4. Wired, console and external modes

In the console mode (Fig. 5), the controllable objects are programmable through home automation box software by defining scenarios (lighting, motor, heating, intrusion security and domestic security). This mode is particularly interesting in middle school because the functional aspect of smart home can be easily explained and understood by kids, without going into too technical considerations.

In the external mode, inputs and outputs of each object can be used with CONNECT I/O or third party technologies (software and hardware). CONNECT I/O is a soft PLC (programmable logic controllers) that is installed with HOME I/O. CONNECT I/O interfaces, using plugins, to any type of software (Modbus TCP server, OPC server...) or hardware (Arduino, DAQ, Picaxe...) and can also be used with FACTORY I/O (cf. paragraph 4).


Fig. 5. HOME I/O console

The main function blocks of IEC 61131-3 standard for programming PLC - logical and arithmetic operators, counters, timers, front, comparators ... - are present, and CONNECT I/O also allows the connection between different technologies, both software and material. Programming is done by dragged and dropped and interconnecting the different objects (Fig. 6). The external mode is particularly suited to high school and higher education. These 3 modes enable to modify the level of automation and offer a wide range of applications adapted to middle school, high school and university.

This opens the field of applications of HOME I/O. This makes it possible (and easy) for instance to control HOME I/O from a smartphone (using a Modbus TCP server) or to control a room temperature with LabView or MATLAB. Hence, it becomes easy for instance for the students to understand how a PID controller works.

Fig. 6. CONNECT I/O: soft PLC

## 4. PEDAGOGICAL APPLICATIONS OF HOME I/O

HOME I/O is today used by more than 500 schools (middle, high and Universities) in France and several pedagogical resources can be found at www.teachathomeio.com.

At Reims Champagne-Ardenne University, HOME I/O has been used to start automatic control courses through the control of the brightness of a room. Students start by looking for actuator (light) and sensor (brightness sensor). Using CONNECT I/O, it is possible for them to observe the influences of external parameters like date, night and day cycle, weather conditions (clouds) and the roller blind position (open or close) on the brightness measure inside the room. Hence, it becomes simple to understand what a disturbance is by acting on real time on the system. It also becomes easy to explain the concepts of open loop and closed loop. Considering the actuator as a simple proportional model, the fact to add an integrator with a gain Ki and to close the loop enables to get a first order model. At least, students can calculate Ki and to test their first controller with LabView using the HOME I/O SDK (Fig. 7).

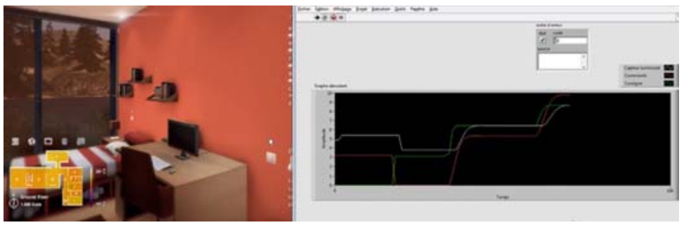

Fig. 7. Brightness control room J using LabView and HOME I/O

HOME I/O, at Reims Champagne-Ardenne University, has also been used for 2 years to start combinatory and sequential courses through the control of the roller shade and the garage door. First year students (Bachelor 1, 50 students) at the Packaging department use HOME I/O and CONNECT I/O to discover the basements of automation and sequential logic. Usually, it is not an easy course for young people having almost no background in technology. The theoretical course aims at supplying the basic knowledge about logical systems, combinatory logic, simplification of logic functions, and sequential logic. Previously, 4 hours of practical courses were performed using digital logic simulators like LogicSim. It works well, except the fact there is no possibility to connect it to a dynamic simulator or to the real world. Hence, the students had to simulate and imagine the behavior of the operative part to check their logical circuits. These practical courses were considered as not so interesting by students. HOME I/O and CONNECT I/O have really brought an added value for the students. CONNECT I/O is used as the digital logic simulator. The connection with HOME I/O is direct through the external mode. The first part of the practical course aims at controlling the opening and the closing of a roller shade using a remote control. The control in this case is seen as a combinatory problem. During the second part of the practical course, students have to display on a real 7 segment LED display the % of the opening of the roller shade (*0* means closed, *6* means 60% openness and *1.* (one with a dot), totally open). For that, a DAQ board 4704 from ADVANTEC is used with a 7 segment LED display HDSP-5503. Hence, students use real and virtual systems at the same time (Fig. 8). The application is much more interesting and that increases the students' motivation.

Fig. 8. Roller shade openness room H display with a 7 segment LED display HDSP-5503

The last part of the practical courses is an introduction to sequential systems. The idea is to have students understood that a sequential system is a closed loop combinatorial system. First, the system (Fig. 9) is studied with CONNECT I/O and students have to demonstrate that it is a RS flip-flop.

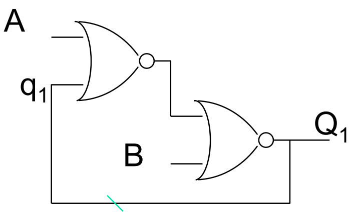


Fig. 9. Sequential logic circuit

At the end students have to design and test a controller using this basic logic diagram to open and close the garage door with 2 click buttons of the virtual HOME I/O remote control. This practical course is really well appreciated by students and teachers. HOME I/O with CONNECT I/O have shown that:

- 3D brings efficient « situation awareness » for the learner. It is a positive factor to discover, understand and learn automation.
- Interactivity, « game play » and « game design » support « motivation » factor.

## 4. FACTORY I/O: A VIRTUAL PLANT FOR PLC TRAINING

FACTORY I/O (https://factoryio.com/) is a new generation of 3D factory simulation for learning automation technologies. It integrates most of the features described in the paper "Virtual systems to train and assist control applications in future factories" (Riera and Vigario, 2013). It has been designed using the same technologies as HOME I/O. Designed to be easy to use, it allows to quickly build a virtual factory using a selection of common industrial parts. FACTORY I/O also includes many scenes inspired by typical industrial applications ranging from beginner to advanced difficulty levels (Fig. 10). Contrary to the previous software ITS PLC, most parts include digital and analog I/O. For example, it is possible to use a digital value to start or stop a conveyor or an analog value to weigh items or control liquid levels. Hence, it is possible to design sequential controller as well as feed-back controller (PI, PD, PID…).

The most common scenario is to use FACTORY I/O as a PLC training platform since PLC are the most common controllers found in industrial applications. However, it can also be used with microcontrollers, SoftPLC, Modbus TCP/IP, among many other technologies. Like HOME I/O, FACTORY I/O can be connected to CONNECT I/O. FACTORY I/O can also be very useful in training HMI (Human Machine Interface) design and programming, SCADA (Supervisory Control and Data Acquisition), MES (Manufacturing Execution Systems) and even ERP (Enterprise Resource Planning) systems. The total interactivity with the environment, allowing the introduction of disturbances on the controlled plant and faults in sensors and actuators, is an important feature of this software.


Fig. 10. Example of pre built FACTORY I/O system

The possibility to build virtual plants enables to create systems similar to real ones used in teaching laboratory. Hence, pedagogical virtual commissioning becomes a new way of teaching, enabling to test in a first stage, without risk, controllers.

## 5. PEDAGOGICAL VIRTUAL COMMISSIONING WITH FACTORY I/O

Virtual commissioning (Heidari et al., 2012) is a process which allows a comprehensive evaluation of production systems before performing physical commissioning. The programmable logic controller (PLC) code can be debugged before using it in a real production system. A growing number of companies have recently started taking interest in this technology related to Industry 4.0 as it reduces the time and cost of introducing new products and different scenarios can be performed to validate the manufacturing controllers in the virtual environments prior to the physical commissioning. Virtual commissioning is based on a real time plant simulation. This approach can be used with FACTORY I/O for pedagogical applications. It has been successfully tested with a project with Chalmers University in Sweden.

The lab equipment is a “ball track”, featuring a set of steel balls travelling on a track equipped with pneumatically driven gates and lifts, and also a simple robot arm (Fig. 11). The process is controlled by a PLC from ABB. Many industrial processes consist of different work-pieces being transported between different workstations for processing. In this case, the workpieces are steel balls of different size, and the processing consists of measuring the size of the balls and sorting them. Two kinds of balls are transported on the track using pneumatics and gravitation. At the start, the balls are all in a storage location from where they can be fed into the system through a gate. The size of the balls can then be measured. Small balls are to be sorted at the bottom floor, and big balls at the top floor. From the two floors, the balls are passed back to the storage location by the Arm. The lab equipment consists of 13 pressure driven pistons, 17 inductive sensors, two pushbuttons, two switches, and a lamp. Some of the pistons are balanced by springs and therefore retract automatically while others are pressure driven in both directions. However, all pistons are controlled in the same way, using only one signal. There are several safety problems with this system. Indeed, the robot arm can be rotated to the right (where balls can be picked up). To protect the arm from being damaged, there are some situations where one must be careful. For example, for obvious reasons, the arm must never be lifted or lowered when it is at the right position. Hence, a wrong controller designed by students can destroy it. One can understand the interest to test first on a virtual system the controller. In addition, learning from errors is often useful. Virtual systems enable it.

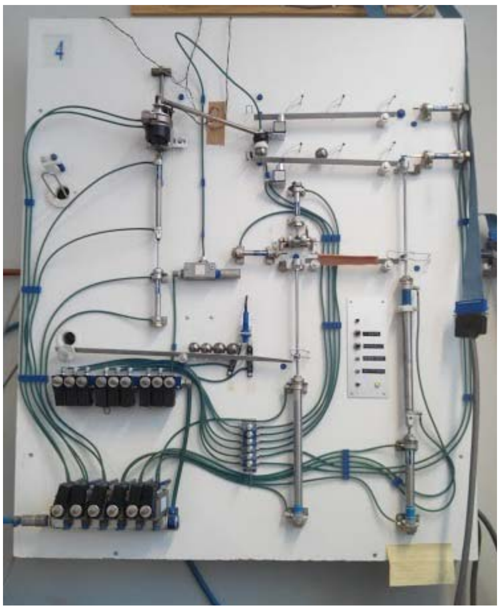

Fig. 11. Ball track system from Chalmers University

With FACTORY I/O, it is not possible to build exactly the ball track system with the available elements. However, it is possible to design an equivalent system (Fig. 12). Indeed, over the 80 available industrial parts, it becomes possible to create a virtual ball track system using the palette of industrial parts, including sensors, conveyors, elevators, stations, and many others. CONNECT I/O has been used as a gateway between FACTORY I/O and the PLC in order to have exactly the same I/O as for the ball track system from the PLC point of view. Instead of balls, pallets are used.

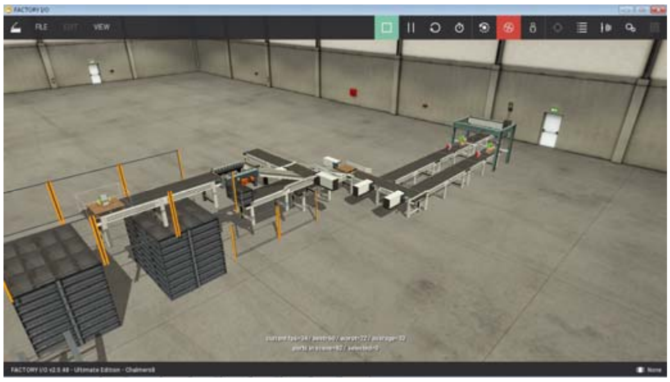

Fig. 12. Ball track equivalent system with FACTORY I/O

At the beginning, instead of gravity a conveyor, automatically controlled by CONNECT I/O is used. At the start, the balls are all in a storage location from where they can be fed into the system through a gate which has been modelled in FACTORY I/O using 2 rollers stop. This pneumatically actuated device can be used to stop, accumulate or prevent material collisions on conveyors. In the real ball track system, two pistons have been combined to make up a lift (the hiss) with two stops, floor 1 and floor 2. One piston is attached on top of the other in a way so that extracting only the upper piston brings the lift to the first floor, and extracting both pistons brings the lift to the second floor. In the laboratory, this logic is pre-programmed. That is, 2 output signals can be used separately to bring the lift to the respective floors. The Hiss has been modelled with FACTORY I/O (Fig. 13) using a piston and a conveyor. Once again, CONNECT I/O is used in order to have similar I/O like for the real hiss.

Fig. 13. Equivalent hiss system

At least, the arm has been modelled using Pick and Place station with three axes controlled by servomotors (Fig. 14). The Pick and Place has four degrees of freedom, three corresponding to the axes linear movement and another to the gripper rotation. The gripper is enabled by suction cups and includes a proximity sensor. The Pick and Place can be controlled by digital and analog values, according to the selected configuration. When controlled with digital I/O, axis movement is performed incrementally (step by step) on each rising edge of the controlling tag value. Once again, the pick and place is controlled, from the PLC point of view, exactly like the arm of the ball track system.

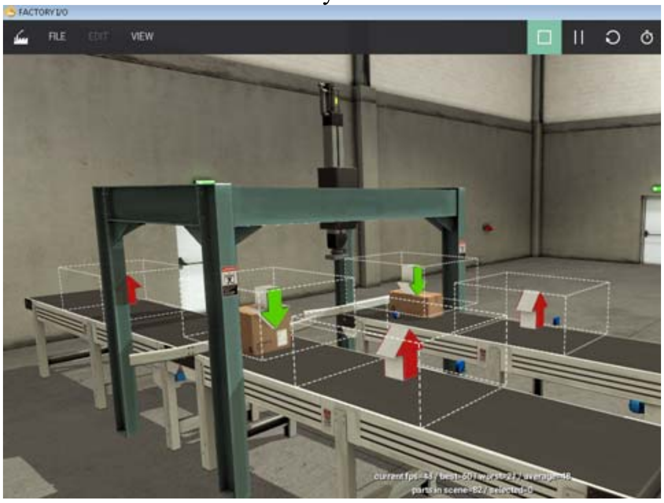


Fig. 14. Equivalent arm robot system

Aligners, which are thin metal structures attachable to a conveyor to prevent parts from falling when transported at high speeds, have been placed in order to forbid and to show unsafety states of the arm (Fig. 15).

Fig. 15. Aligner

The main interest of the approach is to guarantee the safety of the real system. However, in real world applications there are often all kinds of ugly problems to be taken care of. The ball track is no exception to this. For example, some sensors may give false indications in some situations. It is why, real commissioning and the use of real systems remain necessary. One can notice that this approach of pedagogical virtual commissioning is close to the Industry 4.0 framework.

## 6. CONCLUSION

It is possible to show several analogies between the evolution of “training” and the level of automation (Bainbridge, 1983). With the technologies, the tendency today is partially to withdraw the teacher from the “training” loop. Blended learning, flipped classrooms, MOOCs (Massive Open Online Courses) … are experienced all over the world. Our approach to control and STEM education has involved a different way to see serious games without withdrawing the teacher from the loop. The results are software like HOME I/O and FACTORY I/O. With state of the art in 3D graphics and FPS video game approach (first-person shooter), HOME I/O and FACTORY I/O offer a unique learning experience with immersive and motivating hands-on activities for several educational areas. With HOME I/O and FACTORY I/O, control and STEM education becomes a game where the teacher is the game master. The main challenge for the controls community in a near future would be to propose methodologies and tools matching the two worlds: IT (Information Technology) and OT (Operational Technology). Indeed, control and system engineers will have in the future to combine know-how related to ICT with strong IT competencies that range from basic (using spreadsheets and accessing interfaces) to advanced (applying advanced programming and analytics skills). The need for multiple hard and soft skills will become more and more important day after day. Employees will have to possess greater flexibility to adapt to new roles and work environments, and get accustomed to continual interdisciplinary IT and OT learning. It is why the area of control education, training and outreach, with new pedagogical tools like HOME I/O and FACTORY I/O, has to evolve in order to be adapted to the requirements of the Factory of the Future and more generally to our society.

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