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ASID: Advanced System for Process Control towards Intelligent Specialization in the Power Engineering Field

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Abstract – **The paper presents the system architecture, development and prototype implementation of a new integrated system for simulation of automated industrial processes using advanced technologies, in accordance with CPS/Industry 4.0 principles. The need to develop such a system is underscored by the interest of the educational stakeholders: students, faculty members, high-level industry partners, for an educational system to be used in specialized training in interdisciplinary areas including edge systems in terms of modern control technologies, open systems available to be reconfigured upon request with other technologies and mission-critical applications for different process engineering fields such as key energy applications. The process simulator can be operated in educational environments as follows: as didactic equipment for learning and deepening PLCs programming languages skills; equipment for testing various complex scenarios of some energy processes while allowing on-demand reconfiguration for some industrial systems which cannot be implemented in reality due to the high cost and/or the operational safety. Given its properties - flexibility, interoperability, open architecture, compatibility in communication, friendly human-machine interface and industrial applications, ASID is able to cover a vast array of teaching scenarios as well as serve as a platform for control algorithm implementation and testing. The modular configuration allows for increased versatility and flexibility and the long-term competitiveness of the final demonstrator is assured through hardware and software updates.**

Keywords – **process control, industry automation, simulation, embedded systems, cyber-physical systems**

I. INTRODUCTION

As control applications become ubiquitous and deeply embedded in many area of industry, the economy and society as a whole, there is the need to constantly upgrade current teaching and research infrastructure to the latest standards. This is further underscored by the emergence of new paradigms such as Cyber-physical Systems (CPS), more broader, abstract and academia-focused, together with Industry 4.0 as more applied alternative and focused on digitalisation in the manufacturing field. Both concepts however focus on bridging of the virtual and physical worlds through pervasive networks of software-intensive intelligent devices. In practice this amounts to a convergence between several areas of the IT/CSE fields with conventional control topics. Within this context, both universities and training centers require up-to-date educational tools which apply and implement these new concepts and contribute to the formation and updating of specialists through platforms which are flexible to accomodate several educational outcomes.

Allowing particular emphasis on energy applications, which can range from generation, transport/distribution and consumption, these cover a wide area of applications of discrete and continuous control. Through the future Smart Grid, real-time large scale system control becomes a necessity, while accounting for the specific challenges brought upon by distributed and unpredictable generation, limited energy storage infrastructure and shifting consumption patterns. When translated into simulated processes, the applications range from flow/level control, temperature control, control of electrical drive systems with electrical motors, electrical grid protection systems, automatic line/reserve switching, monitoring and control of energy storage systems and electrical vehicles, etc. In parallel, key importance is given to the creation of HMI-SCADA solutions which offer intuitive insights into the process, from both the educational and operational points of view. Underlying communication drivers support ModBus RTU and TCP/IP functionality which is encountered in many applications of automation for the energy field. The open software tools used to develop the simulated models that run on the ASID platform give proficient end-users the ability to develop their own processes according to specific curriculum requirements.

The *main contribution* of this paper is thus the de-

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sign, implementation and prototype realisation of a next-generation, touch-enabled, industrial process simulator for technical education and training, with special focus on application in the energy field. The salient features of the proposed demonstrator system are listed below:

- large 15.6” color touch display for an immersive and intuitive education experience;
- robust and scalable Industry 4.0 compliant hardware architecture;
- complete software package for discrete automation applications in various industries and in increasing complexity;
- 4mm signal connectors for universal industry-standard analog and digital signal interfacing to control devices such as PLC, DCS, RTU and others;
- rugged, safe and tamper-proof enclosure for demanding training scenarios.

The rest of the paper is structured as follows. Section 2 presents related work, both of other researchers and within our own group, concerned with building advanced platforms for control engineering education. Section 3 discusses the ASID hardware and software architecture, while emphasizing the particular design choices. We provide the detailed description of two reference applications in Section 4, along with insights into implementing continuous plant models into the simulator. Section 5 concludes the work with main conclusions and outlook on the further development of the system.

II. RELATED WORK

Enabling simulation-based control engineering training through computer-based environments and embedded systems has been a concern of many academic groups. These mostly address dangerous, complex systems such as chemical processes in oil and gas facilities, which allow for experimentation in a contained environment within the classroom or through remote access. The authors of (1) discuss the development of a Windows-based simulation environment with over twenty case studies. The main topics approached relate to classiscal control loop design, including PID, cascade and feedforward control, as well as SCADA concepts and communication via OPC standard middleware. The application is run locally without interfacing to dedicated control hardware.

Another relevant category for our application is that of embedded simulators for hardware-in-the-loop testing of control strategies. Several have been described for both control prototyping of complex systems and for educational purposes. One example is the work of (2) where a 3D animated HiL simulator tool is presented for non-real-time dynamic system modeling. The project can be connected to real hardware and provide support for graduate-level courses. (3) presents an embedded industrial application for PVD coating of materials which is controlled by means of a PC acting as both controller and HMI. The authors argue the benefits that such preliminary simulation approach brings in subsequent deployment time of the real system. A more complex simulation system is presented in (4), where the authors aim at multivariable adaptive control for a drum-type boiler turbine system. The LabVIEW environment is preferred for joint modeling and HMI deployment while the OPC server provides integration to external controllers.

The current system builds upon considerable experience with building industrial process simulators. In (5) and (6) the design of a microprocessor-based simulator with several process diagrams is described. The student could operate the system through push buttons and potentiometers on the panel in accordance to a static process layout (P&ID type) while viewing the output on led-based indicators. The system is currently in use for several years and has been proven as an essential tool for control engineering courses. The need for a thoroughly revised system under new teaching and research paradigms has been identified given the limited flexibility, versatility and communication options of the initial device.

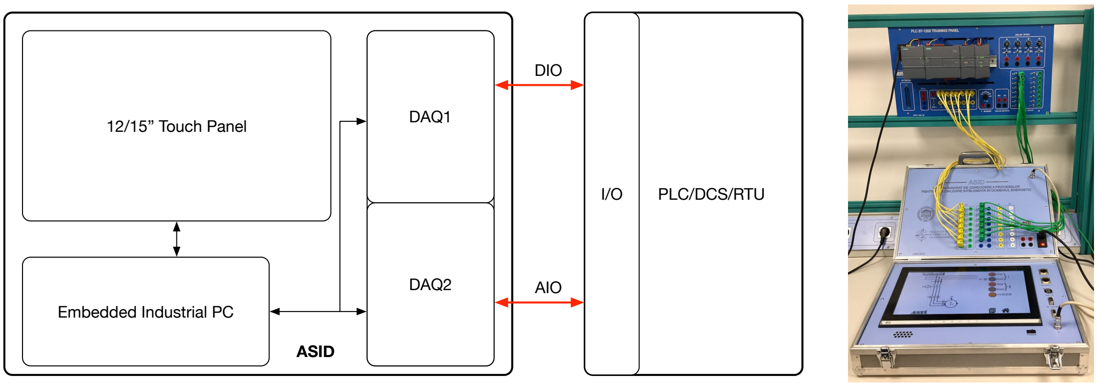
Related work also concerns developments of system architectures for Internet of Things (IoT) based monitoring and control of energy storage in (7). The concept and implementation of SCADA integrated laboratories is discussed (8). Several other applications relevant for modeling and control of complex power systems are introduced in (9). These are relevant to the extent to which the new ASID platform can incorporate and integrate the experience for improved educational outcomes. The focus is on power engineering applications of various aspects of automation.

III. SYSTEM ARCHITECTURE

The main design goal has been to build a robust, easy to use, open system which can be operated reliably in a classroom, laboratory or other training facility. Beyond pre-defined simulated processes, the intention was to enable the more advanced end-users to build on top of it, new models and HMI screens for niche control engineering applications.

Hardware-wise, the process simulator follows a modular architecture which enables multiple configuration options as well as easy replacement and upgrading of parts. The components that provide the integrated functionality to the ASID platform are subsequently described:

- Embedded Industrial PC: robust embedded system with up-to-date hardware configuration including multi-core processor, solid state drive, good graphical processing capabilities, multiple connectivity options: Ethernet, WiFi, RS485, RS232, RFID;
- Touch panel: 12-15” capacitive high-resolution touch display enabling HMI-like process visualization and operation;
- DAQ: two data acquisition modules are integrated with the embedded PC via ModBus RTU fieldbus



(a) Functional block diagram (b) Demonstration system

Figure 1: ASID Process Control Simulator

system; the functionality of the two modules is split between the digital inputs and outputs and the analog inputs and outputs;

- Control hardware: this component is external to the ASID system and can be implemented as any type of control hardware (PLC, DCS, RTU), general or real-time computing platform; the control hardware is connected to the process simulator by means of 24V DIO signals and 0-10V voltage or 4-20mA current AIO signals.

The system block diagram along with the picture of the early prototype are showcased in Figure 1.

With regard to the software architecture, a non-real time Windows 8.1 embedded operating system is used. The embedded version has been chosen due to the fact that it allows building a customized bare OS image, to be easily deployed on multiple hardware units. This optimizes resource usage and allows for better performance and stability of the models. Also the essential components and drivers needed are included while limiting the effect of unwanted external threats to the system. Process models, including graphical user interfaces, are implemented as stand-alone applications using a main menu selector application to switch among them. The development of the backend communication, logic and processing tasks is done in C#, leveraging the .NET 4.5 framework. The GUI/HMI of the individual applications has been developed using Microsoft Expression Blend under Visual Studio 2015.

IV. EXAMPLE APPLICATIONS

In this section, we present two applications in increasing order of complexity: sequential command of an electrical motor and control of a three tank system.

The first implemented application (Fig. 2) depicts the delta-star connector of a three-phase asynchronous motor.

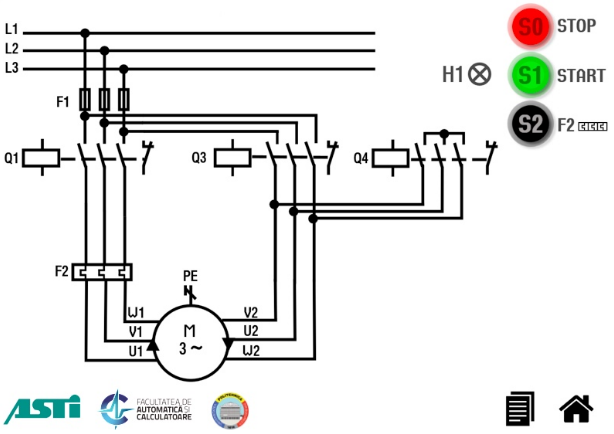


Figure 2: Delta-star connection of a three-phase asynchronous motor

In order to avoid high starting currents, a three-phase asynchronous motor must be started in star configuration and automatically switched to delta configuration after some time. The functional description of the application is presented below. When the button S_1 is pressed, the motor starts in star configuration: contacts Q_1 and Q_4 must be turned on. After about 10 seconds, the circuit must be reconfigured to provide delta motor connection to the mains: contact Q_1 remains turned on, contact Q_4 must be turned off and contact Q_3 must be turned on. Motor status (on/off) is shown by the lamp H_1. Regardless of circuit configuration, the motor should stop when button S_0 is pressed (all contacts off). A protection relay (F_2 - simulated by pressing S_2 button) must disconnect the motor in case of overload.

The second described application (Fig. 3) consists of the control of three liquid tanks (R_1, R_2 and R_3) connected in series, a typical control topic encounter

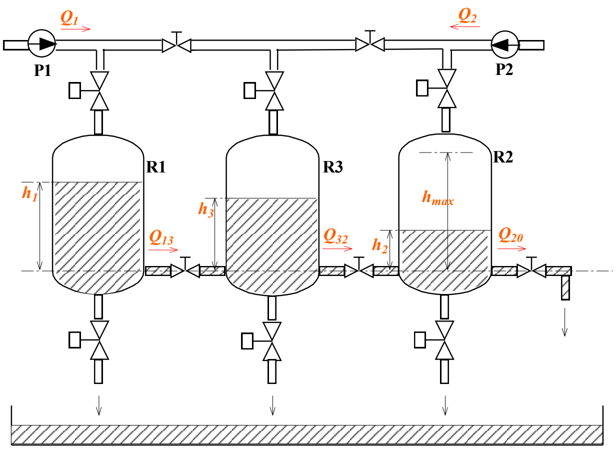


Figure 3: Three tank system: Model

in many teaching scenarios at the undergraduate and graduate level. Industrial processes of the application can be identified with the following: a three cell reactors that require the level control in one or two tanks or/and a light water level control in compartments of a PHWR nuclear reactor. The system configuration with a series of valves that can be controlled manually or automatically allows both command and control applications of a linear process as well as application for detection and diagnosis of defects in industrial installations.

In the proposed application the three tanks are connected in series via a pipe system with section S_n each tank having a constant section A. The pumped liquid is collected in a reservoir that feeds the pump P_1 and P_2. If the maximum amount of liquid in tanks h_{max} is reached, in any of the three tanks, the feeding pumps in operation will be closed automatically.

The tank system depicted in Figure 3 is a nonlinear process characterised by the following parameters and variables:

1) runoff coefficient a_i [dimensionless];
2) liquid level h_i, $i = 1, 2, 3$, [m];
3) feeding rates Q_i, $i = 1, 2, 3$ $[m^3/sec]$;
4) liquid flows through the three tank pipies Q_{ij}, $i = 1, 2, 3$; $j = 2, 3$ and 0 for the collecting tank, $(i, j) = [(1, 3); (3, 2); (2, 0)][m^3/sec]$;
5) cylindrical tank sections A_i $[m^2]$;
6) pipe section S_n $[m^2]$;

The equation of balance for each tank refers to equality between the volume of liquid accumulated in unit time and the difference between the inlet and the exhaust fluid flow from the tank. Tanking into consideration the equation of balance for each tank and the definition of debits for each passing section of the tank Q_{13}, Q_{32} and Q_{20} which can be determined using Bernoulli's law, we can model the system the using state equation:

$$\frac{dx}{dt} = Ax + Bu \tag{1}$$

$$y = Cx + Du \tag{2}$$

where the x variable is the state variable, u represent the command variable and y the output of the system.

$$x = [h_1 \;\; h_2 \;\; h_3]^T \tag{3}$$

$$u = [Q_1 \;\; Q_2]^T \tag{4}$$

$$y = [h_1 \;\; h_2]^T \tag{5}$$

This representation of the process is a third order nonlinear model, so we proceed further to obtain the linear model. The equilibrium point (EP) of the nonlinear model of the average flow for the input flows is set. We proceed to the linearisation of the system around this point using the following relations:

$$\frac{dx}{dt} = f(x, u) \tag{6}$$

where

$$x = \Delta x + x_0 \tag{7}$$

$$u = \Delta u + u_0 \tag{8}$$

then

$$\frac{dx}{dt} = \frac{d\Delta x}{dt} = \left.\frac{\delta f}{\delta x}\right|_{EP} \cdot \Delta x + \left.\frac{\delta f}{\delta u}\right|_{EP} \cdot \Delta u \tag{9}$$

The linear model is valid for small variation of input/output variable around the equilibrium point.

$$\frac{dh_1}{dt} = \frac{1}{A}\left(-\frac{a_1 S_n\sqrt{2g}}{2\sqrt{(h_{10}-h_{30})}}h_1 + \frac{a_1 S_n\sqrt{2g}}{2\sqrt{(h_{10}-h_{30})}}h_3 + Q_1\right) \tag{10}$$

$$\begin{aligned}\frac{dh_2}{dt} = \frac{S_n\sqrt{2g}}{A}\Bigg(&\frac{a_3}{2\sqrt{(h_{30}-h_{20})}}h_3 \\ &- \left(\frac{a_3}{2\sqrt{(h_{30}-h_{20})}} + \frac{a_2}{2\sqrt{h_{20}}}\right)h_2\Bigg)\end{aligned} \tag{11}$$

$$\begin{aligned}\frac{dh_3}{dt} = \frac{S_n\sqrt{2g}}{A}\Bigg(&\frac{a_1}{2\sqrt{(h_{10}-h_{30})}}h_1 \\ &- \left(\frac{a_1}{2\sqrt{(h_{10}-h_{30})}} + \frac{a_2}{2\sqrt{h_{30}-h_{20}}}\right)h_3 \\ &+ \frac{a_2}{2\sqrt{h_{30}-h_{20}}}h_2\Bigg)\end{aligned} \tag{12}$$

Using the ASID platform the three tanks connected in cascade can be implemented for a sequential control scheme for loading/unloading (Fig. 4). In the following

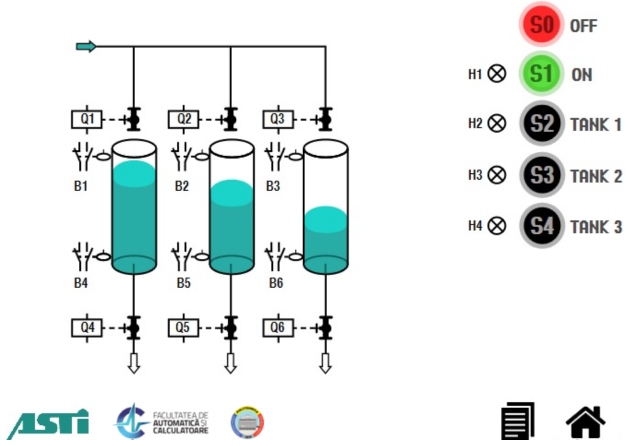


Figure 4: Three tank system: GUI

paragraphs a functional description of the process and its implementation will be depicted.

The functional description of the sequential control scheme for loading/unloading of the three tanks is described next. If a tank is completely empty, it takes 1.6 seconds for the lower level sensor to trigger the filling process and another 23 seconds for the upper level sensor to trigger the emptying of the tank. For the emptying process the exhaust flow is identical the inlet flow of the liquid in the tank. The tanks are field in the same order as they are emptied. When the system is started the reservoirs can be filled in any order, or partially filled. The level sensors (B_1 to B_6) are designed to indicate if a tank is full or empty. The liquid is discharged from a tank as long as the buttons S_2, S_3 or S_4 (Table **??**) are pressed and the liquid outlet valve is open. Emptying can be done simultaneously. The tank is filled automatically in the order of their emptying. However only a tank can be filled completely before the next tank to be filled. Emptying a tank is not possible as long as the tank is filled e.g. loading valve is open. If the system is turned off by pressing button S_0 (OFF) or due to disruptions supply charging the process will be automatically stopped. The system will be continued automatically by pressing the S_1 (ON). If the tank system is functioning the H_1 lamp is on. A permanent light of the lamps H_2, H_3 and H_4 indicates that the tank is not empty. During charging, the light will flashes with 0.5 Hz.

The process is controlled using a programable logic controller (PLC). Using a computer with PLC programming software a application which controls the installation according to the requirements described in the above is implemented.

Once the program is implemented and loaded into the PLC, the user can watch (on the computer) its execution, and he can test the interaction between the PLC and the simulated installation. The simulated installation receives control signals from the PLC and then generates status signals for the PLC (the signals may be digital or analog). The process evolution may be examined by watching the visual changes. A zone used as control panel allows direct interaction of the operator with the simulated plant.

The ASID platform gives the possibility to control the simulated plant with any programable logic controller existing on the market. All inputs and outputs have been designed in compliance with industry standards, namely 24V for digital signals and 0-10 V for analog. The showcased application is controlled using a Siemens PLC (e.g. S7-1200). For Simatic series the STEP 7 - TIA Portal programming environment is needed (TIA stands for ”Totally Integrated Automation”). PLC programming can be done using one of several languages complying international standards. The main languages available in STEP 7 - TIA Portal are: Ladder diagram (LAD), Function Block Diagram (FBD), Statement List (STL) and Structured Text (SCL). The S7-1200 series PLCs included with the demonstrator system can be programmed only using LAD or FBD.

The application will allow a complete configuration for the tank system. The users can configure parameters like the cross section and the height for each tank, the cross section for each evacuation pipe or the maxim flow rates for pumps. The system will work in two modes, automatic and manual. In manual mode the user can change, from the user interface, provided through the capacitive touch panel, the flow rate of pumps and the cross section of connection pipes. In automatic mode the tank system is controlled with a programmable logic control (PLC) by using the input/output industrial ports.

An error module is included, that can be used for studding detection and diagnosis methods. With this the instructor can simulate a partial or total defect of pumps or level sensors. In addition the structure of that system

Variable name	Significance of the variables
S_0	System off
S_1	System on
S_2	Tank 1 emptying
S_3	Tank 2 emptying
S_4	Tank 3 emptying
B_1	Upper sensor tank 1
B_2	Upper sensor tank 2
B_3	Upper sensor tank 3
B_4	Lower sensor tank 1
B_5	Lower sensor tank 2
B_6	Lower sensor tank 3
Y_1	Opening valve for filling tank 1
Y_2	Opening valve for filling tank 2
Y_3	Opening valve for filling tank 3
Y_4	Opening valve for emptying tank 1
Y_5	Opening valve for emptying tank 2
Y_6	Opening valve for emptying tank 3
H_1	Lamp which indicates that system in on
H_2	Lamp which indicates that tank 1 is not empty
H_3	Lamp which indicates that tank 2 is not empty
H_4	Lamp which indicates that tank 3 is not empty

allows to simulate leakage from tanks or clogs in connection pipes. For a better connectivity of ASID with industrial control devices, it will design a complementary architecture that will allow a direct connection with many PLC types by using industrial communication protocols like Modbus RTU, Modbus TCP/IP or EtherNet/IP. This functionality will allow the extension towards new control strategies like hierarchical and distributed control.

V. CONCLUSION AND ONGOING WORK

The paper presented the development of a novel platform for supporting control engineering education in various academic and training applications. The embedded-PC based approach has been proven to offer a modular hardware and software architecture with good performance which will support more demanding and complex process models in the future.

Several features are currently under implementation, which include: multiple fieldbus integration, IoT compatible interfaces, software-side quasi-real-time environment for continuous control and switching to a Linux-based OS.

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