IMPROVEMENTS OF A THREE-TANK-SYSTEM OPERATED IN REAL TIME WITH MATLAB IN A PLC-PROFIBUS-NETWORK

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Abstract: This paper summarizes the authors efforts to establish a well working laboratory system of worthwhile character for student courses, accounting for aspects of system modelling, control theory and state of the art industrial automation. Therefore, a Three Tank System operated by a standard industry PLC and MATLAB/SIMULINK in real time has been chosen as laboratory setup. Besides an overview of the hardware setup and the necessary software applications this paper addresses some interesting improvements of the Three Tank System, that have been developed in the recent years and enhance accuracy and reproducibility of the dynamic system behavior. Through these developments, this laboratory facility shows motivating validation results and combines the instructive practical aspects of an up-to-date decentralized PLC-System and the comfort of a system analysis and control design tool like MATLAB in real time application, thus having high educational value.

Keywords: control education, Three Tank System, PLC

1. INTRODUCTION

The Three Tank System is widely used as an educational experiment in control laboratories. The system can be modelled consistently and model based control applications range from simple one and two tank applications to classic MIMO-control systems and state space methods. In many cases laboratory experiments of that kind (characterized by the number of in- and outputs, speed of system dynamics, etc.) can be operated from MATLAB/SIMULINK by some real time software packages combined with an analog and/or digital I/O-Card. These systems are compact and easy to use, but on the other hand their application is strictly limited to the software capabilities and these systems sometimes are rather fragile resulting in computer crashes. Furthermore, they have no relevance in industry, thus missing an important educational aspect.

In order to accomplish these important aspects we have implemented a control structure as depicted schematically in Figure 1. The central SIMATIC PLC is acting as a bus master and the Three Tank System is connected by PROFIBUS via a decentralized periphery interface as a bus slave. The Three Tank System has been chosen as the primary experimental setup in this paper, but many other systems with analog and/or digital interfaces could be connected, also simul-

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taneously, as indicated by the extension with the "Flow/Temperature Control System" and the dotted line in Figure 1.

The central PLC is connected to a HMI (a PC with SIMATIC Software) via MPI (Multiple Point Interface, a network protocol supported by Siemens SIMATIC devices) and can be parameterized, analyzed and programmed in classic PLC languages e.g. instruction set.

Furthermore, the PLC is equipped with a communication processor for ethernet communication via TCP/IP. This enables standard automation tasks like remote control or error reports by email. By the use of an OPC server WINDOWS applications can be addressed through the ethernet. This feature has been utilized to connect MATLAB to the ethernet and thus also to communicate with the PLC and its bus clients.

Following this introduction, the experimental setup and the investigated improvements of the Three Tank System will be illustrated in section 2, given by a structured survey of the final state of the system. A modelling approach of the Three Tank System and validation results will be presented in section 3. Concluding remarks will be given in section 4.

2. THE EXPERIMENTAL SETUP

The experimental setup may be structured into the Three Tank System, the SIMATIC equipment and the OPC-server with MATLAB connection.

2.1 The Three Tank System

The AMIRA DTS200 - Three Tank System (Amira, 1991) has been modified and looks as depicted in Figure 5. The three tanks are connected with manually driven valves, tanks 1 and 2 have one outlet and tank 3 has two outlets for simulating an extra disturbance situation like leakage. All outlet valves are driven manually except valve V_1, which can be operated both manually and electromechanically by a 2 bit binary signal. A converter to make the digital signal level $5V\,TTL$ of the AMIRA system compatible to the $24V\,TTL$ SIMATIC In/Outputs has been added.

The tanks 1 and 2 can be filled from top by two controllable membrane pumps, both have analog input signals and can be controlled continuously. Measurement of the water levels is done indirectly by pressure sensitive piezo sensors.

The modifications on the system setup in order to improve the performance compared to the original state are as follows:

2.1.1. Inner tank cylinders The tanks are equipped with sealed, inner cylinders resulting in a reduced cross sectional area of the remaining annulus by 50% (see Figure 5). This reduces the system time constant and enables less experimental waiting time, eg. in the case of waiting for a set point of the open system. Furthermore, it increases the dynamic coupling between the tanks and, hence, enables demonstrative decoupling by feed forward control.

2.1.2. Measurement and control of the input flow

The input flows into tanks 1 and 3 are measured by two flow measurement turbines (Engolit, 2004), which produce a rectangular signal of flow proportional frequency. The subsequent f/u-converter produces a suitable analog voltage signal. The continuous flow measurement can be advantageously used for flow control and thus enables precise model validation, as the input flow given by a characteristic pump diagram is rather imprecise and vulnerable to disturbances. The controller of the flow must then be implemented in the PLC with a sampling time of $10ms$, since the system behavior of this loop is very fast and this information can not be transported completely through the ethernet - OPC connection.

The system behavior of the pump (G_p) and the measurement devices (G_m) may be approximated by a dead time system represented as a transfer function as follows:

$$G(s) = G_p \cdot G_m = 0.86e^{-0.4s} \qquad (1)$$

A simple PI-controller G_C can be used to control this system, see the block diagram according to Figure 2.

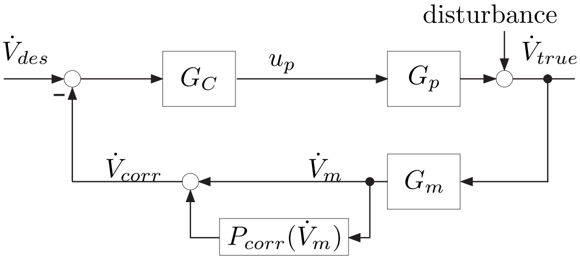

Fig. 2. Flow control implemented as a low level controller on the PLC

Due to the availability of accurate level measurements the volumes within the tanks can be calculated precisely and by feeding a tank at constant flow rates the measured flow rate can be compared to the filled volume per time. We have experienced that the flow measurement turbines with a specified accuracy of ±0.25% (Engolit, 2004) give a measurement error of up to 2% (of max. flow) in this application (see Figure 3). It may be the case that the pulsating flow characteristics produced by the membrane pumps is not suitable for the turbines and the length of the connecting tubes is not long enough to smooth the pressure peaks. Nevertheless, is has been worked out, that the additional measurement error is time independent

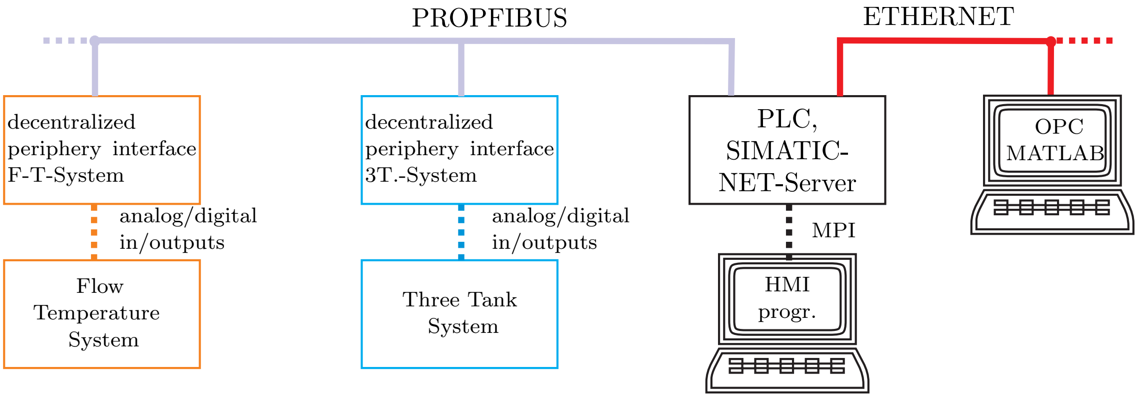

Fig. 1. Laboratory setup

and can be identified up to a range of the specified accuracy. Thus, a correction of the measured flows can be implemented. The dependency according to Figure 3 has been approximated by a polynomial function of 4^{th} order (dotted lines) and the corrected flow $\dot{V}_{corr}$ may be calculated from the measured flow $\dot{V}_m$ according to Equation 2 (see also Figure 2).

$$\begin{aligned} \dot{V}_{corr} &= \dot{V}_m + P_{corr}(\dot{V}_m) \\ &= \dot{V}_m + p_0 + p_1\dot{V}_m + p_2\dot{V}_m^2 + p_3\dot{V}_m^3 + p_4\dot{V}_m^4 \end{aligned} \tag{2}$$

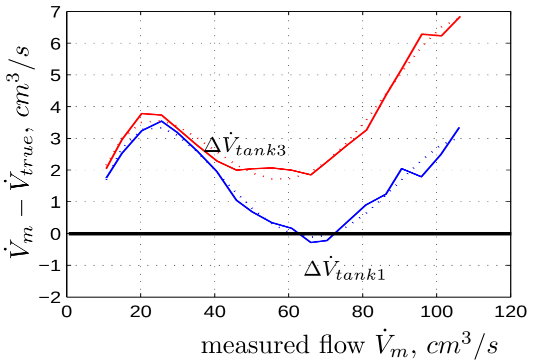

Fig. 3. Measurement error over flow range (measurement and polynomial approximation)

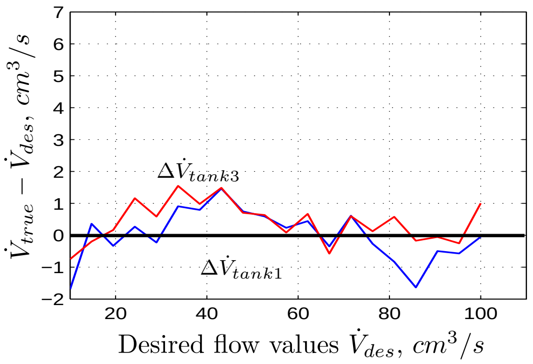

Fig. 4. Flow error over desired value after correction

After implementation of the correction algorithm on the PLC the deviation of the corrected flow from the true flow comes within $1cm^3/s$, as can be seen from the measurement sample in Figure 4 ($\dot{V}_{des} \ldots$ desired value, $\dot{V}_{true} \ldots$ true value). The result may still be improved by reducing the influence of measurement noise on the correction after calculating the mean error of multiple samples of $\dot{V}_m$ and $\dot{V}_{true}$.

2.1.3. Outlet filter for regular Bernoulli flow The outlet of the tanks is given by a 90^o bend with a vertical height of about $4cm$. Depending on the actual outlet flow the inner tube of the bend is filled for high flow rates or only partly filled for smaller flow rates. In the case when the inner tube is just not filled completely, the surrounding air pressure may spread right into the tube to the horizontal level (level 0, see Figure 6 for illustration). The hydrostatic equilibrium height counts from the cylinder base to the upper water level.

On the other hand, if the inner tube is just filled, the surrounding air pressure can not spread into the tube but only to the actual outlet surface. Therefore, the hydrostatic height counts from the outlet level to the upper water level, resulting in a difference of the previously mentioned $4cm$. Thus, if the water level rises from the first case only slightly to produce an outlet flow that fills the inner tube, the water level is about $4cm$ to high for hydrostatic height, so the water level will drop immedeately!

This nonlinear behavior is unwanted for simple modelling and leads to additional validation error. It can be abandoned by additional outlet filters that retain the water and fill the inner tube also at small flow rates. In order to prevent filtering of particles and an instationary pressure drop at the outlet, filters at the inlet at the water reservoir have been added. One filter can be seen schematically in Figure 5, realized by a mesh grid.

2.2 SIMATIC S7 300

The Three Tank System and other laboratory experiments are connected to the PROFIBUS via decentralized periphery terminals, which contain the necessary number and types of in- and out-

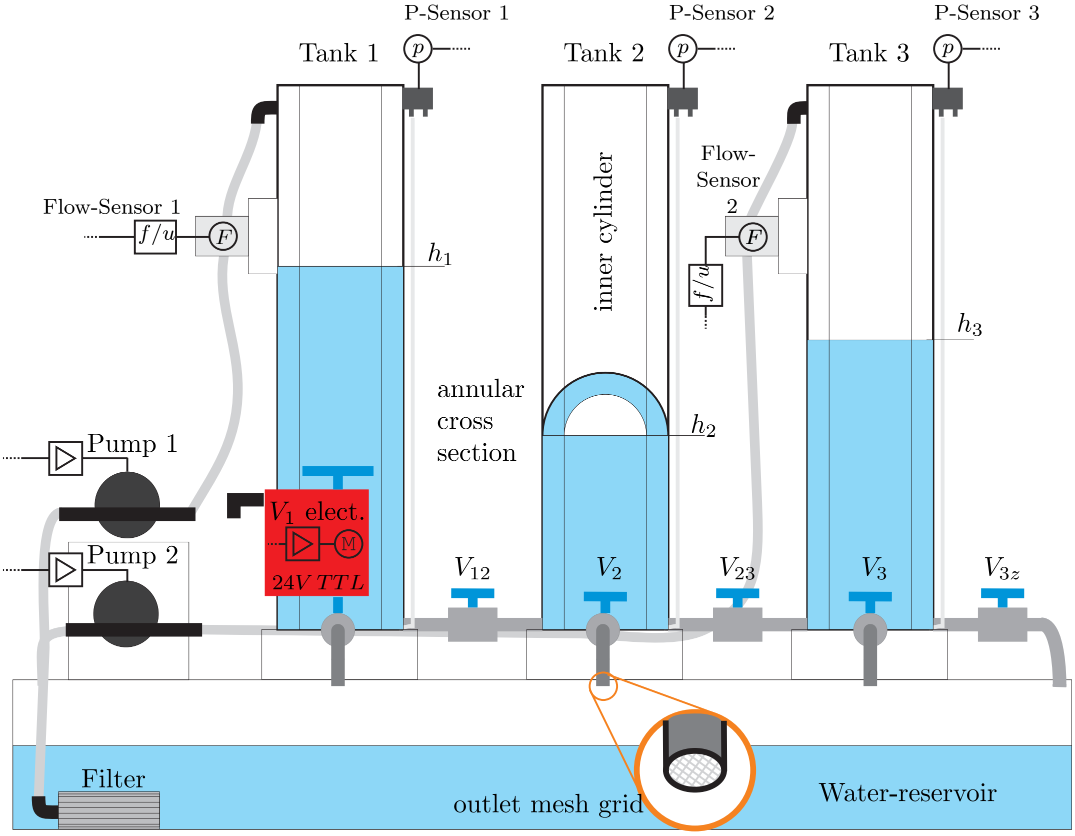

Fig. 5. The Three Tank System and its modifications

puts. The PROFIBUS is operated at a sampling rate of 10 ms by the bus master, the central PLC. The central PLC unit contains a CPU (315-2DP) of the SIMATIC S7 300 series and a Communications Processor (CP 343-1) for ethernet access via TCP/IP at 100 Mbit/s.

The central PLC can be programmed by conventional PLC codes (SIMATIC uses the software STEP7) at a memory space of up to 128kB. Furthermore, defined variables, e.g. a measurement variable assigned to a certain PROFIBUS address, are available through the communications processor on the ethernet and can be accessed (read or write). This property is utilized for the communication with MATLAB.

2.3 OPC and MATLAB/SIMULINK

OLE for Process Control (OPC) is an ethernet based technology designed to bridge WINDOWS based applications and process control hardware. It is an open standard that permits a consistent method of accessing field data from plant floor devices. In this case MATLAB is used for accessing the process data from the SIMATIC PLC. Therefore, an OPC server has been established and OPC items have been defined, that are regularly updated at a given sampling rate. Now, MATLAB is writing or reading to or from the OPC server at a fixed sampling rate T_S. This has been solved with the help of SIMULINK s-functions. s-functions help to customize SIMULINK models with M- or C-code. They calculate the state derivatives in the continuous case or the new state updates in the discrete case and the outputs alternately, what can be used for communication with the OPC server. At every sampling instance the system state vector, which is now the vector of measurements, will be updated by reading the item values of the OPC server. In the same manner, the outputs will be written to the assigned OPC server items.

A necessary attribute of a hardware-in-the-loop application is to make MATLAB run in real time. In order to use MATLAB runtime version on WINDOWS for real-time hardware-in-the-loop simulation the time handling according to Equations 3 to 5 is proposed:

$$\Delta t = T_S - t_{real} + t_{sim} \tag{3}$$

$$\text{If } \Delta t < 0: \ \text{"bad synchronization"} \tag{4}$$

$$\text{If } \Delta t > 0: \ \text{pause } \Delta t \tag{5}$$

If the difference between simulation time t_{sim} and real time t_{real} after the assignment of the state vector is greater than the sampling time T_S, the synchronization is not valid and MATLAB has to catch up time. On the other hand, if t_{sim} minus t_{real} is less than T_S, respectively the calculation is faster than the real process time, then MATLAB is forced to pause for the time of the difference.

Naturally, MATLAB takes some time at the start of the simulation run for initialization tasks. This causes a lack of synchronization every time the process has been started. Also, if the sampling time is chosen too small, the calculation process may easily take longer than the sampling interval, again resulting in bad synchronization. For the present application with a sampling time of $T_S = 0.2s$ the gap is big enough and synchronization works well after initialization.

3. THE PROCESS-MODEL

The process model can be derived by basic modelling approaches, hydrodynamic relations may be found in standard reference books (Dubbel, 1997).

3.1 Modelling

The modelling approach of the Three Tank System starts with the elementary balance equation for the three tank volumes, which for constant cross sectional areas A may be written in vector notation as

$$A\dot{\mathbf{h}} = \dot{\mathbf{V}}_{in} - \dot{\mathbf{V}}_{out} \tag{6}$$

with $\dot{\mathbf{h}} = [\dot{h}_1 \;\; \dot{h}_2 \;\; \dot{h}_3]^T$ being the change in time of the individual levels of the three tanks and $\dot{\mathbf{V}}_{in}$, $\dot{\mathbf{V}}_{out}$ the in- and output flows, respectively. The Vector of input flows is given by

$$\dot{\mathbf{V}}_{in} = [\dot{V}_{P1} \;\; 0 \;\; \dot{V}_{P2}]^T$$

with $\dot{V}_{P1}$, $\dot{V}_{P2}$ representing the flows through the pumps 1 and 2. The vector of output flows has to be determined by superposition of the flows through the outlet into the reservoir and the flows through the connections between the tanks.

3.1.1. Flow through the outlet For the flow through the outlet (in the case of an open valve!) as depicted in Figure 6 it is assumed that the stationary Bernoulli equation with additional pressure loss according to Equation 7 may be applied:

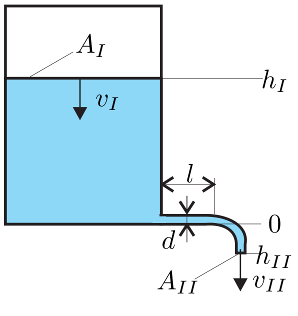

Fig. 6. Scheme for the outlet flow

$$h_I + \frac{v_I^2}{2g} = h_{II} + \frac{v_{II}^2}{2g} + \frac{\Delta p_{loss}}{\varrho\, g} \tag{7}$$

with

$$v_I = \dot{h}_I \quad v_{II} = v_I \frac{A_I}{A_{II}} \tag{8}$$

and $\varrho \ldots$ fluid density, $g \ldots$ acceleration of gravity, $Re \ldots$ Reynolds number, $\nu \ldots$ dynamic viscosity, see also Figure 6.

The pressure loss Δp_{loss} has been modelled as the sum of the pressure loss Δp_{lam} due to a steady laminar flow in a circular pipe of length l and a lump sum pressure loss $\Delta p_{nonideal}$ due to all remaining effects, e.g. bends, turbulency, discontinuities etc., see Equation 9.

$$\Delta p_{loss} = \Delta p_{lam} + \Delta p_{nonideal} \tag{9}$$

$$= \frac{64 l \varrho v_{II}^2}{2\, Re\, d} + \zeta \frac{\varrho v_{II}^2}{2} \tag{10}$$

The only unknown parameter in Equation 10 is the friction coefficient ζ. It has been determined experimentally by draining the initially completely filled tanks through the outlet valves and fitting the modelled $h_{i|i=1\ldots3} - t$-curves (according to the above given model) to the measured curve.
The resulting change in time of the level is given implicitly by the quadratic equation (11).

$$\dot{h}_I^2 \left[\frac{A_I^2}{A_{II}^2} \frac{(1+\zeta)}{2g} - \frac{1}{2g} \right] + \dot{h}_I \frac{A_I}{A_{II}} \frac{32 l\, \nu}{g\, d^2} + h_{II} - h_I = 0 \tag{11}$$

3.1.2. Flow through the connecting valve For the flow through the connection between two tanks as depicted in Figure 7 it is assumed that the stationary Bernoulli equation with additional pressure loss according to Equation 12 may be applied:

$$h_I + \frac{v_I^2}{2g} = h_{II} + \frac{v_{II}^2}{2g} + \frac{\Delta p_{loss}}{\varrho\, g} + \frac{\Delta p_{III}}{\varrho\, g} \tag{12}$$

with

$$v_I = \dot{h}_I \quad v_{II} = v_I \frac{A_I}{A_{II}} \quad \Delta p_{III} = \varrho\, g\, h_{III} \tag{13}$$

Again Δp_{loss} is assumed to satisfy Equations 9 and 10 and individual friction coefficients ζ for both connections can be determined experimentally.

The resulting change in time of the level is given implicitly by the quadratic equation 14.

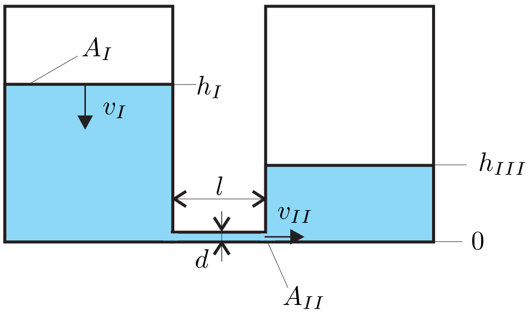

Fig. 7. Scheme for the connecting flow

$$\dot{h}_I^2\left(\frac{A_I^2}{A_{II}^2}\frac{(1+\zeta)}{2g}-\frac{1}{2g}\right)+\dot{h}_I\frac{A_I}{A_{II}\frac{32l}{\nu}}g\,d^2+$$
$$+h_{II}+h_{III}-h_I=0 \qquad (14)$$

3.1.3. Combining outlet- and connecting flow In order to model the Three Tank System it is assumed that the interacting influence of outlet and connecting flow is negligible. Equations 11 and 14 can both be solved explicitly, thus the overall change in time of the level **h** in Equation 6 can be calculated by Equation 15.

$$\dot{\mathbf{h}} = (\dot{\mathbf{h}})_{outlet} + (\dot{\mathbf{h}})_{connection} \qquad (15)$$

The individual output flows are calculated by Equation 16:

$$\dot{V}_{out} = A_{II} \cdot v_{II} \qquad (16)$$

3.2 Validation

The validity of the assumed modelling approach could be proved by comparing simulation results and experimental data. Figure 8 shows a section of a validation run, where both input flows have been changed stepwise and the outlet valves have been opened or closed arbitrarily. It indicates that the model (dashed lines) and experiment (continuous lines) match very well according to the expected accuracy.

In comparison, the results of previous experiments, without recent improvements like flow control, outlet mesh grids and the use of a friction coefficient in a slightly more complex model instead of an empirically derived effective outlet cross section, did not yield such a good match. A good match has to be aimed at to give encouraging validation results in the students courses and for successful implementation of more complex control methods like dynamic feed forward control.

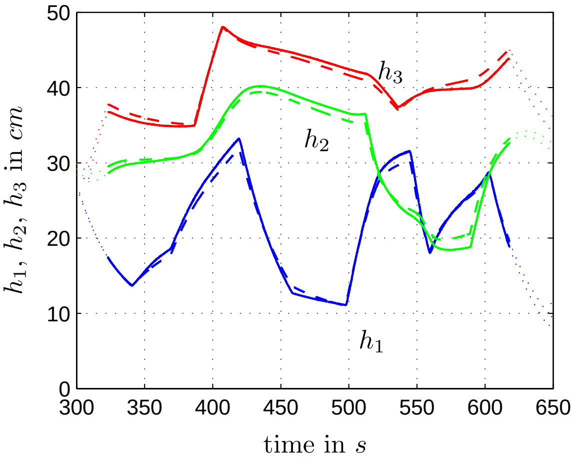

Fig. 8. Validation experiment: measurement '—', simulation '- - -'

4. CONCLUSIONS

The laboratory experiment presented in this paper is characterized by the combination of a representative automation system according to industry standards and MATLAB under real time operation with a three tank system as hardware-in-the-loop. The system has been used successfully in the past laboratory student courses. It proved to run stable for a long time, not causing any demotivating irritations to students as experienced with previous setups.

Special benefits to students may be expected through the integrated use of the PLC and PROFIBUS Network representing the control infrastructure of industrial applications on the on hand and MATLAB as a powerful control design tool on the other.

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