A LABORATORY SCALE PLANT WITH HYBRID DYNAMICS AND REMOTE ACCESS VIA INTERNET FOR CONTROL ENGINEERING EDUCATION

J. Hlava[*], B. Šulc[**] and J. Tamáš[**]

[*]*Technical University of Liberec, Faculty of Mechatronics*
Department of Control Engineering, 416 17 Liberec, Hálkova 6, Czech Republic
[**]*Czech Technical University in Prague, Faculty of Mechanical Engineering*
Institute of Instrumentation and Control Engineering, 166 07 Praha 6, Technická 4, Czech Republic
jaroslav.hlava@vslib.cz, bohumil.sulc@fs.cvut.cz, jan.tamas@fs.cvut.cz

Abstract: The major challenge in modern control engineering education is to bring the increasingly sophisticated theory closer to those students who will follow industrial careers. Hybrid system theory addresses practical needs, but its potential is usually not understood by people from industry. Presented laboratory scale plant designed for original educational experiments with hybrid systems is a contribution to introducing this theory at a practical level. The paper includes a description of the plant structure, an outline of the mathematical model and suggested control experiments. The proposed internet access solves the lack of such laboratory set-ups. Web services architecture provides a standards-based access to all who want to learn about the principles of hybrid systems through remote experiments.

Keywords: hybrid systems, control education, remote experiments, Internet, man–experiment interface

1. INTRODUCTION

The dynamic behaviour of many important industrial plants involves both continuous and discrete/logical components and subsystems. For example, continuous dynamics are often combined with on/off actuators and sensors (e.g. solenoid valves, level and proximity switches, relays). In an even more general setting, the values of signals associated with sensors and actuators are taken from a finite discrete set (e.g. a gearbox with several gear positions). There are also many plants that exhibit considerably different dynamic behaviour in different operation modes or in different working points. Such plants can be modelled as a combination of several continuous dynamic models and discrete valued variables that determine which of these models is valid in the current operation mode or range.

This has been the motivation behind growing interest in studying the theory of hybrid systems (see e.g. Hlava and Šulc, 2002 for a short survey) which includes both continuous and discrete valued dynamics and variables in one general framework. Many important results concerning hybrid systems have been achieved recently (see e.g. Borrelli, 2003; Savkin and Evans, 2002). However, this field is still mostly the topic of highly theoretical papers and PhD level courses. Its high application potential remains almost completely unexploited.

It is the purpose of this paper to contribute to introducing hybrid systems into control engineering education at a less theoretical and more practical level. The rationale is quite simple. If process control engineers do not understand what hybrid system theory is all about, hardly any real world applications of this theory can be expected. In particular, this paper is concerned with a laboratory scale plant that exhibits several hybrid phenomena and is designed for the purpose of practical experiments with modelling and control of hybrid systems. The plant is relatively simple and inexpensive to build.

A laboratory plant satisfying these requirements can hardly be found in the literature. There are several technical reports describing complex laboratory plants designed mainly for the purposes of European research projects (in particular the plants used as case studies in the Esprit project Verification of Hybrid Systems www-verimag.imag.fr/VHS/). Other papers just sketch simple model plants that are used to illustrate some ideas described in the paper but were not intended to be built and used for educational purposes (e.g., Lennartson *et al.*, 1996). Still other papers include hybrid control or modelling experiments with educational models. Although these models exhibit certain hybrid phenomena, they were primarily designed for continuous control experiments (see e.g., Kowalewski *et al.*, 1999). No laboratory plant designed primarily for experiments with hybrid control is described anywhere.

2. THE LABORATORY SCALE PLANT

The plant is sketched in Fig. 1. Similarly as in most process control applications, the measured and controlled variables are water level, temperature and flow. The sensors and actuators were (if possible) chosen from standard industrial ranges. Thus, although the plant does not represent any particular industrial process exactly, both the plant itself and its instrumentation are well representative of many plants commonly used in the process industries.

The basic components of the plant are three water tanks. However, the plant structure is considerably different from the standard three tank system. Water from the reservoir mounted under the plant can be drawn by pumps 1 and 3 to the respective tanks. In both cases, the delivery rate can be continuously changed and the water flow rate is measured with a turbine flowmeter. The flowmeter output is available to the plant control system and it is also used by a slave controller. In this way, it is possible to keep the flow rate at a desired value. The water flow from pump 3 is fed directly to tank 3. The water flow from pump 1 goes through a heater and it is further controlled by an on/off solenoid valve S1. Due to a built-in pressure switch, the pump is automatically switched off if S1 is closed and the internal tank of the heater is full. The temperature at the heater output is measured by sensor TT4. The power consumption of the heater can be changed continuously using a solid state relay with triac output. Depending on the selected control scenario, the inflows to tanks 1 and 3 can be used as manipulated variables or as deterministic disturbances with specified flow rates and also with a specified temperature in the case of inflow 1.

Tanks 1 and 2 are thermally insulated to make the heat losses negligible. Tank 3 and the water reservoir are not insulated and, if the air cooler motor is on, their temperature roughly equals the ambient temperature in the laboratory. Tanks 2 and 3 have a special shape that introduces a change of dynamics at a certain level. Their behaviour is thus described by switched models. Water from tanks 1 and 3 is fed to tank 2. The flow from tank 1 is controlled by solenoid valves S3, S4 and it can be changed in three steps: no valve open, one valve open, both valves open. Closing and opening the valves is instantane-

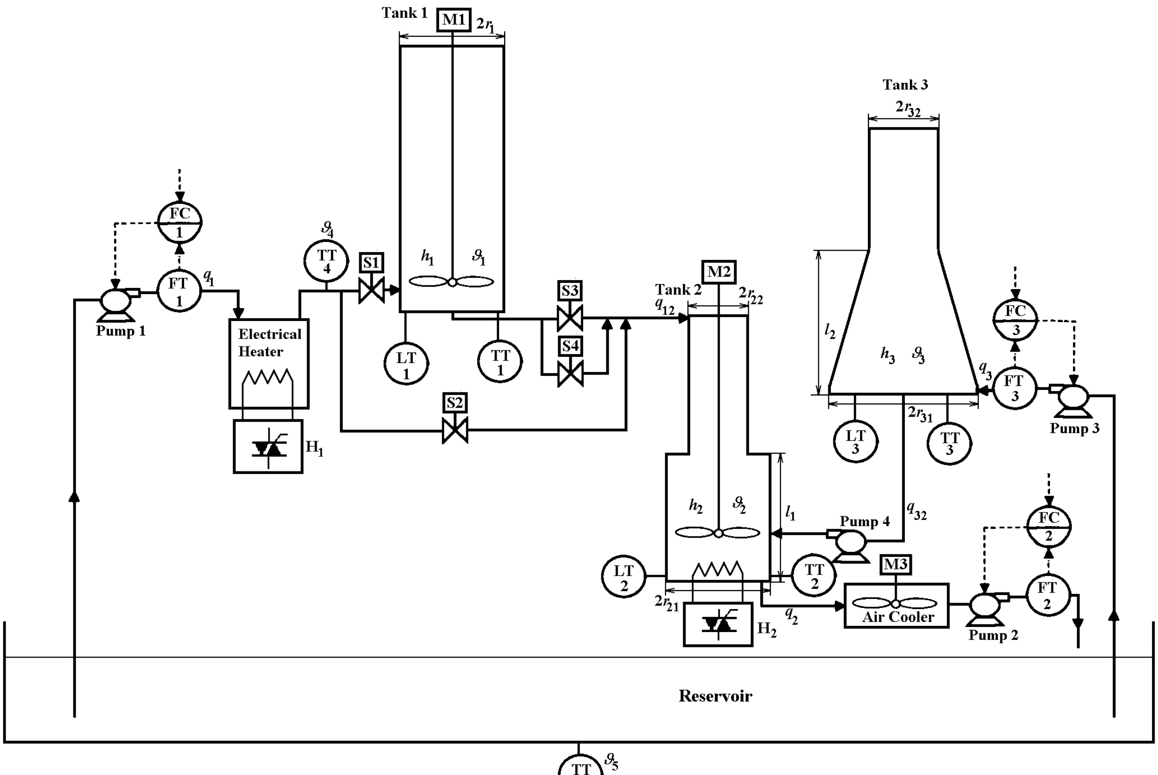

Fig. 1 Structure of the plant (FT, LT, TT stands for flow, level and temperature transmitter respectively, FC – flow controller, S – solenoid valve, M – motor)

ous. Tank 1 can be by-passed by closing S1 and opening S2. The flow from tank 3 is controlled by a pump. Its delivery rate can be changed in four steps (0, 1/3, 2/3, max.).

Another heater is mounted at the bottom of tank 2. The water from tank 2 is drawn by a pump. The turbine flowmeter and slave controller FC2 allow simulation of the changes in demand of the downstream processes. The water goes back to the reservoir through an air-water heat exchanger that is cooled by two fans. This arrangement is used to keep the water temperature in the reservoir roughly constant during the experiments. If desired, the cooling fans can be switched off. This introduces an additional degree of complexity to the system. If the fans are off, the temperature of the water in the reservoir increases depending on the flow rate and the temperature of the outflow stream from tank 2, and affects the inflows to tanks 1 and 3. In this way, an internal delayed feedback loop arises in the controlled system.

The water levels are measured with pressure sensors. These can be configured either as continuous sensors or level switches (indicating three different water levels). The plant is controlled from a PC using two data acquisition boards.

3. MATHEMATICAL MODEL OF THE PLANT AND HYBRID PHENOMENA

There are several phenomena that are usually referred to as hybrid. Most of them are included in the general hybrid system model as described, e.g., by Branicky *et al.* (1998). A hybrid system is described by

$$\begin{aligned}
\dot{\mathbf{x}}(t) &= \mathbf{f}(\mathbf{x}(t), \mathbf{m}(t), \mathbf{u}(t)) \\
\mathbf{y}(t) &= \mathbf{g}(\mathbf{x}(t), \mathbf{m}(t), \mathbf{u}(t)) \\
\mathbf{m}(t^+) &= \boldsymbol{\varphi}(\mathbf{x}(t), \mathbf{m}(t), \mathbf{u}(t), \boldsymbol{\sigma}(t)) \\
\mathbf{o}(t^+) &= \varphi(\mathbf{x}(t), \mathbf{m}(t), \mathbf{u}(t), \boldsymbol{\sigma}(t)) \\
\mathbf{x}(t^+) &= \boldsymbol{\psi}(\mathbf{x}(t), \mathbf{m}(t), \mathbf{u}(t), \boldsymbol{\sigma}(t))
\end{aligned} \tag{1}$$

where $\boldsymbol{x}(t)$, $\boldsymbol{u}(t)$ and $\boldsymbol{y}(t)$ are continuous state, input and output respectively (continuous in the sense that they take values from a continuous set), $\boldsymbol{m}(t)$ is the discrete state that indexes the vector fields $\boldsymbol{f}(.,.,.)$, $\boldsymbol{\sigma}(t)$ is discrete input and $\boldsymbol{o}(t)$ is discrete output. The last equation in (1) models possible state jumps.

The plant features most of the phenomena included in (1). There are several on/off and discrete-valued actuators, and the water level sensors may also be configured as discrete-valued. Further, it includes switching of vector field $\boldsymbol{f}$. This switching is caused both by on/off and discrete-valued inputs and by abrupt changes in the dynamics of the water tanks at levels l_1 and l_2. This plant does not exhibit state jumps. These are typical of certain mechanical systems (e.g., systems involving collisions). State variables in process control applications (temperature, liquid level, concentration etc.) cannot be abruptly changed in steps.

A reasonably accurate first principles model of the plant can be derived using mass and energy balance equations. The liquid (water) can be considered incompressible. The mass balance equation of a single tank is then

$$\frac{dV(t)}{dt} = \frac{d}{dt}\left(\int_0^{h(t)} A(x)dx\right) = A(h)\frac{dh(t)}{dt} = q_{in}(t) - q_{out}(t) \tag{2}$$

where h is water level, A(h) is the cross sectional area of the tank at level h, and q_{in} and q_{out} are inlet and outlet volume flow rates.

Assuming further that the liquid heat capacity c is constant, the heat losses are negligible and the tank is well mixed, the energy balance equation of a single tank can be expressed as

$$\begin{aligned}
\frac{d}{dt}\left(\rho c V(t)\left(\vartheta(t) - \vartheta_{ref}\right)\right) &= q_{in}(t)\rho c\left(\vartheta_{in}(t) - \vartheta_{ref}\right) \\
&\quad - q_{out}(t)\rho c\left(\vartheta(t) - \vartheta_{ref}\right) + P(t)
\end{aligned} \tag{3}$$

where P is heater power output, ϑ_{in} is inlet water temperature, ϑ is the temperature of the water in the tank. Because of the assumption of perfect mixing, the outlet water temperature can be equated with ϑ. After a simple manipulation (3) can be modified to

$$V(h)\frac{d\vartheta(t)}{dt} = q_{in}(t)\left(\vartheta_{in}(t) - \vartheta(t)\right) + \frac{P(t)}{\rho c} \tag{4}$$

The volume flow rate from a tank with water level h can be expressed by

$$q = 0.1k_v\sqrt{gh} \tag{5}$$

Combining (2), (4) and (5), plant model can be built

$$\dot{h}_1(t) = (1/A_1)\left(q_1(t) - 0.1k_v\sigma_1(t)\sqrt{gh_1(t)}\right) \tag{6}$$

$$\dot{h}_2(t) = \begin{cases} (1/A_{21})\begin{pmatrix} 0.1k_v\sigma_1(t)\sqrt{gh_1(t)} \\ +\sigma_2(t)q_0 - q_2(t)\end{pmatrix} & \text{if } m_1 = 0 \\ (1/A_{22})\begin{pmatrix} 0.1k_v\sigma_1(t)\sqrt{gh_1(t)} \\ +\sigma_2(t)q_0 - q_2(t)\end{pmatrix} & \text{if } m_1 = 1 \end{cases} \tag{7}$$

$$\dot{h}_3(t) = \begin{cases} \dfrac{q_3(t) - \sigma_2(t)q_0}{\pi(r_{31} - h_3(t)\Delta r/l_2)^2} & \text{if } m_2 = 0 \\ \dfrac{q_3(t) - \sigma_2(t)q_0}{A_{32}} & \text{if } m_2 = 1 \end{cases} \tag{8}$$

$$\dot{\vartheta}_1(t) = \frac{q_1(t)\left(\vartheta_4(t) - \vartheta_1(t)\right)}{A_1h_1(t)} \tag{9}$$

$$\dot{\vartheta}_2(t) = \begin{cases} \dfrac{\begin{pmatrix} 0.1k_v\sigma_1(t)\sqrt{gh_1(t)}\left(\vartheta_1(t) - \vartheta_2(t)\right) \\ +\sigma_2(t)q_0\left(\vartheta_3(t) - \vartheta_2(t)\right) \\ +P(t)/\rho c\end{pmatrix}}{A_{21}h_2(t)} & \text{if } m_1 = 0 \\ \dfrac{\begin{pmatrix} 0.1k_v\sigma_1(t)\sqrt{gh_1(t)}\left(\vartheta_1(t) - \vartheta_2(t)\right) \\ +\sigma_2(t)q_0\left(\vartheta_3(t) - \vartheta_2(t)\right) \\ +P(t)/\rho c\end{pmatrix}}{A_{21}l_1 + A_{22}(h_2(t) - l_1)} & \text{if } m_1 = 1 \end{cases} \tag{10}$$

$$m_1(t^+) = \langle\begin{matrix} 0 & \text{if } h_2(t) \le l_1 \\ 1 & \text{if } h_2(t) > l_1 \end{matrix} \quad (11)$$

$$m_2(t^+) = \langle\begin{matrix} 0 & \text{if } h_3(t) \le l_2 \\ 1 & \text{if } h_3(t) > l_2 \end{matrix} \quad (12)$$

where $A_i = \pi r_i^2$, $\Delta r = r_{31} - r_{32}$, m_1 and m_2 are discrete state variables, discrete valued input σ_1 assumes values 0,1,2 (no valve open, S3 open, S3 and S4 open), discrete valued input σ_2 assumes values 0,1,2,3 (pump 4 delivery rate is 0, 1/3 max., 2/3 max., maximum), q_0 is the delivery rate of pump 4 running at 1/3 of maximum. The measurable outputs are identical with the state variables. The water levels in the tanks can be used as continuous valued or discrete valued outputs depending on the configuration of the level sensors. Equation for ϑ_3 is not included in the model. This tank is neither heated nor insulated, ϑ_3 is roughly equal to the ambient temperature and the mixing dynamics of tank 3 are not important. Valves S1, S3 and S4 can be closed and S2 used as a control input. The plant model is then simplified: h_1 and ϑ_1 are omitted and the square root term in the respective equations is replaced by $q_1(t)\sigma_1(t)$ (σ_1 =0 or 1).

The vector field defined by equations (6) to (10) involves both controlled and autonomous switching. Controlled switching due to changes of discrete valued inputs σ_1, σ_2 results in vector field discontinuity in (6), (7), (8) and (10). Autonomous switching due to changes of h_2 and h_3 results in vector field discontinuity in (7). The dynamic behaviours of (8) and (10) are also switched, but the vector field remains continuous.

4. SUGGESTED EDUCATIONAL EXPERIMENTS WITH THE PLANT

Although this plant is fairly simple and easy to understand, it allows us to define many modelling and control scenarios that can be used to teach various aspects of hybrid modelling and control. Some of these will be outlined below, but the treatment can be by no means exhaustive. Many other scenarios are possible depending on what is appropriate for a particular course in hybrid systems.

At first it is possible to start with scenarios that emphasise the part of hybrid systems simulation and modelling. In particular, it is important to note that equations (11), (12) are simpler than the respective equation in (1). The future values of discrete state variables depend on continuous state only $\mathbf{m}(t^+) = \boldsymbol{\varphi}(\mathbf{x}(t))$. There is no discrete memory in the system. This is typical of process control applications where full discrete dynamics are usually introduced by auxiliary logic controllers. For example, the plant can be augmented with a simple controller whose task is to avoid tank 1 overflow. The controller opens S2 if h_1 reaches a specified level, say h_{11}. If h_1 reaches h_{12}, it also opens S3. Both valves are closed at the same time when h_1 reaches h_{11} again. The discrete state equations of the augmented plant now contain $m(t)$ also on the right side, and the plant is hybrid in the full sense of this word. Now it can be used, e.g., for experiments with identification and simulation of hybrid systems using various tools (Simulink/Stateflow, Modelica etc.).

Further, it is possible to define uncomplicated control tasks such as water level control in tank 2 or 3 or temperature control in tank 2. In this case, the controlled system features switched dynamics, and certain basic classes of hybrid systems can be demonstrated to the students. For instance, if the control objective is to control h_2 using q_1 as the manipulated variable (valve S2 constantly open, S1, S3, S4 closed) and q_2 being a disturbance (in this scenario both q_1 and q_2 can be changed in several steps) the controlled system is a simple integrator hybrid system. Alternatively, the objective can be water level control in tank 3. The dynamics of (8) are nonlinear for $h_3 \le l_2$. The nonlinear range of h_3 can be divided into several sub-ranges and the whole system including switching and non-linearity can be approximated with a piecewise affine (PWA) system.

More complicated scenarios use two tanks. One suggestion (inspired in part by Slupphaug *et al.*, 1997) can be formulated as follows. Tank 1 serves as a buffer that receives water from an upstream process. Water flow rate and temperature are disturbances. Since the plant includes continuously controlled heater H_1 and slave flow controller FC1 these disturbances can follow a defined function of time as required by a particular experiment. The main control objective is to deliver the water to a downstream process at a desired temperature. The flow demand of the downstream process is another disturbance. Valves S1, S2 and S3 are discrete valued manipulated variables and the power output of heater H_2 is a continuous manipulated variable. The main control objective necessarily includes several auxiliary objectives. Tank levels must be kept within specified limits, and overflow as well as emptying of the tanks must be avoided. It is also necessary to avoid the necessity to close valve S1 in order to prevent tank 1 overflow. In a real control situation, closing S1 would mean that water from the upstream process cannot flow to the buffer but must be re-routed to the environment.

The controlled system is again hybrid and nonlinear, allowing approximate modelling, e.g., as a PWA system. However, unlike the previous simpler scenarios it includes nontrivial interactions of continuous and discrete controls. For example, if valve S3 is already open and S4 must also be opened to avoid tank 1 overflow, temperature ϑ_2 may also be significantly affected, particularly if temperatures ϑ_1 and ϑ_2 are much different. The plant in this configuration can be used to test various approaches to hybrid system control. It is possible to follow the traditional approach and to design the water level control logic and continuous heater control independently. Alternatively, a hybrid approach can be followed and both the discrete and the continuous manipulated variables can be controlled with a single controller designed using hybrid controller synthesis methods (e.g., those developed in Borrelli, 2003). The control performances achieved with both approaches can be compared.

Even more complicated interactions can occur in scenarios that use all three tanks. In this case, there are many possible combinations of manipulated, controlled and disturbance variables. For example, tanks 1 and 3 can be used as buffers that receive water from two upstream processes. Flow rates q_1, q_2 and q_3 as well as temperature ϑ_4 ($\vartheta_4 > \vartheta_3$) are disturbances. The control task is to deliver the water at a desired temperature and flow rate q_2 to a downstream process using S3, S4, pump 4 and heater H_2 as control inputs. The control objective must be achieved while satisfying necessary constraints such as avoiding emptying and overflow of the tanks. Optimization sub-objectives can be included, e.g. it may be desirable to make use of the fact that $\vartheta_4 > \vartheta_3$ in order to minimize the power consumption of heater H_2.

5. CONCEPT OF REMOTE ACCESS TO LABORATORY SCALE PLANT EXPERIMENTS

Experience from modelling real heat and power processes (Jan, 2002; Hrdlička, *et al.,* 2002;) as well as designing and implementing remote access to laboratory experiments (Tamáš, 2001; Tamáš, Šulc, 2003) gave a solid foundation for building a remote access to the hybrid system described above.

The diploma project (Tamáš, 2001) was focused on gathering experience with remote control of a lab set up (shown in Fig. 2), leading to effective use of the laboratory equipment and giving students the convenience of performing their laboratory experiments from any computer connected to the Internet. The system was built on a client/server architecture where both the client and the server were custom-built standalone win32 applications. The system proved to be working and served as proof of the concept; however, it had the significant disadvantage that it was a) based on a proprietary protocol, therefore scaling and future development become an issue and, b) it was platform dependent, as it only ran on win32 operating systems.

The currently developed system of remote access to the hybrid lab plant described above takes into account and is built on all the experience gained during previous implementations. The most important change is that it is based on the progressive web services foundation, which provides a set of web methods that can be accessed by the client programs. These programs can be implemented on a number of desktop platforms, from Win32 through Apple to Linux. It is also possible to connect computers with greater computing power, if necessary. This can be useful when applying sophisticated power-intensive control algorithms that can only run on very fast computing platforms such as Unix. The system architecture is shown in Fig. 3.

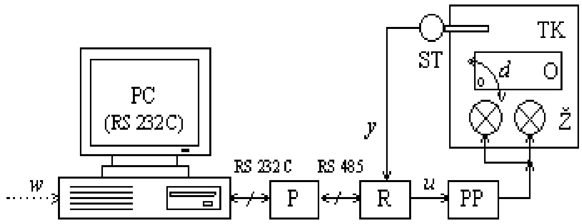

Fig. 2 Scheme of a remotely controlled laboratory experiment (heat chamber - TK, Honeywell UDC 1000 controller – R, heating bulbs – Ž, temperature sensor - ST)

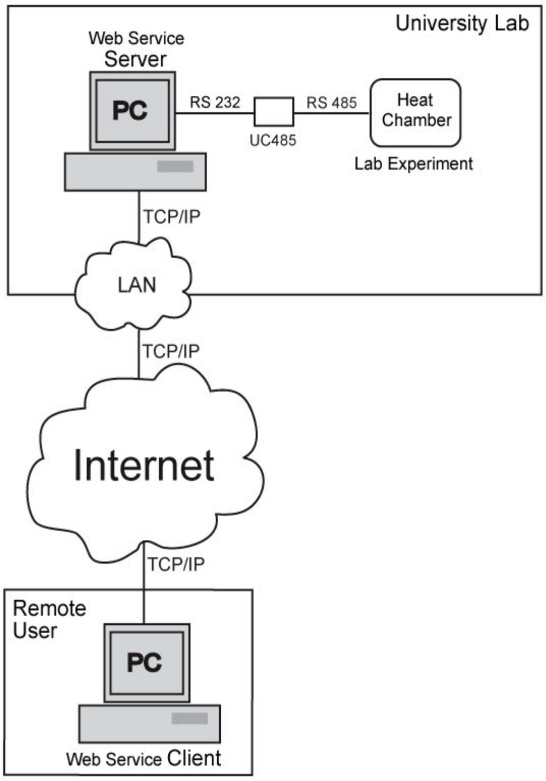

Fig. 3 Scheme of the connection of the remote user to the laboratory experiment (hardware point of view)

The following are the main advantages of the use of web services:

- Unified cross-platform interface – based on TCP/IP, HTTP, XML and WSDL standards, this solution can be implemented on a variety of platforms.
- Scalability - changes to the experiment (server side) can be made without having to change the client software.
- Passes through most firewalls – HTTP protocol is used, therefore no changes need to be imple-

mented in the setup of most firewalls, as HTTP traffic is allowed on most networks.

- Allows cooperation between on-line users – connection of several users to the experiment at one time is allowed and better management of access rights is provided.
- Easy discovery of the searched web service with the help of Universal Description, Discovery and Integration (UDDI) registries, which include lists of registered web services described using Web Services Description Language (WSDL).

Remote access in the case of the described hybrid system forms a part of a broader automatic control education system that aims at unifying the application programming interfaces (APIs) of different automatic control education-related systems and the content in different learning management systems and web sites (Tamáš, Šulc, 2004). The results of the work being carried out now will be presented in the framework of a doctoral dissertation at the Czech Technical University in Prague during the summer months of 2005.

6. CONCLUSION

One of the important contributions of the laboratory scale plant described in the paper is the fact that it demonstrates hybrid phenomena typical of process control applications. The plant instrumentation was mostly chosen from industrial ranges in order to make its operation as close as possible to real plants, which is in accordance with a practical orientation toward industry. The plant features considerable flexibility. It can be configured just to demonstrate simple hybrid behaviours such as switching between two dynamic models or logic control of continuous plants. Thus, it can be adapted to the needs of introductory courses in hybrid systems. However, if it is used fully, it is well suited for advanced level courses: it includes several non-linearities and non-trivial interactions of continuous and logical/discrete dynamics. Thus, it can also be used for research purposes, such as testing new hybrid control algorithms. The Internet access to this plant uses web services architecture to allow a uniform standards-based application programming interface. This approach makes it easier for remote users to connect to the plant and experiment with the behaviour of a hybrid system, thus gaining a deeper level of understanding of the studied phenomenon. By combining the versatile laboratory set-up with the remote Internet access a new set of possibilities is created with many potential applications in university education in industrial training courses, and also in research.

7. ACKNOWLEDGEMENT

This research has been supported by the Czech Science Foundation within project 101/04/1182.

8. REFERENCES

Borrelli F.(2003), *Constrained Optimal Control of Linear and Hybrid Systems*, Springer Verlag, Heidelberg.

Branicky M., V. S. Borkar and S.K. Mitter (1998), A Unified Framework for Hybrid Control: Model and Optimal Control Theory. *IEEE Transactions on Automatic Control*, **Vol. 43**, pp. 31-45.

Haas, H. (2002): Web Services Activity. www.w3.org/2002/ws.

Hlava, J., and B. Šulc (2002), Hybrid Systems: New prospects for further development of automatic control theory and practice, Automatizace, No.3, pp. 193- 195 (in Czech).

Hrdlička, P., Neuman, P., Šulc, B. (2002): Process Instrumentation Modular Models of Thermal Power Plant for Operator Training Simulators, 15th IFAC World Congress on Automatic Control, Barcelona, Spain.

Jan, J. A. (2002): Soft Computing in Object Oriented Nonlinear Modelling and Control of Thermo-Fluid Dynamic Systems. PhD Thesis. Czech Technical University in Prague.

Kowalewski S. *et al.*(1999), A Case Study in Tool-Aided Analysis of Discretely Controlled Continuous Systems: The Two Tanks Problem, *Lecture Notes in Computer Science*, **Vol.1567,** pp. 163-185, Springer-Verlag Heidelberg.

Lennartson B., M. Titus, B. Egardt and S. Pettersson (1996), Hybrid Systems in Process Control. *IEEE Control Systems Magazine*, **Vol. 16**, pp. 45-56.

Neuman, P., B. Šulc and T. Dlouhý (2000): Nonlinear Model of a Coal Fired Boiler Applied to an Engineering Simulator. Preprints IFAC Symposium on Power Plants and Power Systems Control 2000, Brussels.

Savkin A.V. and R. J. Evans (2002), *Hybrid Dynamical Systems – Controller and Sensor Switching problems*. Birkhäuser.

Slupphaug, O., J. Vada and B. A. Foss (1997), MPC in Systems with Continuous and Discrete Control Inputs, Proceedings of ACC97, CDROM.

Šulc B. and P. Neuman (2000): Engineering Models of a Coal Fired Steam Boiler in Teaching, Training and Research Applications. ACE 2000, Gold Coast, Australia.

Tamáš, J. (2001): Performing Laboratory Experiments in Control Engineering via Internet. Diploma thesis (in Czech). Czech Technical University in Prague.

Tamáš, J., Šulc, B. (2003). Using Web services to control lab experiment and a power plant simulator. Preprints of the 6th IFAC ACE Symposium, Oulu, Finland.

Tamáš, J., Šulc, B. (2004). New Possibilities of E-learning Systems based on the Semantic Web Principles. CD-ROM preprints of the IFAC Workshop on Internet Based Control Education, Grenoble, France.