AN EXPERIMENTAL APPARATUS FOR SIGNAL CONDITIONING CIRCUITS DEVELOPMENT AND TESTING: A TEACHING EXPERIENCE

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Abstract

This document describes a teaching experience using an experimental apparatus developed by the authors. This apparatus has a pedagogical nature and has been in use for five years, so some conclusions may now be attained. It incorporates several sensors and actuators in two small tanks of water, and is intended for training the development of signal conditioning electronic circuits and programming control algorithms. It may be observed as a small scale reproduction of an industrial process. Students develop the signal conditioning circuits and interface them to a microcontroller. In one specific course context, the development, study and experimental testing of those circuits is the main focus of the student's work, however the system has polyvalence to be used in other courses.

1. INTRODUCTION

The relevance of the study of feedback systems and, in a broader sense, the study of control systems, is often stated in articles with a pedagogical nature [1], [3], [5], even if only simple or basic concepts are involved. Experimental setups are commercially available for specific tasks, with particular sets of experiences in mind, which normally include sensors with built-in signal conditioning.

Because the focus of such setups are frequently the control theory validation (normally for algorithm development and testing), there isn't much room left for the development of electronic circuits to accomplish the signal conditioning of sensors, either for simple displaying or for interfacing with a microcontroller (or some other computational system).

In some academic contexts, as in some specific electronic courses, there is the need to study the electronic circuits used for signal conditioning of sensors and actuators. It would be much more motivating for students if this could be done in such a context where these sensors or actuators would be part of a process to be controlled, even if it's just for academic purposes, as long as real hardware (sensors and/or actuators) were used. To fulfill this need, the authors developed the experimental apparatus described in this document.

2. APPARATUS DESCRIPTION

The experimental apparatus is composed by two small tanks of water (approximate dimensions 40cm x 20cm x 30cm), each incorporating several sensors and actuators.

Figure 1 presents a schematic diagram of the setup connected to a microcontroller which in turn is connected to a personal computer. Given that the two tanks are very similar, a schematic diagram of one tank (the one in the left in figure 1) is shown in figure 2.

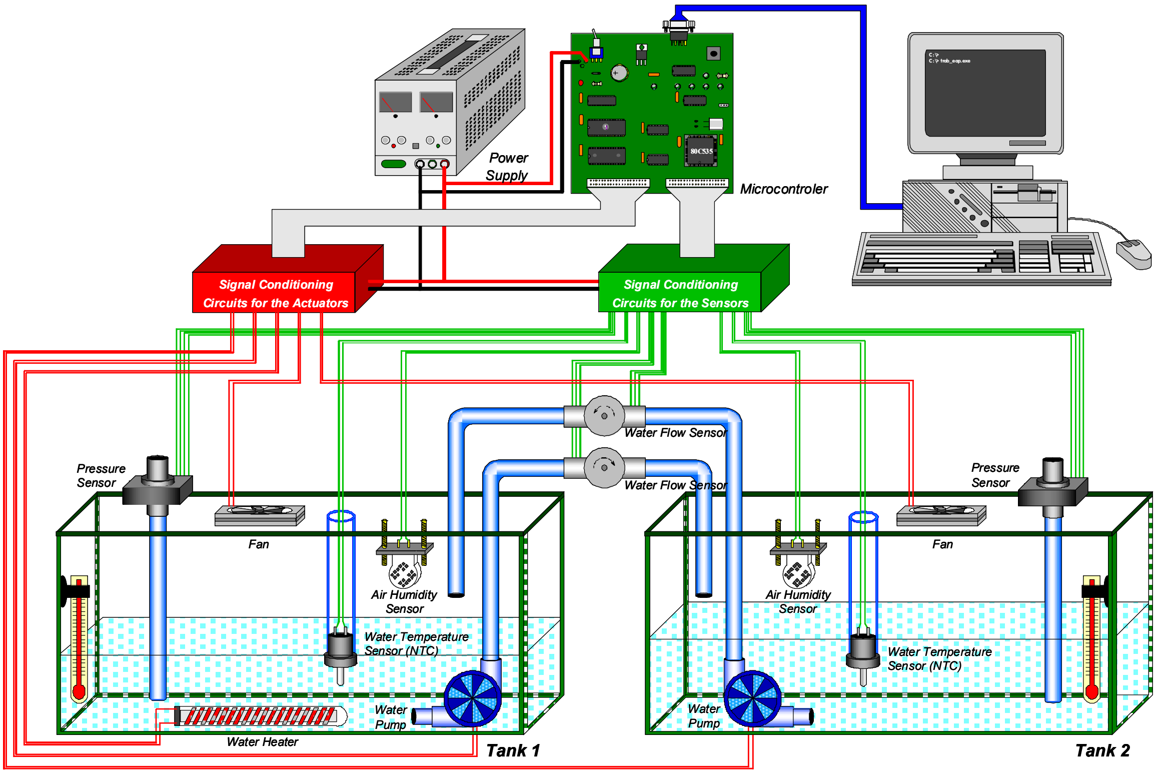

Figure 1 : Schematic diagram of the experimental apparatus interfaced to a microcontroller kit and to a personal computer.

Each tank has a Plexiglas cover that is not drawn in the pictures. This cover holds the fan and the humidity sensor depicted in the diagrams, and enables some degree of isolation between the air inside the tank and the room atmosphere. When the fan is switched on, the air is forced to circulate, being exhausted from the interior of the tank to the outside through the fan and entering the tank by the borders of the Plexiglas cover (which is intentionally not sealed to enable this air flow).

Figure 2 shows several sensors and actuators that exist in tank 1. Some of the system's variables are measured by the following sensors: a temperature sensor for water temperature measurement; a humidity sensor to measure the air humidity inside the tank; a pressure sensor placed on top of a tube which is immersed in water and enables the estimation of the water level (and consequently the volume of water within the tank); and a water flow sensor inserted in the water exhaust tube to allow the measurement of the water quantity exhausted from the tank. There is another sensor that is not shown in the diagrams: the fan has a speed sensor, which enables the measurement of its rotational speed.

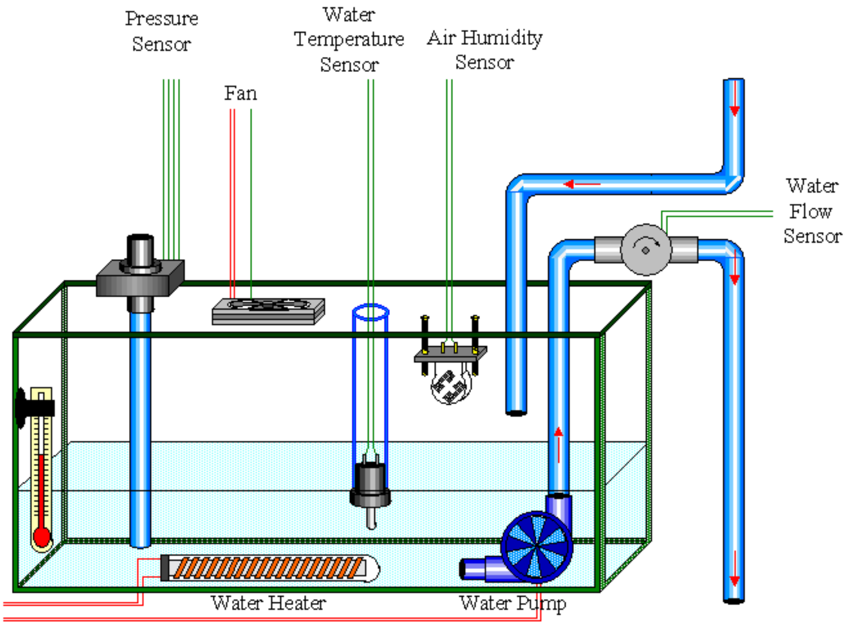

Figure 2 : Overview of one tank and associated sensors and actuators.

To actuate with the system (tank), there are three actuators: a small fan (already mentioned), a water pump used to pump water out of this tank (pumping water into the other tank, the one on the right in figure 1) and a heater resistor used to heat up the water in the tank.

2.1. Temperature measurement and control

Water temperature is measured by a thermistor that is permanently immersed in water. In order to minimize the thermal gradient in the water, there is a small water pump (not shown neither in figure 1 nor in figure 2) that is always switched on, whose effect is just to stir the water by causing its continuous run inside the tank.

The water temperature can be raised by the heater resistor inside tank 1, but there is no process to quickly lower its temperature, besides waiting for its natural cool down or by the addition of cooler water (eventually pumped out from tank 2). This heater resistor (actually there are three heaters connected in parallel summing up to 600 W of heating power under water) is driven by a switching relay that isolates the 220 V sector voltage applied to the heater from the 12 V used to operate the relay. For safety reasons, students do not deal with the high voltage that drives the heaters, although, in some cases, an exception may be considered (provided the proper teacher supervision is enforced) if, for instance, any student suggests the use of triacs or thyristors to control the voltage supplied to the heaters.

2.1.1. Signal conditioning for the temperature sensor and heater resistors.

The water temperature sensor is a negative temperature coefficient thermistor (NTC thermistor). The signal conditioning hardware can be relatively simple and, with the software running on a microcontroller, what students really project is in fact a simple ohmmeter, optimized for a specific resistance range calculated in order to accommodate the required temperature range.

The signal conditioning of the NTC thermistor can be implemented with simple circuits as those depicted in figure 3, or by more sophisticated circuits as those shown in figure 4.

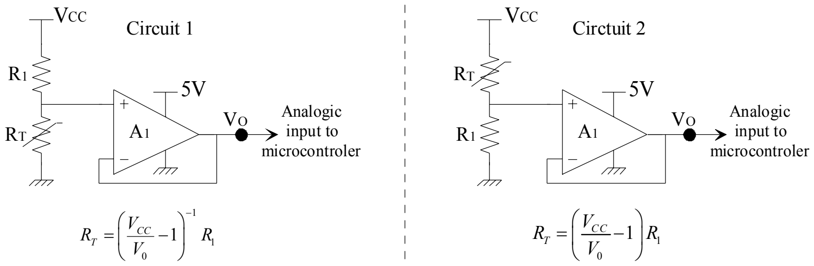

Figure 3 : Simple circuits to interface the NTC thermistor to the microcontroller.

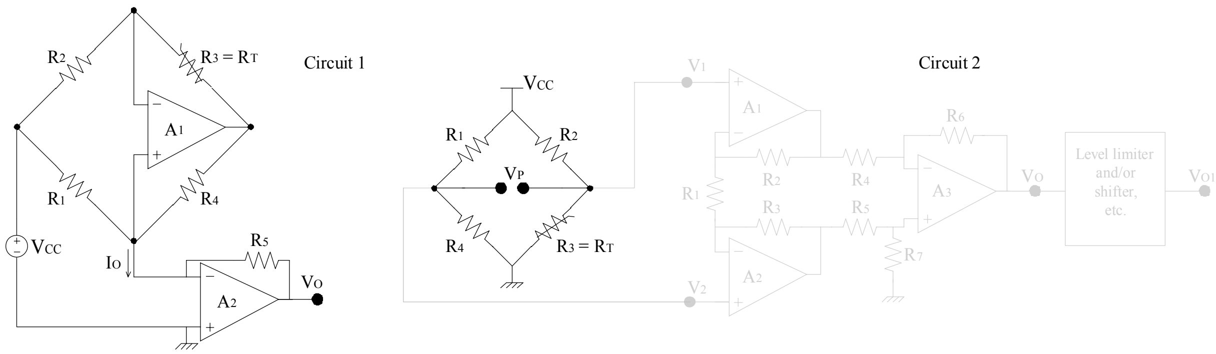

Figure 4 : Other examples of circuits used by students with the NTC thermistor.

The NTC thermistor serves an example of a sensor that has a non linear characteristic but has a known model. Students almost always employ the commonly used [2] two parameter equation $R_T \approx R_0 e^{\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)}$, adopting for R_0 and β the typical values provided by the manufacturer's datasheet. Some students try to validate this equation and its parameters by testing its results against the measurements obtained with two mercury thermometers that are immersed in the same tank. This attitude is welcome because it exercises the students' critical capabilities concerning the use of the so called "typical values", too often effortlessly applied for fast attainment of results without the mandatory validation in precision measurement situations.

The signal conditioning circuits usually suggested by students to actuate the heaters, interfacing the microcontroller to the relay, are based on simple switching dc amplifier topologies, like the circuit presented in figure 5.

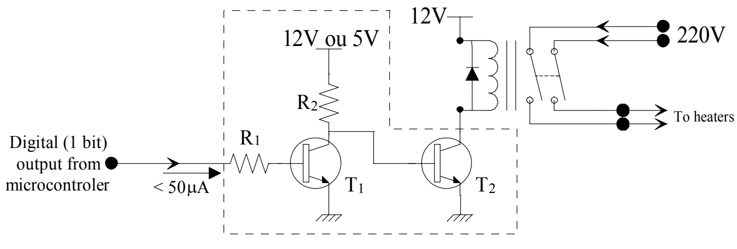

Figure 5 : Example of a driver circuit for the heater's relay.

In this circuit both transistors operate in the saturation or cut-off region, allowing for enough current gain (the microcontroller output current is restrained to a maximum of 50 μA, just for academic purposes) and obeying the restriction that all actuators must be switched off after the reset of the microcontroller (which justifies the inverter role of T_1).

2.2. Humidity measurement and control

In this experimental apparatus there is also an air humidity sensor. Since the tanks are covered by a Plexiglas cover, the air flow between the interior of the tank and the room atmosphere can be controlled by the small fan shown in figure 2.

As a result of having the Plexiglas cover, the air humidity may differ between the inside and outside of the tanks. For instance, by heating the water, the air humidity inside the tank increases fast (production of vapour) and easily reaches saturation (100% RH). Then, switching on the fan, which extracts air from the tank interior, an air exchange situation will occur, lowering the air humidity inside the tank. So, by measuring the air humidity and actuating the fan, it is possible to control (e.g. stabilize) the air humidity inside the tank.

The humidity sensor is a capacitive sensor with a non linear response, as depicted in figure 6. Although this response curve has a monotonous evolution, its non linear characteristic entails some extra difficulty, particularly because the manufacturer's datasheet does not suggest any function (polynomial or other) to model that response.

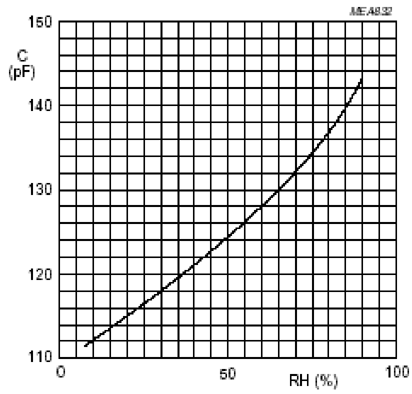

Figure 6 : Transfer characteristic of the humidity sensor. Note its non linear characteristic.

The student's approaches to this problem are diverse, but almost all solutions imply the manual extraction of data from the curve shown in figure 6. The data points are then interpolated either by a polynomial function or by linear approximation functions. In short, this sensor presents the following challenges: it is a capacitive sensor, it has a non linear characteristic response and a model function has to be established based only on the graphical data provided by the manufacturer.

2.2.1. Signal conditioning often used for the humidity sensor.

Amongst students, this sensor is frequently considered to be the most trickiest one to use, since they tend to consider that measuring capacitance is inherently harder than measuring resistance or current. In spite of this undue fame, the circuits often suggested (and used) by students in signal conditioning for this sensor are not necessarily more complex than those used for the other sensors of the apparatus. For instance, one solution frequently used is based on the ubiquitous NE555 i.c., running either in monostable or astable mode (figure 7). Alternatively, an astable multivibrator made with an operational amplifier can be used (or other circuits based on dedicated integrated circuits).

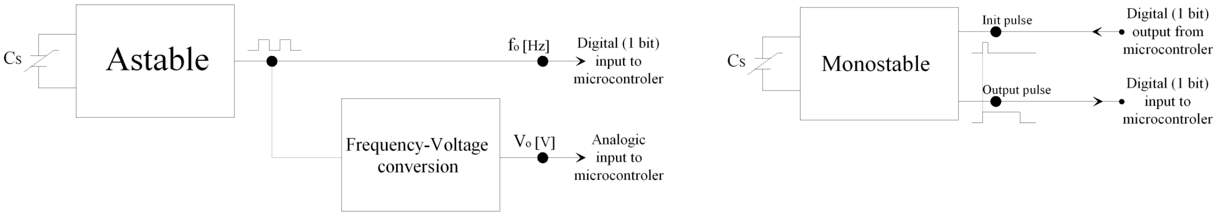

Figure 7 : Typical methodology used by students to measure the humidity sensor capacitance.

Occasionally other solutions are used, based on the topology presented in figure 8. In these circuits, the change in the sensor's reactance caused by changes of humidity in the air produces a change in the circuit's output dc voltage (eventually in a linear fashion). It is quite simple to achieve a null average voltage across the sensor with these circuits, which is sometimes required for some humidity sensors.

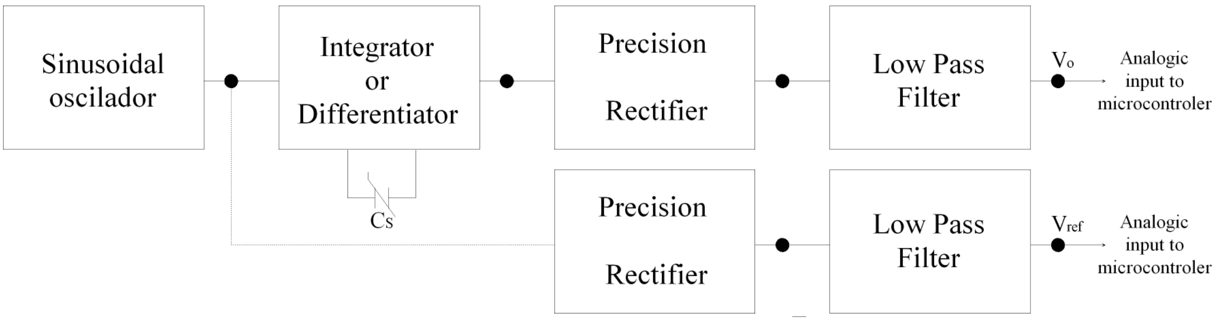

Figure 8 : Capacitance measurement using envelope detection.

The software running in the microcontroller must be able to measure the frequency (or period) of the generated signals of circuits in figure 7, or measure the output voltage of circuits in figure 8, and then calculate the required conversion to relative air humidity.

2.3. Pressure measurement and water level estimation

Water level in the tank is estimated by the air pressure measured inside a vertical tube inserted in the water, as it is depicted in figure 9. A differential pressure sensor is used to measure the air pressure inside the tube relatively to the atmospheric pressure. With this measurement, students are able to calculate how deep the tube is inserted in the water, which enables the calculus of the water level. Since the other two dimensions are constant, the volume of water inside the tank can also be calculated at any time.

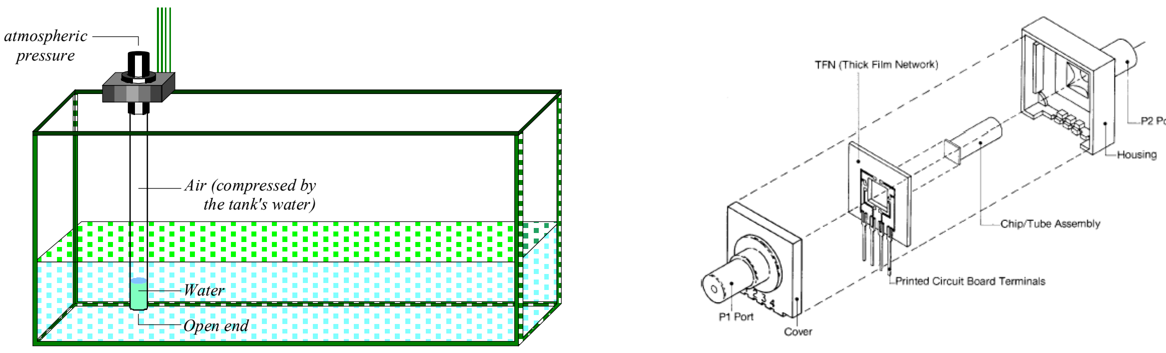

Figure 9 : Water level estimation using a differential pressure sensor based in piezoresistors.

This sensor is electrically modelled by a Wheatstone bridge that has a differential output voltage proportional to the input differential pressure. The sensor has a small diaphragm placed between the two chambers connected to the pressure ports. This diaphragm undergoes some deformation when the differential pressure is not null. There are four piezoresistors connected in a Wheatstone bridge configuration deployed in the diaphragm. This topology is frequently used in inexpensive pressure sensors (either differential or absolute types) [6]. Although it is a linear sensor, with a known sensibility, the relation between the differential pressure and the water level is unknown to students and has to be estimated by them.

2.3.1. Signal conditioning often used for this sensor.

The usual choice for the signal conditioning of this sensor is the instrumentation amplifier, which has the typical topology presented in figure 10. Since the supply voltage of the Wheatstone bridge is predefined and equal to 10 V, the common mode output voltage of the bridge is near 5 V, which implies that some of the operational amplifiers must have a positive supply voltage greater than 5 V. However the analogical input voltage to the microcontroller is limited to 5 V, and students have to implement the amplifier complying with both restrictions at the same time.

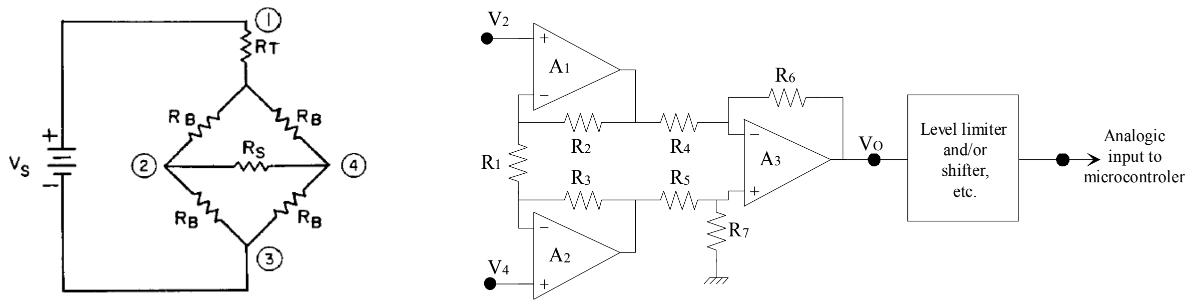

Figure 10 : Electrical model for the pressure sensor and signal conditioning often used by students.

The differential output voltage of the bridge is normally less than 20 mV, so students often implement an amplifier with a differential gain of about 200 in order to amplify a few tenth of milivolts superimposed on almost 5 V.

2.4. Water flow measurement

The outgoing tubes of each tank have water flow sensors that allow for the measurement of the water expelled from the tanks.

Although there has been an effort in the conception and building stage of this experimental apparatus to avoid sensors with built-in signal conditioning, this goal was not fulfilled in this case. The authors weren't able to find commercially available water flow sensors (for the flow rates required) without some sort of already built-in signal conditioning. Nevertheless, and for the sake of one more sensor application example, two water flow sensors based in the Hall effect were used. These sensors have signal conditioning already built-in and produce a square signal whose frequency is proportional to the measured flow rate. The sensor output is an open collector *npn* bipolar transistor, that is easily interfaced to the microcontroller.

The software that students need to produce calculates the instant water flow rate and the accumulated volume of water expelled from the tank. It also allows the detection of the correct pump operation when the pump is switched on.

2.5. Example of a course work developed in this apparatus

In a specific course of our institute, students are required to develop hardware and software to solve the following academic problem (this problem is focused only in tank 1).

It is suggested to the student that this tank (tank 1) is an intermediate buffer tank in some industrial process. Its buffer effect is used to avoid that water (or some other liquid, although this apparatus uses only plain water) is pumped into the public sewage system in improper conditions, for instance, too cold. To achieve this goal, water cannot be pumped out of tank 1 unless its temperature is over some predefined threshold. Simultaneously, a minimum level of water inside the tank must be guaranteed, otherwise the heater elements and the pumps might breakdown due to overheating (by lack of enough heat sink). At the same time the air humidity inside the tank must be kept below some predefined threshold (in order to reduce metal oxidization and the consequent generation of rust). It must be assumed that the water input to the tank may occur randomly.

To accomplish these tasks, students must monitor the water temperature, the air humidity and the water level inside the tank. Then, accordingly to algorithms developed by them, the microcontroller has to actuate the heaters, the fan and/or the water pump in an automatic non supervised fashion. None of the signal conditioning circuits needed to interface the sensors and actuators to the microcontroller is supplied to students, so it's their job to implement them.

3. INTERNET CONNECTIVITY

The experimental apparatus herein described has some sensors duplicated for the purpose of monitoring the apparatus status and display measured data on internet pages (and also for detecting abnormal situations that may trigger alarms intended to force some kind of human intervention). Other sensors are not duplicated because they inherently allow for output signal sharing, which means that both the circuits developed by students and the circuits developed (by the authors) for monitoring can be connected together without interfering with each other.

The displayed data on internet pages is used by students for comparison with their own collected data, e. g. for calibration purposes, and also for long run time analysis, since the data shown in the internet pages is acquired and stored during several hours.

Although the interaction between such an apparatus as the one described here and the internet is nowadays a relatively straightforward task, its implementation still involves a lot of hardware and software that has been developed by the authors in this particular context. Just to illustrate the connectivity path and the servers involved in data migration from the apparatus and the internet, the diagram of figure 11 is presented. In this diagram, the yellow area represents hardware for signal conditioning (developed by the authors) used to interface the sensors (and also some actuators) to the internet pages.

It has been noticed by the authors that the internet connectivity feature of this experimental apparatus is a motivating factor for most students, which is an interesting side effect of this feature that has not been anticipated.

Students must identify themselves (using a username and password) in a web page specially designed to change the apparatus status from standby to fully operational. So, it is possible to parameterize the apparatus settings in a per student basis.

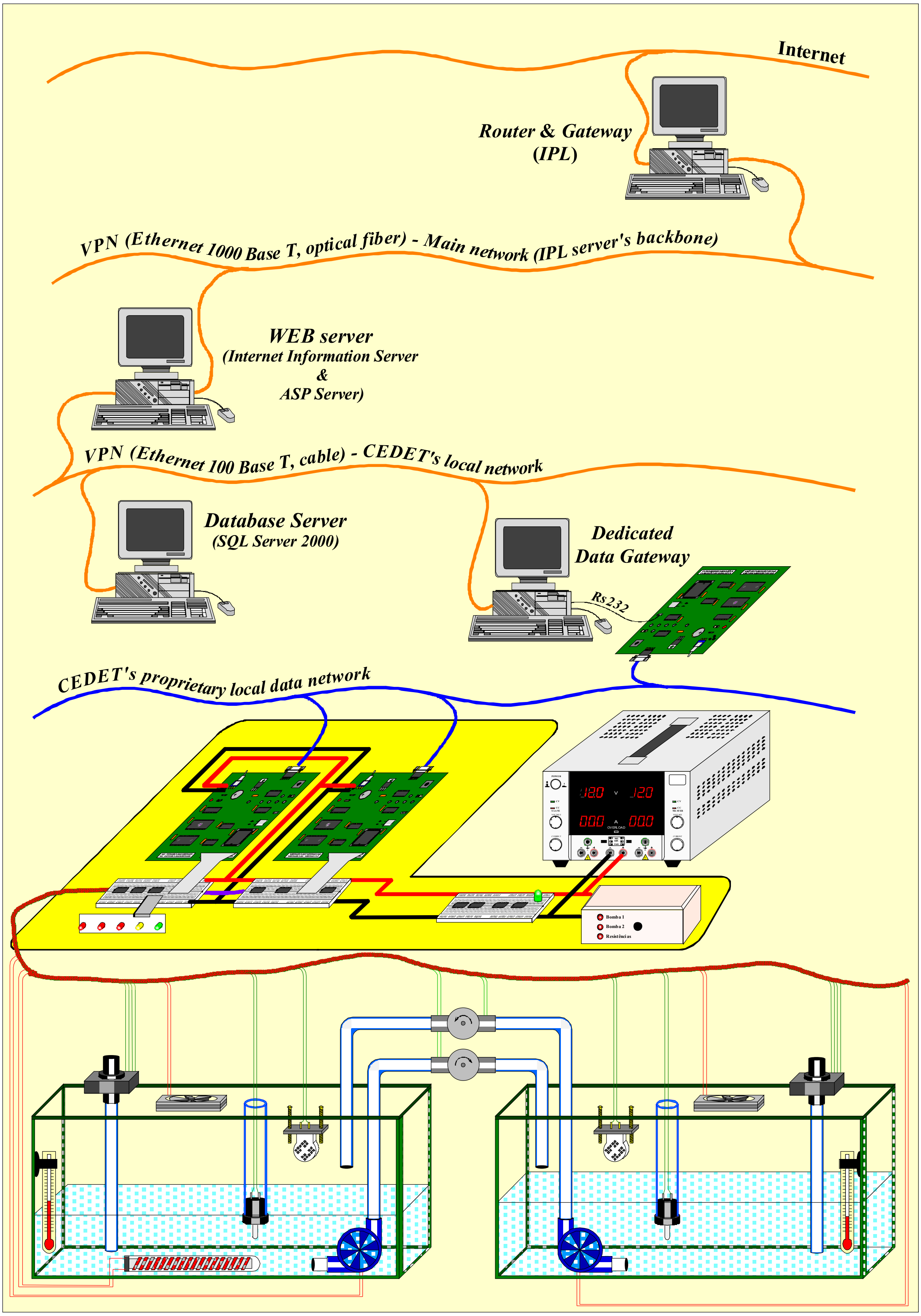

Figure 11 : Internet connectivity diagram.

4. FINAL REMARKS

In this paper an experimental apparatus, with a strong academic nature, was described and some aspects of the resultant pedagogical experience acquired in laboratorial lectures were referred.

Although the focus given in this document is mainly the signal conditioning circuits developed by students in a particular course at our institute, this apparatus may easily be used with other perspectives in mind, namely the testing of control algorithms (applied to this hardware) or the parametric function modeling applied to the included sensors. For instance, in a basic control course the apparatus may be used for simple experiences to illustrate classical control methods like PID controllers or for higher complexity procedures like multivariable control or non linear control methods.

In this academic context, this system's use also intends to promote the ability to recognize the problem(s) to be solved, to correctly state them, and then to solve them by methodological procedures that have been tried and tested, as is often required in an engineering practical application. It encourages an attitude more focused in the problem, and not so much on the individual task, as it is often the case in engineering works: "*As business organizations move from Task-Centered (TCO) to Process-Centered (PCO) Organizations, people work on* ***processes****, not in individual tasks. A* ***process*** *is a complete, end-to-end set of related tasks (or activities) that together create value for a customer*" (see reference [7] for the original article).

Students frequently refer that a great deal of time is needed to work in academic projects that use this apparatus, namely those centred in the conception of the signal conditioning circuits. They often claim that a lot of time is invested out of the regular laboratorial lectures. However, it's the author's opinion that the amount of work done out of the regular laboratorial lectures is of major importance for the students, because this work is developed without the stress or restraints of a time limited class. Being work done without the supervision of a teacher, students tend to be less inhibited, therefore they don't hold back themselves so much and, eventually, will broaden their search for solutions. This search, being wider than it would normally be if a possible answer is at the reach of an arm (just ask your teacher if he/she is standing nearby), occasionally leads to signal conditioning circuits different from the typical standard solution. Furthermore, the presence of a teacher in a class commonly has some kind of inhibitory effect over students, particularly if some type of assessment is implied.

The apparatus is available to students for about 12 hours per day during the week and, although there is only one hardware setup (apparatus), students can easily manage the mutual exclusivity of access by booking time slots in advance through an internet based application.

As a major positive aspect, it is worth mentioning that it is quite rewarding to observe the diversity of solutions attained by students, as opposed to the monotonous off-the-shelf (standard) solutions frequently used in some laboratorial works. Even though there are no direct suggestions during the theoretical classes of the circuits they could use in their work, students are often able to project, study, calculate and test circuits that achieve the proposed goals. It's the author's opinion that the use of such kind of experimental apparatus encourages the exercise of an attitude towards the systems instead of an approach too much biased in the isolated device, which seems to be a more proficient academic stance.

In the Portuguese academic métier this kind of enterprises are far from being frequent, maybe because teachers find it not worthy, bearing in mind the time-consuming characteristic of these activities. As it is common knowledge in our academic scene, "*The amount of effort that the academic staff dedicates to pedagogical activities is relatively small. These activities are much less rewarded then research activities*" [4]. Nevertheless, it's the opinion of the authors that these pedagogical experiences are important in the continuous search for better teaching techniques and results.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Albright, Robert J. and Hoffbeck, Joseph P., "Discovering the Effects of Feedback on Control Systems: Informative and Interesting Numerical Exercises", *IEEE Transactions on Education, 44(2)*, pp. 104-108, 2001.

[**2**] Areny, Ramón Pallás, *Sensores y Acondicionadores de Señal.* 3ª Ed., Marcombo Boixareu Editores, Barcelona, 1998.

[**3**] Eydgahi, Ali M. e Ghavamzadeh, Mohammad, "Complementary Root Locus Revisited", *IEEE Transactions on Education, 44(2),* pp. 137-143, 2001.

[**4**] Pereira, Manuel Seabra, *European Pilot Project for Evaluating Higher Education: An Exchange of Experiences in Engineering Programmes*, Instituto Superior Técnico, Lisboa., 1997.

[**5**] Giron-Sierra, José Maria, "A Simple Device and a Project for the Nonlinear Control Systems Laboratory", *IEEE Transactions on Education, 44(2),* pp. 144-150, 2001.

[**6**] Tandeske, Duane, *Pressure Sensors,* Ed. Marcel Dekker, New York, chapter 5, pp. 77-115, 1991.

[**7**] Teixeira, I. C. e Teixeira, J. P., "Trends on Microelectronics Systems Education", T. J. Mouthaan and C. Salm (eds.), *Microelectronics Education*, pp. 117-120. Kluwer Academic Publishers, Holanda, 1998.