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Integration of Local Industry Theme Examples in Process Control Education: a Case from North-Eastern Quebec*

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A set of realistic applications inspired by local industries were integrated in a process control course at UQAR. The course employs a multidisciplinary approach, integrating notions from various fields of engineering through theme examples such as wastewater treatment, pulp and paper making, and mineral grinding (mining industry). Laboratories involving these processes were realized using a simulation software designed for process control education. A fourth laboratory comprising the use of an industrial programmable controller was also part of the course. Feedback and comparative appreciation from the students is included.

Keywords: control systems; process control education; simulation software; local regional industry

1. Introduction

As the global economy is seen to add uncertainties to the engineering job market, there is an increasing need for people 'with the ability to bridge across several disciplines' [1]. Interdisciplinary education in engineering is more and more emphasized, as the demand grows in the global job market for 'value-added' engineers [2]. Tomorrow's engineering graduates will also need to have an increased familiarity with a wide range of real-world problems and solution methods, which most often imply interdisciplinary knowledge and interaction between specialists from different fields [3–6]. Engineering education is under strong pressure to change to respond to this new reality [3–7]. Students have to learn to stretch out of their 'comfort zone' and experience true multidisciplinary situations as part of their formation. Reports of successful implementation for design courses can be found in [3, 4], and for control systems in [5] where the contents were adapted for electrical and mechanical engineering undergraduate students from distinct departments.

This paper presents a process control course designed for the particular context of UQAR (Université du Québec à Rimouski), where engineering is structured around the electrical and mechanical engineering disciplines in the same department. The first program offered (since 1995) was electromechanical systems engineering. Even back then, the program was forged around interdisciplinary considerations and a vision anticipating the need for a more versatile formation. As engineering at UQAR established its reputation, a demand also grew for the more traditional programs electrical and mechanical engineering. These two programs were offered starting in 2005, preserving interdisciplinary contents (to a certain extent) in the curriculum of these programs.

The course had to be designed without distinction for students in electrical, mechanical or electromechanical engineering, and this was seized as an opportunity to present them with a widest possible range of process control applications, inspired by the local industrial activity in the region. This was also an opportunity to involve notions from chemical engineering and metallurgical engineering disciplines through various process considerations, further enhancing the multidisciplinary formation of our students. Course contents are intended for the third year (second semester) of all our undergraduate curriculums, following two preparative courses to the field: a linear systems analysis course (end of second year) and a general introductory course on feedback control systems (beginning of the third year).

This paper presents the complete set of laboratories used in the course, with particular emphasis on the software laboratories, the subjects that were possible to cover and the innovative formula employed for the two first activities. Examples inspired by a few local (North-Eastern Quebec, more specifically Côte-Nord, Bas Saint-Laurent and Gaspésie regions, a very vast ($\sim$280 000 km^2) and rather sparingly populated ($\sim$396 000 people) territory) most important industrial and economic sectors such as wastewater treatment, pulp and paper, and mining and metallurgical extraction were elaborated to enhance the course contents. It is important to point out at this stage that such subjects could not have been covered as well without the availability of a proper software simulator [8]. One laboratory on a physical system was also included in the course, to balance between the

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advantages of software and more 'hands-on' laboratory activities. General feedback and comparative appreciation from students is then finally presented, followed by the overall conclusions.

2. Organization of the course

The general organization of the course is as follows: the most basic concepts such as the Laplace transform, Z-transform, transfer functions and basic nomenclature on feedback control loops are first reviewed. PID controller tuning and system identification methods are then presented for open-loop stable processes [9] followed by integrating and unstable processes [10]. At this stage, a competitive challenge on the control of an unstable process (in simulation), inspired from the single-stage anaerobic digestion system design, is assigned to the students, as presented in section 2.1.

Then, prior to presenting other control algorithms and since the course is project-oriented, essential notions for the modeling of pipe flow are presented to prepare students for the following case study. Comprehensive models for valves, pumps, tanks, pipes, and closely related equipment are introduced, with particular emphasis on the sizing of valves and pumps as actuators for control. Sensor selection and calibration around common process variables (temperature, level, flow, etc.) are also discussed. Finally, impacts of process design on process control are discussed over a case study from the pulp and paper industry [11]. A simulation set-up of the process is handed out to the students at this point, for experimentation with all of the abovementioned notions.

Advanced process control strategies such as cascade control, feed-forward, internal model control, Smith predictor, etc., are next presented, along with industrial aspects such as anti-reset windup and bumpless transition between the automatic and manual modes. Constraints handling and compensation of nonlinearities are addressed, followed by digital control design and its specific considerations (sampling rate, discretization techniques, stability considerations, etc.). At this point, students are given the opportunity to integrate most of the preceding notions on a physical set-up, comprising the use of an industrial programmable controller, in implementing an advanced cascade control strategy on a DC motor, as detailed in section 2.3.

The last part of the course is on multivariable process control. The characterization of a multivariable process is first addressed: the concepts of directionality and degree of interaction between variables are introduced, defined and discussed, under both static and dynamic considerations. A decentralized control design procedure based on such considerations is then presented, with regards to specification dynamics and pairing selection. Finally, various decoupling methods are presented, along with associated multivariable control techniques. Students then familiarize with the subject using the simulation set-up of a mineral grinding circuit, as detailed in section 2.4.

2.1 Anaerobic digestion (wastewater treatment)

The anaerobic digestion process is used as the last step in wastewater treatment. It has also recently gained in popularity around the globe as the « methanization » process, as a means of producing « biogas » (a mixture of methane and few other gases) from a variety of organic waste. Methane (or CH_4) is highly flammable, and can be used as an energy source either directly as fuel, or indirectly for electricity generation. The anaerobic digestion process for producing methane is considered a renewable energy source, as its use would contribute to reduce mankind's dependence over fossil fuels [12].

Although the end task handed out to the students is the tuning of a simple linear SISO control loop, this setup is used as an opportunity to teach some process notions, give the students a physical background to allow them better reason the system, and introduce the students to this important process.

2.1.1 The Process

The anaerobic digestion part of the methanization process involves two main types of micro-organisms: the *acetogenic* and *methanogenic* bacteria. The acetogenic bacteria are accountable for the breakdown of simple organic matter (organic acids, alcohols, etc.) into acetate and carbon dioxide. In turn, the methanogenic bacteria are necessary for the conversion of acetate or carbon dioxide into methane. The stability of the system is often an issue, since the optimal operation of the system involves a rather fragile equilibrium between bacterial populations that evolve in a competitive environment [13].

2.1.2 Process dynamics

Focusing only on the two main bacterial species aforementioned, their metabolism and growth rate will depend on the same environmental conditions present in the digester. As the optimal conditions for growth differ between the two species, one can easily become favored over the other, thus leading to an exponentially increasing (related to the growth dynamics) disequilibrium between the bacterial populations.

Taking a closer look at the example of pH, a more acid environment favors the growth of the acetogenic bacteria, while less acid might favor the methanogenic bacteria over the acetogenics. The methanogenic bacteria can feed on the acidic compounds produced by the acetogenic bacteria, however too much acid would hamper their growth and thus their ability to metabolize the acid into the desired methane. Once the acetogenic bacteria is to be favored over the other, they would produce more and more acid, further hampering the growth of the methanogenics, etc. This self-accentuating nature is typical of unstable systems.

2.1.3 Simplifications and Linearized Process Model

The previous discussion stated that the process dynamics are unstable in nature. It should then be possible to find an output variable that clearly expresses this behavior. A biomass concentration signal presents this behavior when the overall equivalent growth is positive but not when it is negative (*i.e.* death rate > growth rate).

An important quantity in this process is the balance between the two bacterial populations that is necessary to achieve good process efficiency. A quantitative measure of this ratio or balance must be obtained in order to control the process and thus ensure its efficiency. Fortunately, it is possible to obtain estimates for both cell populations using online data available from the gas composition flow rates [14].

These individual estimates can be combined into an arbitrary output variable representing the population balance. The strict population ratio does not fully render the typical behavior of unstable systems: similar to a single cell concentration signal, it has an asymmetric behavior between the positive and negative equivalent growth rate situations. A combination that would have a symmetric behavior for either condition is the difference of the normalized initial cell concentrations (assuming the system has been manually brought to or close to the optimal set-point), as expressed in equation (1). Note that all the considered biomass concentrations correspond to living cells.

$$y(t) = \frac{X_1(t)}{X_{1\_opt}(0)} - \frac{X_2(t)}{X_{2\_opt}(0)} \qquad (1)$$

Additional assumptions are that the system operates under fed-batch conditions, the feed rate (also acting as a *dilution* rate) is constant in an approximate range that compensates the total biomass growth (*i.e.* the total biomass concentration remains roughly constant), and is of constant composition (although rather unrealistic, this assumption is however necessary to allow the students to dissociate the effects of the control action to the system and the constantly arising disturbances in feed composition).

The considered manipulated variable (or control action) is the addition of base (or acid) to the digester. This addition is considered to be implemented in the influent (feed rate) in order to avoid the occurrence of 'local spots' of highly basic (or acid) pH in the digester. Such a setup however induces a time-delay in the system, due to transportation through pipes. A positive control action corresponds to base addition, while a negative control action corresponds to the addition of acid. The global transfer function between the input and output considered is of the form:

$$G_p(s) = \frac{K_p e^{-\theta s}}{1 - T_1 s} \qquad (2)$$

Which is the general transfer function form for unstable, first-order with time delay systems.

2.1.4 Details of Assignment and Evaluation

The assignment given to the students is not in the 'classic form' of a sequential list of elements to try and to discuss in a report, but instead in the form of an open challenge to all student teams (2–3 students per team). The objective is to develop a control strategy that would obtain the best control performances possible for given fixed transfer function parameters, and remain robust towards quantified variations in those parameters. Weekly guidelines are provided to the students, to help them organize their search: first, they are invited to review and implement a few basic control structures (*e.g.* PID, cascade control, etc.) and evaluate the achievable performances (week # 1). They are then pressed to search through the literature for more advanced or recent control techniques applicable to such systems (weeks # 2 and 3).

Evaluation of the project takes the form of an oral presentation in front of the class (instead of a written report), where students are asked to present their results and explain their system's behavior in different test conditions (set-point change, disturbance rejection, etc.). They also have to revert to physical reasoning of the system in their explanations. This is a good opportunity to practice communicating scientific contents in front of their colleagues, which a required skill for future engineers. The size of the classes (< 20 students) also makes this possible, and this would be almost unthinkable in much larger groups. General comprehension questions (different for each team, following their presentation) are also asked to the students (from both the teaching team and their student colleagues) to gauge their degree of comprehension. For each team presentation, one other team of students (selected at random) is involved in the evaluation process, and this really proved to have a positive impact on student implication.

Results have shown that all student teams were able to realize original control designs as well as demonstrate their ability to analyze and understand often rather complex research papers on control engineering. They also effectively demonstrated their ability to analyze control performances using the recognized standards in the field.

2.2 Pulp consistency regulation (papermaking)

This process is commonly found in different industries where the blending of two process streams is required for a given production. The inspiration for this process here, however, is in the context of the pulp and paper industry: the pulp feeding at the wet end of a paper machine. In this application, the consistency must be tightly regulated in order to produce a paper of good quality, as well as reduce the risks of paper breaks during drying. Paper pulp from a pulp inventory and white water (containing a certain percentage of fibers) are mixed to feed the paper machine at the required feed rate (furnish flow). An introduction to this process, followed by a clever discussion and guidelines for the development of a robust and well-performing basic regulatory system is found in [11]. Since no results were given in the latter, a more complete analysis and a detailed implementation in simulation were developed in [15], which can be seen as a basis for this assignment.

2.2.1 The process and process dynamics

The physical setup of the process is shown in figure 1. Pulp from the inventory and white water (dilution stream) are mixed preceding a variable-speed driven pump, which is used to provide the total furnish flow to the paper machine. This configuration allows a better mixing of the fluids, since it benefits from the turbulence occurring inside the pump head.

The consistency sensor is physically installed after a certain length of pipe, downstream from the pump, following the manufacturer's specifications for accurate measurement and laminar flux considerations.

As detailed in [15], since the variable-speed drive of the pump directly acts on the furnish flow, the control problem for consistency can be seen as a SISO system with the demand as a (measurable) disturbance. This system has a highly nonlinear nature in relation to the furnish flow. From basic model equations [11, 15], it can be derived that the process gain is inversely proportional to the furnish flow. Furthermore, the same result can be obtained for the process dead time, which has even far more devastating consequences on control than the gain. This provides for an interesting setup for the implementation of different control strategies (simple PID control loop, static and dynamic feedforward, IMC control, etc.), as well as nonlinearities compensation strategies (controller gain scheduling, etc.).

2.2.2 Details of assignment and evaluation

Once again in short, teams of 2–3 students are handed out the task of determining the best control strategy for this process, which would maintain stability even following a sudden reduction by a factor of 10 in the furnish flow compared to the initial (nominal) operation point. Such a variation also implies an instantaneous variation by a factor of 10 on both the system gain and dead time in the system transfer function, which is rather extreme for a control loop. So once again the problem is presented as an open challenge for all student teams, to determine the control strategy that would provide the best performances at both operating points (nominal and low furnish flow) under consistency set-point changes and for disturbance rejection for small and large disturbances.

A side objective of the course is to provide the students with the necessary background for sizing actuators, at least for common actuators such as pumps and valves. Students are thus asked, during the first week of the project, to select the right pump

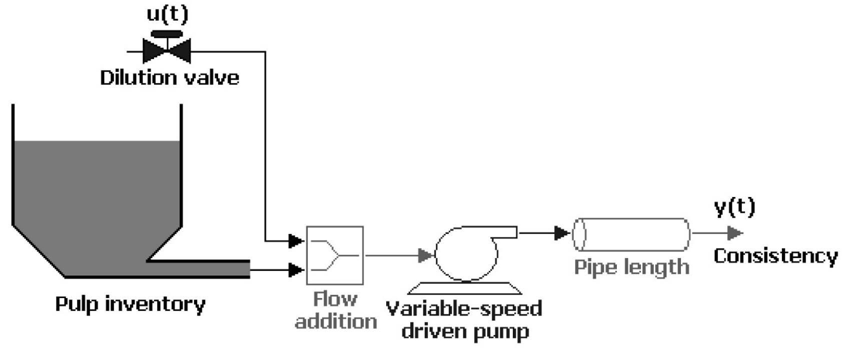

Fig. 1. Physical setup of the mixing process considered.

and valve for the application, given the specifications. Week two is then dedicated to the identification of the relevant transfer functions of the process, and implementation of simple PI control, static and dynamic feedforward control, and combination of the latter.

The limits of these control strategies are then assessed in relation to the admissible decrease in furnish flow. In week 3, students are asked to work on the implementation of a ratio control strategy based on [11], and compare the results with the previous control strategy. Finally, during weeks 4 and 5, the students are pressed to search through the literature and find additional control algorithms that could provide potentially even better performances on this system. They again present their results in front of the class, reverting to physical reasoning about the system whenever appropriate. The quality of their presentation and the appreciation of their work are again evaluated by both the teaching and a random team of colleagues, helping maintain a high level student participation throughout the entire activity. Results once again showed that the students were able to implement original control strategies and demonstrate an ability to analyze and understand complex research papers on control engineering. They also improved their ability to analyze and discuss control performance issues through recognized standards in the field.

2.3 DC motor speed regulation

This system is a common, classical application where the rotational speed of a motor has to be regulated. Many applications however require some precautions to avoid damaging the engine under different possible circumstances. In the case of an electrical motor, the most important variable to monitor to that end is the input current: if careful limitation is set for this variable, damage to the electrical part of the engine can be mainly avoided.

2.3.1 The process and process dynamics

The system used is the LabVolt Power Electronics Training System (model 8032) [16], a flexible, modular, low-power electromechanical system, featuring a variety of motors and power electronics modules. The configuration used for the laboratory consists of two AC-DC thyristor rectifiers for DC motor alimentation, as shown in Fig. 2. The control action for this system is the thyristor firing angle, which allows to modulate the supply voltage to the motor. One sensor is available for each of the variables of interest, being the motor rotation speed (ω) and its input current (i_{dc}), as shown in the figure. These are interfaced with an Allen-Bradley L31 CompactLogix Industrial Programmable Controller [17], equipped with analog input (1769-IF8) and output (1769-OF8V) cards.

Typical responses on the input current following a change in input voltage bear the form of a second-order with stable zero model (equation 3), as the current tends to peak in the transient. This natural behavior of electrical motors often requires special care about the input voltage, such as amplitude limitation. Rotational speed dynamics can be modeled using second-order or first-order transfer func-

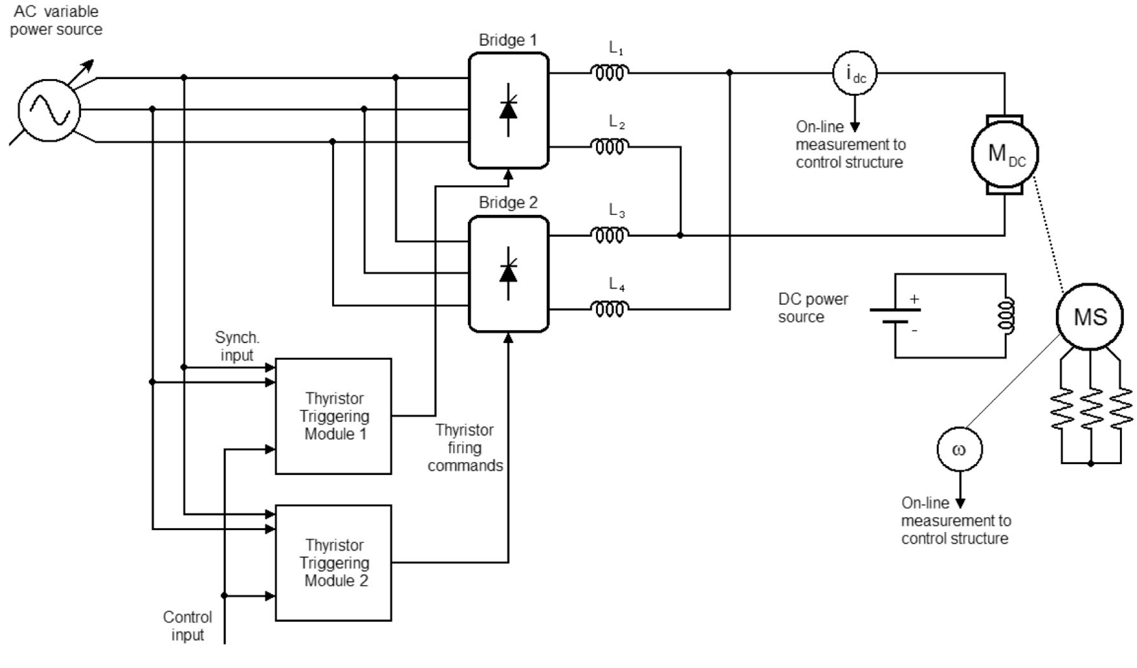

Fig. 2. Physical setup for DC motor speed regulation.

tions, depending on the ratio between the time constants (or inertia and friction coefficient of the load).

$$G_p(s) = \frac{K_p(1 + T_{0s}s)}{(1 + T_1 s)(1 + T_2 s)} \tag{3}$$

Efficient control structures allowing constraint management can be found in [18]. If the process already possesses a cascade form, the necessary control structure can also simply be in cascaded form, as shown in Fig. 3. In this control structure, the anti-reset windup saturation values of the external controller directly correspond to the constraint limits for output $Y_1(s)$, while $Y_2(s)$ is the normally controlled variable. In our case, variable $Y_1(s)$ would represent the input current, while $Y_2(s)$ would represent the rotational speed of the motor. Both controllers $G_{C1}(s)$ and $G_{C2}(s)$ are PID-type controllers.

2.3.2 Details of assignment and evaluation

Teams of 2 to 3 students are assigned the task of controlling the rotational speed of the motor, inside a three to four hours lab session. In this case, we revert to the more classic form of laboratory activity, which implies a series of elements to test and discuss in a lab report. The first task is to implement a simple PID SISO control loop on the rotational speed of the motor by manipulating its input voltage. Students are then asked to observe the control performances obtained, and to look at the time response of the input current. They have to discuss these elements, with an emphasis on the possible consequences of leaving this current unattended in a general control strategy.

The next step is to implement a constrained control strategy, where the input current has to be maintained inside an acceptable range for motor operation (in our case 3 A) and the rotational speed is the variable ultimately controlled. The transfer function between the thyristor firing angle signal U(s) and the input current measurement $Y_1(s)$ has to be first identified. Appropriate controller tuning for $G_{C1}(s)$ has then to be determined based on the identification results. Students then proceed with the identification of the outer loop transfer function, between the input current set point and the actual motor speed. As this dynamic response can be rather slow, students are faced with the challenge of finding a mean of preserving adequate performances for the outer loop (speed regulation) while efficiently respecting the constraints on the input current. They implement their idea and observe the results. These are to be analyzed and further discussed in their lab report.

2.4 Mineral grinding circuit

This process is commonly used in the mineral processing industry as the preparation step for the separation of the valuable mineral from the undesirable gangue material. It aims at reducing the size of the ore particles, so they can be handled by the separation technology appropriate to the mineral of value to be recuperated (*e.g.* flotation). Configurations for this process often include a rod mill for the primary grinding of the coarse mineral and a ball mill for the secondary grinding of the mineral into smaller particle sizes. In some cases, the grinding circuit can include only one mill, while a primary crusher ensures the first action of particle size reduction before supplying the mineral to the conveyor. This latter situation is the considered circuit under study (Fig. 4).

As previously stated, the pre-crushed mineral is fed to the ball mill through a conveyor. Water is also added to the mill to ensure adequate solid concentration for its operation. The ball mill then discharges into a sump box, from which the slurry is pumped to the hydrocyclones for classification. This equipment allows the separation of fine particles from the larger ones, thus redirecting the particles that are ready for the next treatment step towards the appropriate section of the plant. The other particles back to the mill for regrinding. Water addition to the sump box allows to act on the separation efficiency of the hydrocyclones: as the water percentage in the furnished flow to the cyclones grows, so does the separation efficiency [19]. The sump box level is controlled by speed variation on the pump motor.

The choice of controlled and manipulated variables is consistent with the ones found in the industry [20]. The most important variable to con-

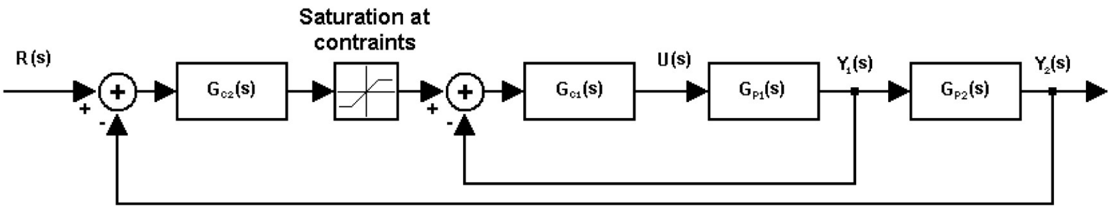

Fig. 3. Cascade control structure for constraints handling.

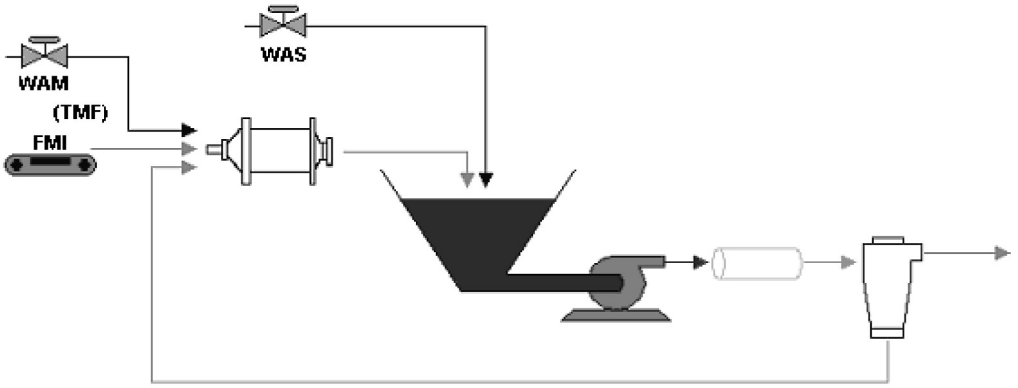

Fig. 4. Configuration considered for the mineral grinding circuit.

trol is the product particle size, to ensure adequate liberation of the valuable mineral from the ore [21]. The other controlled variables are the sump box level, the mill feed ratio and the mill (circulating) load. Water addition to the mill (WAM) is controlled in proportion to the fresh mineral input (FMI) rate via a ratio control structure. The sump box level is directly regulated by variation of the pump motor speed. This leaves two manipulated variables, namely the total (water + mineral) mill feed rate (TMF) and water addition to the sump box (WAS) for the control of the particle product size and mill circulating load. At this point, the design of these two control loops has to account for each other, due to high process interactions [21, 22]. Different multiple input-multiple output (MIMO) control strategies can be considered.

2.4.1 The process and process dynamics

With the two first control loops in place (mill input feed ratio control and sump box level control), the system becomes a two-by-two multivariable process. The control inputs are defined as $U_{WAS}(s)$ for water addition to the sump and $U_{TMF}(s)$ for the total mill feed rate. An example set of transfer functions for each of these inputs on particle size distribution ($G_{PSD}(s)$) and mill circulating load ($G_{MCL}(s)$) is given in Table 1, where the time basis is in units of seconds. Input and output variables are normalized in a 0-100% range prior to the identification. The particle size distribution is measured in percentage passing 200 mesh screens, in an opening range of 70% ± 2%. The mill circulating load is in percentage of 250 t/h, in an operating range of 75% (~185-190 t/h). The dimensions of the mill are a diameter of 3 meters, and length of 4 m (overflow discharge type). The sump box total volume is about 6 m^3, and operates at 3 m^3 (level control at 50%). Input mineral feed is in percentage of 100 t/h (around 60%, thus approx. 60 t/h) and water addition to the sump is in percentage of 120 m^3/h (around 40%, thus approx. 48 m^3/h).

2.4.2 Details of assignment and evaluation

Teams of approximately 2 students are asked to design appropriate control strategies for this (multivariable) process through the following approaches: decentralized control and multivariable decoupling control. They are then asked to implement their strategies in the simulator, and compare their results following different set-point changes and disturbance rejection tests (the main source of disturbance in a grinding circuit being the composition of the mineral feed, with corresponding hardness and particle size distribution of high variability). This is once again a classic laboratory activity with a written lab report for students to hand in. The following paragraphs explain into more detail the work that the students have to realize.

For the decentralized control approach, the process has to be adequately characterized so to mini-

Table 1. Transfer functions identified from the grinding process simulator

	$U_{WAS}(s)$	$U_{TMF}(s)$
$G_{PSD}(s)$	$\frac{0.08\,(925s+1)\,e-200s}{(3575s+1)(26s+1)}$	$\frac{-0.181\,e-200s}{(2650s+1)(280s+1)}$
$G_{MCL}(s)$	$\frac{0.066\,(7300s+1)}{(1285s+1)(160s+1)}$	$\frac{1.225\,(810s+1)}{(1300s+1)(330s+1)}$

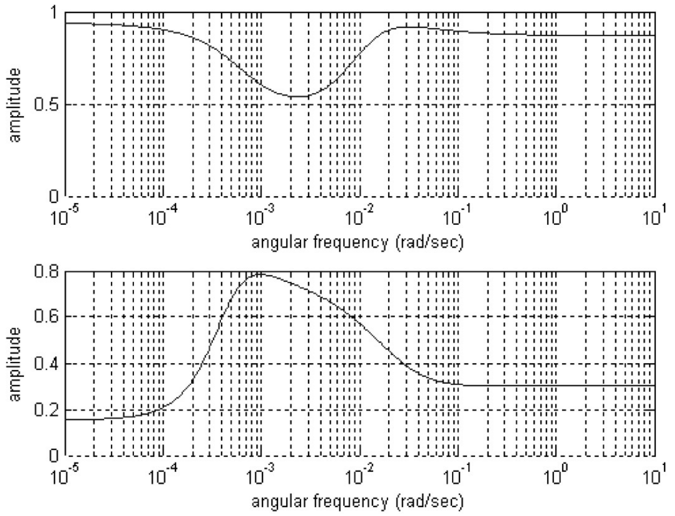

Fig. 5. Generalized dynamic relative gains for direct (above) and inverse pairings.

mize the interactions between control loops. Appropriate input-output pairing and closed-loop dynamic specifications have to be determined. A first tool that can be used is the Bristol's relative gain array (RGA), which is however based solely on the steady-state transfer function information [23]. The idea is a comparison of the open-loop static gain (K_{BO}) with the closed-loop static gain (K_{BF}) in the presence of the second controller. As the ratio of these two quantities approaches unity, the less process interactions there should be. However, since the dynamic interactions are not taken into account, this limits the extent of the measure. Nevertheless, Bristol's method of relative gains remains useful to *proscribe* certain choices of input-output pairings: indeed, for pairing situations where the relative gain is *negative*, the open-loop gain differs *in sign* from the closed-loop gain, which may render the situation unstable whether the second loop is turned off, or even in the case of simple multivariable operation [23]. Calculation of these relative gains and verification of their signs should always be the first step towards the final choice of input-output control pairing.

A generalized idea of Bristol's relative gains has been developed to include the process dynamics [24]. The "generalized dynamic relative gain" follows the same idea that the closer to unity, the less interactions there should be. The x-axis frequency represents the closed-loop dynamics specification (inverse of the time constant). It is thus possible, using this tool, to relate the closed-loop dynamics to the degree of interactions present in the system. A wise choice would be to select the pairing for which the relative gain is closer to unity within realistic specifications, *i.e.* in the frequencies in relative proximity to the inverse of the average dominant time constants of the multivariable system. Fig. 5 shows sample results for this tool using the transfer functions from Table 1. It has to be reemphasized that this tool does not provide information as to the sign of the gains: static relative gains (Bristol) should always be considered prior to the use of this tool.

Other tools for characterization of the multivariable system are also used (singular value decomposition, generalized step response, etc.). The student teams have to develop their decentralized control algorithm based and structured on information obtained from these different sources.

Multivariable (decoupling) control is also an objective of the laboratory. Students are asked to implement a simplified decoupling control strategy [25] and compare the results with the previously implemented decentralized strategy. The decoupling structure is the same as the process, with transfer functions as indicated in Fig. 6. With this decoupling structure, the transfer functions seen by the controllers are the same as in decentralized control, given in expression (4). This allows the use of the same controllers as calculated before, and thus to compare the performances of the two control algorithms on a fair basis.

$$
\begin{aligned}
G_1(s) &= G_{11}(s) - \frac{G_{12}(s)\,G_{21}(s)}{G_{22}(s)} \\
G_2(s) &= G_{22}(s) - \frac{G_{12}(s)\,G_{21}(s)}{G_{11}(s)}
\end{aligned}
\tag{4}
$$

3. Student feed-back

This course was given on a yearly basis and student feedback data was collected for three years (2008, 2009 and 2010). A simple questionnaire was elabo-

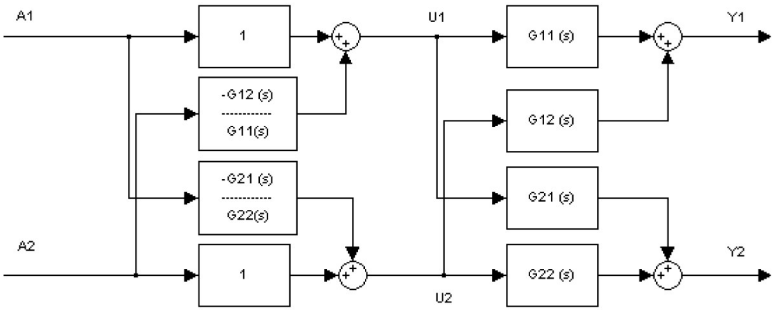

Fig. 6. Simplified decoupling structure.

rated to gauge student preferences, satisfaction on the use of the software tools, and general appreciation of the course contents. Each question allowed space for comments or justifications. Table 2 summarizes the student answers on the questionnaire throughout the years 2008 to 2010.

Since year 2008 was the first time the course was dispended, and where the questionnaire was first elaborated, some adjustments were in order for the following years. Among others, it was afterwards specified to circle only one answer at Q1, and two options were added for Q3 being to slightly reduce the number of processes, or to slightly augment this number. Results not adding up to 100% are due to some student invalid responses (year 2008 only).

Normal student attendance for the course is between 15 and 20 students. However, year 2010 low attendance (8) is due to a change in program course planning from year # 3 to year # 4. This has for effect that only the students that had to graduate this year took the course. However, this planning will be further modified in the following years to go back to year # 3.

A first tendency that we can notice from the results is that the most popular laboratory activity, year after year, remains the physical system with the industrial programmable controller (for between 40% to 50% of students). However, this also tells us that at least half of the students still preferred one of the software laboratories, which is an interesting result. We also notice some variability in the answers from year to year, which could be attributed to the specific interests of the individual students present. Despite the general preference for the hands-on physical system, about 90% of students still appreciated the simulation laboratories the first year, and 100% the two following years. This could be attributed to the laboratories not being fully proofed the first year, and that Matlab had not been previously introduced to the students at that time (2008). However, this is a very high satisfaction level, repeatedly attained for the last two years, once those two aspects were correctly addressed. The last thing reported in the results is that a majority (60% to 77%) of students feel the variety of processes is adequate for the course, and gives a very good span

Table 2. Questionnaire and answers from students throughout the years

	Year 2008	**Year 2009**	**Year 2010**
Student attendance:	**17**	**15**	**8**
Individual student weight (%):	**5.88%**	**6.67%**	**12.50%**
Q1. Which of the following laboratories did you prefer?			
(*a*) Wastewater treatment	(*a*) 23.53%	(*a*) 20.00%	(*a*) 25.00%
(*b*) Pulp and paper	(*b*) 0.00%	(*b*) 26.67%	(*b*) 25.00%
(*c*) Electrical motor (physical system)	(*c*) 47.06%	(*c*) 40.00%	(*c*) 50.00%
(*d*) Mineral grinding process	(*d*) 11.76%	(*d*) 13.33%	(*d*) 0.00%
Q2. Did you appreciate the use of the software in the context of the course, considering it has allowed us to address specific processes that could not have been done otherwise?			
(*a*) Yes.	(*a*) 88.24%	(*a*) 100.00%	(*a*) 100.00%
(*b*) No.	(*b*) 11.76%	(*b*) 0.00%	(*b*) 0.00%
Q3. Looking back at the course from now, do you consider:			
(*a*) Process variety should be kept as it is.	(*a*) 76.59%	(*a*) 60.00%	(*a*) 75.00%
(*b*) Process variety should be diminished a bit*.	(*b*) 0.00%	(*b*) 26.67%	(*b*) 0.00%
(*c*) Process variety should be augmented a bit*.	(*c*) 0.00%	(*c*) 0.00%	(*c*) 12.25%
(*d*) We should choose only one process and study it fully throughout the session.	(*d*) 17.65%	(*d*) 13.33%	(*d*) 12.25%

* This option for an answer was not available in the 2008 questionnaire.

of the application possibilities of the control engineering discipline. Students were invited to comment their experience, and most of them felt the simulator approach was very interesting, as it helped them to focus on the control itself rather than physical system operation constraints. International students felt the course was a very interesting opportunity to be introduced to local (North-Eastern America) most important industries.

4. Conclusions

This paper presented the use of a simulation software inside a control engineering course at UQAR, and some of the possibilities (subjects) it allowed us to cover. Examples from wastewater treatment, pulp and paper and mining and metallurgical industries were covered through use of software laboratories. It was emphasized that without the use of such software, such subjects could not have been insisted upon. The laboratory activities developed towards such a goal were described into a certain level of detail, and feedback from students was provided, over three years of usage in class. It was shown that while the laboratory with the physical system was the most popular, more than half of the students still repeatedly preferred either one of the other software laboratories, depending on personal interests. Over the last two years, all (100%) students however confirmed they well appreciated the software laboratories in the course, and were happy about the variety of subjects it allowed us to cover. Overall results showed a high level of student implication and interest throughout the activities, and helped them develop their skills on communicating scientific knowledge orally to colleagues, in addition to the more classic approach of written reports. The open challenges proved an effective mean for students to develop their autonomy on control systems design.

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