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AUTOMATION OF OPEN-LOOP AND CLOSED-LOOP EXPERIMENTS

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Abstract. The recent interests in artificial intelligence and expert control have motivated the exploration of heuristics used by expert human operators and designers. Such heuristics are the outcome of numerous open-loop and closed-loop experiments. To do these experiments, defining adequate instrumentation and a deep knowledge of control algorithms and tuning techniques are needed. This work presents two tools, ESOL (Excitation of a System in Open Loop) and ESCL (Excitation of a System in Closed Loop), which integrate commercial software (MATLAB and LABTECH NOTEBOOK) and our own experience, with a common objective: to offer a high degree of automation in the open-loop and closed-loop experiments to the user. Both tools have mainly educational purposes but, because of their strong practical accents, they can be very useful in industry.

Keywords. Educational aids; laboratory techniques; PID control; process control; software tools.

INTRODUCTION

Open-loop experiments are good sources to obtain knowledge about the process. An experiment of this type (see Fig. 1) consists of recording and analyzing the process output as response to a specific input. Starting from a steady-state and selecting the adequate input it is possible to know if the process is stable or unstable, if it is of minimum or non-minimum phase , if it is linear or nonlinear, etc... When the step response is monotone, the process can be approximated by a first order model and there are simple techniques to estimate its parameters. To do these experiments a special training and the following basic instrumentation are needed: a low frequencies signal generator, a power supply and a register or oscilloscope.

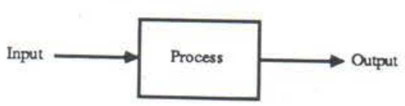


Fig. 1. Open-loop experiment.

Close-loop experiments are good sources to obtain knowledge about the system. An experiment of this type (see Fig. 2) consists of recording and analyzing the process output as response to set-point or load changes. Starting from a steady-state and selecting the adequate change it is possible to know if the system is stable or unstable, if the controller and its parameters are adequate, if it is possible to control the system with a fixed-parameters controller or it is necessary to use an adaptive control strategy, etc... To do these experiments a special training, an industrial regulator and the same basic instrumentation are needed.

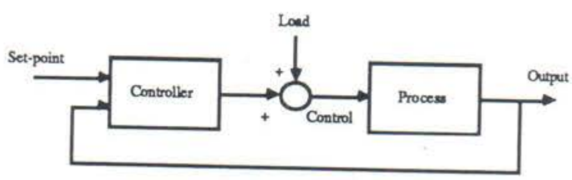


Fig. 2. Closed-loop experiment.

Several commercial industrial regulators are available, which include automatic open-loop and closed-loop experiments based in the works of Aström and Hägglund (1984), Hoopes and co-workers (1983), Kraus and Myron (1984). In these cases: a) The joint (plant+sensors+actuators) is generally stable in open-loop, of minimum phase, with step monotone response, linear in some operation conditions, with saturations and dead zones in actuators and/or sensors. b) The PID controller is normally used. c) The design specifications are normally taken on the transient response.

When a computer with data adquisition boards is available in the laboratory (see Fig. 3) it can replace the register, the oscilloscope and the regulator. It is also possible to do the most habitual tasks in open and closed loop. All this can be done if specific programs for each task are developed or commercial software for data adquisition, control and simulation are used. LABTECH NOTEBOOK from Laboratory Technologies Corporation is a powerful tool for adquisition, processing and displaying data in real time. MATLAB from the MatWorks Inc., is a popular and powerful tool for the study, design and simulation of control systems.

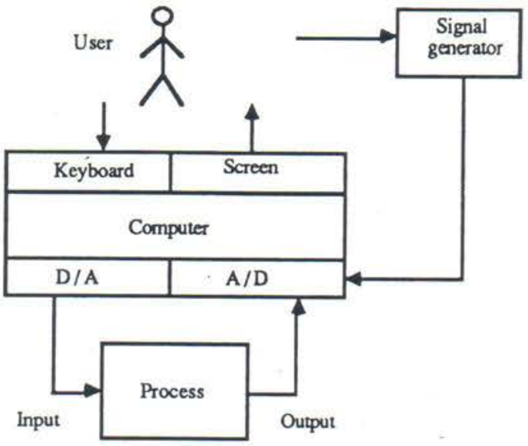


Fig. 3. Process control laboratory by computer.

This work presents the two tools, ESOL and ESCL, developed in our Department, with a common objective: to offer a high degree of automation in the open-loop and closed-loop experiments to the user. Both tools integrate the power of MATLAB and NOTEBOOK and the experience accumulated by us in the last years.

EXCITATION OF A SYSTEM IN OPEN LOOP

The ESOL tool executes or orders, to NOTEBOOK or other programs in MATLAB, the following tasks: defining the excitation, recording a signal, driving the process to a steady-state, exciting the process, analyzing the process response, estimating parameters of a process model, simulating the process response. The execution is automatic, the user only participates in choosing of the task and selecting the possible options during its execution. Each task can be executed independently, because the link with other tasks is carried out through data files by defect or generated the last time that the tool was used. So, the user can continue experiments from previous days in an easy way.

Defining the excitation

The excitation, that will be sent to the process input, can be recorded and stored in a data file or can be necessary to generate it. In both cases the user gives the name of the file, where the excitation is stored or where the excitation will be stored. In the second case the user can choose between non periodic (step, pulse, multiple step) or periodic (square, triangular, sinusoidal) excitation and must fill up the parameters (amplitude, sign and pulse wide or period) that determine it (see Fig. 4).

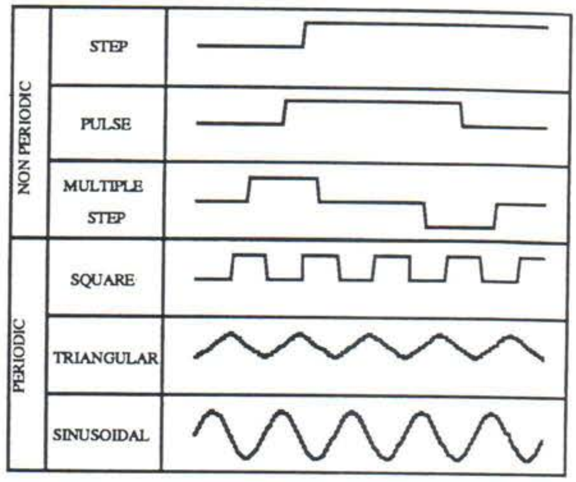


Fig. 4. Types of excitations.

Recording a signal

With this menu option the user can record an analogic signal (externally generated by a signal generator or a power supply) in a data file, for a certain time (in seconds) and a determined frequency. The signal recorded can be used as excitation of the process later, so the user can have a battery of trial signals for any process.

Driving the process to a steady-state

To know the process response to a determined input is necessary to start from a steady-state, so the output evolution responds effectively to the input chosen and does not contain influences of previous experiments. The user can decide between exciting the process from the actual steady-state or driving the process to a new steady-state. A menu option is available for this, the user gives the value for the input process and the approximated time which the process will need to reach the new state. This period of time is very important: it must be long enough to allow the process to reach the steady-state but not too long, because the process could reach the steady-state very soon and the waste of time would be excessive. During this task the input and the output of the process are displayed on the computer screen. If the search of the steady-state has not pleased the user, or the steady-state has not been validated, the user can repeat the experiment with the same or different input.

Exciting the process

The excitation, added to the input value causing the process steady-state, is sent to the process for the period of time and to the frequency, previously defined . This task includes displaying in real time and storing in a data file of the input and the output of the process.

Analyzing the process response

The analysis of a process response has to be different if the input includes sudden changes, ramp changes or sinusoidal changes. For example if the input has sudden changes (step, pulse, multiple step or square wave) is possible to: characterize the process (stability, phase, linearity) and its response (monotone, oscillatory). With an input including ramp changes (triangular wave) it is possible to characterize the process (linearity, saturation, dead-zone). With several sinusoidal inputs it is possible to characterize the process (frequency response).

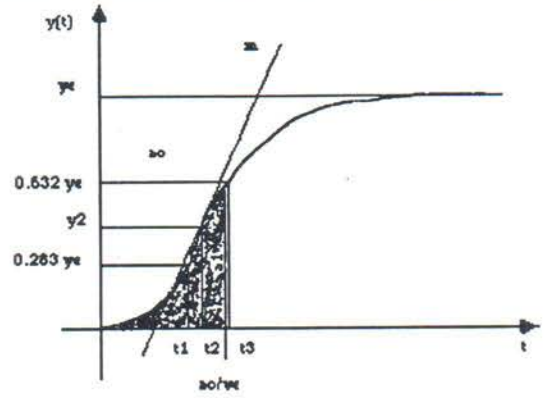


Fig. 5. Typical step response of industrial processes.

The automatic analysis of the process response, offered to the user by ESOL, is limited to excitations which have been internally generated and including only sudden changes. Before the analysis, the user can request a smoothing of the process output. The analysis is made by section, manually or automatically selected, with as many sections as sudden changes are included in the excitation. As a result of the analysis, see Fig. 5, the following values are shown numerically and graphically to the user and stored in a data file:

- y_e , the final steady-state with reference to the initial steady-state
- t_1 , the time when the process output reaches at 28.3% of the final steady-state
- m , the maximum value of the derivative
- t_2 , the time when the maximum value of the derivative happened
- y_2 , the output value in t_2
- t_3 , the time when the process output reaches at 63.2% of the final steady-state
- a_0 , the area bounded by the response and the final steady-state
- a_1 , the partial area bounded by the response and the initial steady-state

Most of these values are conditioned to the existence of the steady-state and to the process output which was monotone.

Estimating parameters

The graphic estimation, that ESOL offers to the user, allows to estimate the three parameters (K, steady-state gain, T_p, time constant, and T_o , dead time) of a first order process model. K is set equal to the ye value determined in the analysis of the process response, for T_p and T_o the user can choose between the four approximations, Morilla and co-workers (1989), shown in the table 1 . The estimation can give so much models as sections analyzed, however the process model, that will be used for the open loop simulation and for the controller tuning, must be unique and it is obtained as the average of the different parameters. Though the process response has been monotone, if ESOL detects some incongruity in the data supplied by the analysis, it will inform the user about the impossibility of doing the estimation.

TABLE 1 Four approximations for the time constant and the dead time

Parameter	Fit 1	Fit 2	Fit 3	Fit 4
T_p	$\frac{y_e}{m}$	$t_3 - T_o$	$\frac{3}{2}(t_3 - t_1)$	$a_1 \frac{e}{y_e}$
T_o	$t_2 - \frac{y_2}{m}$	$t_2 - \frac{y_2}{m}$	$t_3 - T_p$	$\frac{a_0}{y_e} - T_p$

Simulating the process

As well as the model parameters, the results of an estimation can be completed with the presentation of the process response and the model process response to the same input. In this menu option, the user obtains a graphic comparison of these responses and the integrals of the error (iae, ise and itae). With this information the user can decide if the approximation chosen is good enough or if another one is needed.

EXCITATION OF A SYSTEM IN CLOSED LOOP

The ESCL tool executes or orders, at the user's request, the following tasks: defining the excitation, recording a signal, driving the process to a steady-state, configuring the controller, setting the controller parameters, controlling the process, analyzing the system response, simulating the system response. As in ESOL, the execution is automatic and each task can be executed independently.

Defining the excitation

The excitation that will be sent to the system, can affect the set-point and/or the load. The user must be choose between set-point excitation, load excitation or simultaneous excitation. After that, the definition of each signal is similar to the definition of the excitation in ESOL.

Recording a signal

This task is identical to recording a signal in the open loop experiment. What is more, any signal recorded by ESOL can be used in ESCL and vice versa.

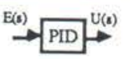
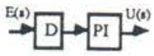
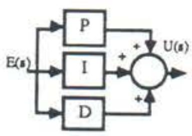
Driving the process to a steady-state

With this option the user can open the loop and drive the process to a steady-state before starting a control experiment. Using two external buttons the user can increase or decrease the control signal (process input) while he is watching the process output in the computer screen. In this way, ESCL emulates the manual mode of the industrial regulators.

Configuring the controller

The PID controller is the controller more used in industrial regulators, nevertheless it is frequent to find different versions of the control algorithm and different structures (processing of the set-point), Morilla (1990a). This menu option covers the lot of possibilities that the industrial regulators offer, the user can choose the type (P, PI, PD, PID), the algorithm (non-interacting, interacting, parallel), see table 2, and the structure (PI, I-P, PD, P-D, PID, PI-D, I-PD), see table 3.

TABLE 2 Three algorithms of PID control

Algorithm	Block diagram	Transfer function
Non interacting		$K_p \left(1+\frac{1}{T_I s}+\frac{T_D s}{1+\beta T_D s}\right)$
Interacting		$K_p \left(1+\frac{1}{T_I s}\right)\left(\frac{1+T_D s}{1+\beta T_D s}\right)$
Parallel		$K_p+\frac{1}{T_I s}+\frac{1+T_D s}{1+\beta T_D s}$

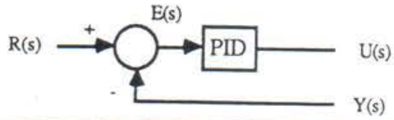
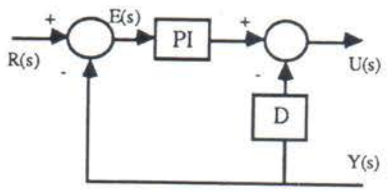
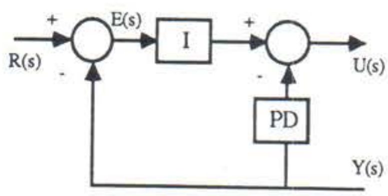
Setting the controller parameters

After configuring the controller, it is necessary to set its parameters. These parameters will remain fixed during the control experiment. The user can chooses between manual or calculated parameters. In the first case, the user must fill up the parameters (K_P, proportional gain, T_I, integral time, T_D derivative time, β the noise filtering constant). In the second case, the user choose the tuning criterion (a quarter decay ratio, minimum iae, minimum ise, minimum itae) and the tuning change (set-point or load change). With this information and the model estimated in the open loop experiment, tuning formulas, described in Morilla (1990b), are applied. The parameters (K_P, T_I, T_D) calculated and β=0.1 (when it is necessary) are showed to the user and stored in a data file.

Controlling the process

The system is set in closed loop and it is controlled for the period of time and to the frequency previously defined. The process control includes: the excitation of the system with the set-point and the load, the calculation of the control signal, displaying set-point, load, control signal and process output in real time and the storing the last two in a data file.

TABLE 3 Structures of PID control

PID	
PI-D	
I-PD	

Analyzing the system response

As in ESOL: a) The automatic analysis of the system response is limited to excitations which have been internally generated and including only sudden changes. b) The user can request a smoothing of the process output. c) The analysis is made by section, with as many sections as sudden changes.

The analysis is slightly different if the selected section includes a set-point or a load change. As a result of the analysis (see Fig. 6) the following values are shown numerically, some of them also graphically, to the user and stored in a data file:

y_i, the initial steady-state
y_e, the final steady-state
t_s, the settling time
iae, the integrated absolute error
ise, the integrated squared error
itae, the integrated absolute error multiplied by time
t_d, the delay time
t_r, the rise time
m_p, the maximum overshoot
t_p, the peak time
to, the pseudoperiod of oscillation
dmp, the damping, defined as $(e_3-e_2)/(e_1-e_2)$
ovr, the overshoot, defined as $-e_2/e_1$
b/a, the decay ratio

Some of these values are conditioned to the existence of the final steady-state, others to being the response oscillatory and the peaks could be measured, and others to the response being caused by a set-point change.

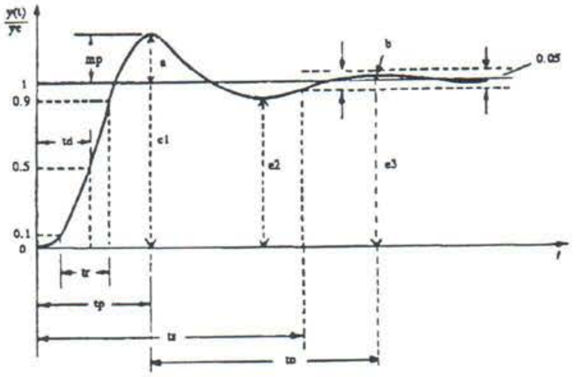


Fig. 6. System response to a set-point change.

Simulating the system response

The process model, estimated in open loop, can be used to calculate the controller parameters. It can also be linked with the controller to obtain a model of the closed loop system. The user can simulate the system response with this model. Looking or analyzing the simulated response, the user can test the controller parameters.

GENERAL CHARACTERISTICS OF BOTH TOOLS

The following equipment is required to use these tools: a) A IBM-AT computer or compatible, with math coprocessor. b) A signal generator or a power supply, only when external signals have to be recorded. c) A board with at least two analog inputs (that will be connected to the process output and to generator) and one output (that will be connected to the process input). ESCL also needs to the board have two digital inputs (that will be connected to the two external buttons). Nowadays DAS-16 or DAS-8 and DAC-02 Metrabyte´s boards can be used. d) The LABTECH NOTEBOOK (version 5.0) software. e) The MATLAB (version 3.5) software with the Control toolbox.

A great number of modules and the main programs (ESOL and ESCL) have been developed in TURBO PASCAL (version 5.0). In particular the modules for: a) File management, movement through directories and the execution of NOTEBOOK or MATLAB programs. b) The generation of internal signals. c) The updating of the SETUP (joint of data files) of NOTEBOOK. Through these files NOTEBOOK receives the information necessary for sending, adquisition, displaying and storing, according to the task selected by the user. d) Dialog with the user.

Another big part of the software has been developed in MATLAB, for example the programs or functions for: signal smoothing, steady-state analyzing, open and closed loop response analyzing, graphic estimation, tuning PID parameters, simulation system with PID control.

CONCLUSIONS

The Ball and Hoop equipment by TecQuipment has been used as testing process during the development of ESOL and ESCL. The multiple experiments carried out have shown the utility of these tools, because: the interaction with the process and the controller is made easier; capacities of the conventional instrumentation for the generation, presentation and recording of signals in real time, are assumed; the repetition of open and closed loop experiments (with the same or a different process, in the same or different conditions of excitation) is facilitated; they show, graphically and numerically, some characteristics of the process or the system response which could be used in open-loop to know the process, and in closed-loop to check if the design specifications are verified; the sampled signals are stored in files that could be used for parametric estimation of a process or a system model and for the controller tuning or autotuning; they allow the emulation of the manual and automatic mode of industrial regulators and specific experiments of some of them, classified as adaptive or expert regulators; they can be used for increasing the heuristic knowledge about characterization of the process dynamic, process control, PID tuning and autotuning, which is very important in the development of expert control systems.

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