

AN ASSIGNMENT TO TEACH CLOSED-LOOP SYSTEM IDENTIFICATION

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Abstract: In this paper a simulation assignment, which was developed to teach both undergraduate and postgraduate students at the University of Pretoria some of the main issues regarding closed-loop system identification, is discussed. A motivation for closed-loop system identification and a simulation assignment in this field is given. Then the simulation assignment is outlined, each step discussed, and the assignment is evaluated.
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1. INTRODUCTION

Closed-loop identification refers to the process in which plant models are identified using data collected from closed-loop experiments, where the underlying process is fully or partly under feedback control (Ljung, 1999).

It is sometimes necessary to perform identification experiments in closed-loop. The reason may be that the plant is unstable, or that it has to be controlled for production, economic, or safety reasons, or that it contains inherent feedback mechanisms (Ljung, 1999).

In the past identification in closed-loop was considered difficult, but it is now considered a very feasible approach that offers a number of practical advantages (Landau, 2001):

- validation of the designed controller and on-site re-tuning,
- obtaining better models for controller design,
- controller maintenance,
- iterative identification in closed-loop and controller redesign, and
- controller order reduction.

According to Landau (2001), identification in closed-loop appears in practice to be one of the most convenient methods to provide good design models.

The problem of identifying systems operating in closed-loop, is one that has generated significant interest in the identification literature (Forssell, 1999). The problem offers many possibilities and also some difficulties, and a wide variety of

approaches have been suggested, many quite recently.

An astonishing fact is that industrial control engineers do not use most of the identification techniques developed over the last 30 years, although there is an urgent need for efficient and effective identification methods in control engineering (Zhu, 1998).

In the light of these facts, it is considered a good idea to give students an overview of closed-loop system identification. This could encourage the students, who will later work as industrial control engineers, to make use of the closed-loop system identification approaches.

Computer-based simulation is considered to be important and is increasingly used for education (Kheir, *et. al.*, 1996). Thus, it was decided to design a simulation assignment that educates students in closed-loop system identification. For the proposed simulation assignment the ABET criteria, EC-2000, desired outcomes were identified as (a), (b), (e) and (k) (Besterfield-Sacre, *et. al.*, 2000). These outcomes are discussed in the evaluation section of the paper.

The measurement and control group at the University of Pretoria has undergraduate as well as postgraduate control courses with process identification components (Braae, *et. al.*, 1996). The proposed simulation assignment is aimed at the postgraduate course, Control Practice (Craig, 1999), and the SISO component of the assignment at the undergraduate final-year course on automation.

2. BASIC OUTLINE OF THE SIMULATION ASSIGNMENT

2.1 System Identification Steps

System identification deals with the construction of models from data. According to Forssell (1999) the system identification problem can be divided into a number of subproblems:

- experiment design,
- data collection,
- model structure selection,
- model estimation, and
- model validation.

These steps are also applicable in closed-loop identification. Closed-loop identification results when the identification experiment is performed with the output being fed back to the input by means of some feedback mechanism, as in figure 1 (Forssell, 1999).

Most of the standard open-loop estimation methods fail when applied directly to closed-loop data. The main reason for this is the correlation between the input and the additive output noise, which models all disturbances in the system. A method that does work is the prediction error method.

Thus the above-mentioned steps will be followed in the closed-loop simulation assignment, but with very specific model estimation methods.

2.2 Closed-loop Model Estimation Methods

Forssell (1999) focused on analyzing and devising prediction error methods for closed-loop identification. Ljung (1999) also states that a prediction error method will consistently estimate a system if the data is informative and the model set contains the true system, irrespective if the data have been collected under feedback or not.

Different ways for avoiding the problems associated with closed-loop identification were studied, which lead to a characterization of the possible approaches into three categories: the direct, the indirect and the joint input-output approaches (Ljung, 1999). All these approaches are based on the prediction error method. The first two approaches are used, analyzed and compared for the simulation assignment:

The Direct Approach: In this approach the basic prediction error method is applied in a straightforward manner. The output, y , of the process

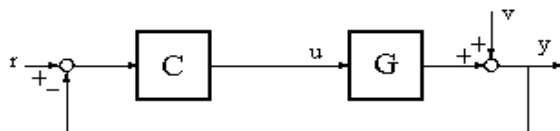


Fig. 1. A closed-loop system.

and the input, u , are used in the same way as for open-loop operation, ignoring any possible feedback, and not using the reference signal, r , to estimate the model.

The Indirect Approach: The closed-loop system is identified from reference input, r , to output, y . From this identified closed-loop system the open-loop system (plant) is retrieved making use of the known controller.

2.3 Models to be Estimated

A few different models are used and their results are compared in this simulation assignment. First two SISO models in closed-loop are identified in order to explain the basic concept. Then a MIMO model in closed-loop is identified. These models are described in Goodwin, *et. al.* (2001), a textbook that is used in some of the control courses at the University of Pretoria. The models thus link this simulation with the relevant work studied by the students in the textbook.

SISO 1: The system is shown in figure 2. A PID controller, synthesized using the pole allocation method for a closed-loop polynomial, $(s^2+4s+9)(s+4)^2$, controls the plant.

SISO 2: Figure 3 shows the feedback system. The PID controller is such that the system is stable with complementary sensitivity as in equation (1).

$$T_0(s) = \frac{4}{(s+2)^2} \quad (1)$$

MIMO 1: This system, shown in figure 4, is a controlled distillation column. A decentralized controller, consisting of two PI controllers, controls the distillation column. The theory of this system together with an interactive simulation is given on the website associated with the textbook of Goodwin, *et. al.* (2001). This system is good for educational purposes since it provide a connection between abstract control theory and the real world by giving an indication of how the theory can be applied (Kheir, *et. al.*, 1996)

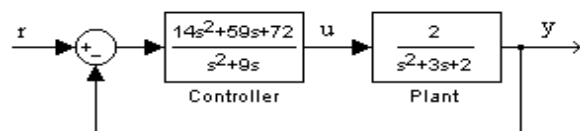


Fig. 2. SISO 1 system.

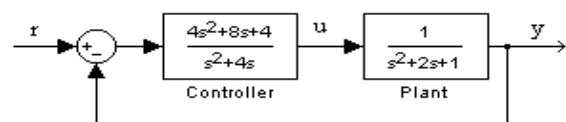


Fig. 3. SISO 2 system.

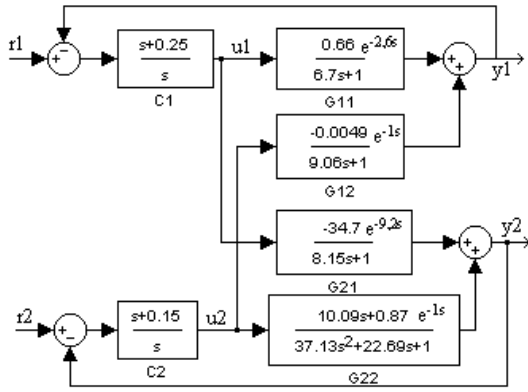


Fig. 4. MIMO 1 system.

2.4 Background knowledge

To complete the assignment successfully, knowledge of the following is necessary:

- dynamic SISO and MIMO (postgraduate) systems,
- dynamic compensation, PID and decentralized control (postgraduate),
- MATLAB, including Simulink, and
- basic system identification theory.

3. IMPLEMENTATION OF THE SIMULATION

3.1 The Steps

The following steps are applicable to each of the three systems (SISO 1, SISO 2 and MIMO 1):

Step 1: Simulate the open-loop system.

Step 2: Design experiment(s) and collect the necessary data for open-loop system identification.

Step 3: Select a model structure and estimate the plant model from the open-loop data.

Step 4: Simulate the closed-loop system.

Step 5: Design experiment(s) and collect the necessary data for both the direct and indirect method of closed-loop system identification.

Step 6: Estimate the model using the direct closed-loop system identification method.

Step 7: Validate the obtained model by comparing it to the model obtained from the open-loop data.

Step 8: Estimate the model using the indirect closed-loop system identification method and validate.

Step 9: Compare the different closed-loop system identification methods and also the results for the different systems.

3.2 Implementation of the Steps

For this simulation assignment, students are guided through all the steps for the SISO 1 model in the classroom and the outcome is discussed. They are then asked to repeat the steps for the SISO 2 and the MIMO 1 models on their own.

It will now be explained how each of the specific steps was implemented.

Step 1: According to Kheir, *et. al.* (1996), Simulink is a powerful interactive workbench for dynamic system simulation. Simulink was therefore used to build block diagrams of the three systems (without controllers and feedback) in order to simulate the open-loop systems. A signal generator (or two generators in the MIMO case) drove the input of each system and the output of each system was observed using a scope.

Step 2: The “To Workspace” blocks, which write their input to the MATLAB workspace, were used to collect the data sets for identification. In the open-loop case each data set contained the input to a plant, u ($u1$ and $u2$ in the MIMO case) and the output from a plant, y ($y1$ and $y2$ in the MIMO case).

For each of the SISO experiments the input was stepped after 1 second and the sampling interval was 0.1s. These data were used for identification. Another signal, e.g. a sinusoid, was also used as input and this input together with the output was used as validation data.

For the MIMO experiment, $u1$ was first stepped whilst $u2$ was kept constant, and the effect of this change on $y1$ and $y2$ were measured. Then $u2$ was stepped with $u1$ constant. The two loops interact, but with one of the inputs constant each output is influenced by only one scalar transfer function at a time.

Step 3: The graphical user interface (GUI) of the system identification toolbox in MATLAB was used for identification (see the user’s guide (Ljung, 1995) for an in-depth explanation of the GUI):

- the data sets were imported into the GUI,
- the data sets were examined to determine the time-delays,
- the data sets were preprocessed by detrending the data so that the offset parameters were not fit (no other preprocessing was necessary),
- an ARX model structure was used to estimate the models, since the prediction error method is the only method that works with direct closed-loop system identification and it is easier to compare models of the same structure,
- the order of each model was already known, since the number of poles and zeros were known for each model and thus it was not necessary to estimate many models to find the best fit. This will not be the case in the real world.

- in the MIMO case $u1$ and $y1$ (with $u2$ constant) were used to estimate $G11$, $u1$ and $y2$ (with $u2$ constant) were used to estimate $G12$, etc, and
- the validation data were used for validation by comparing the simulated outputs from the estimated models with the true outputs and by determining the models' residuals.

Step 4: In this step the controllers and feedback were added to the Simulink models to simulate the closed-loop systems.

Step 5: The same input for each system was used as in the open-loop case with the difference that the input was applied at r ($r1$ and $r2$ in the MIMO case). The data collected for each system were the set point input to the system, r ($r1$ and $r2$), the input to the plant, u ($u1$ and $u2$), and the output, y ($y1$ and $y2$).

Step 6: The direct system identification method works exactly like the open-loop system identification method. In this case the prediction error method has to be used and thus the ARX model was used. The procedure was the same as in step 3 with u ($u1$ and $u2$) being the input in each data set and y ($y1$ and $y2$) being the output in each data set.

Step 7: Comparing the closed-loop identified models with the open-loop identified models validated these models. The validation was done in the LTI Viewer of MATLAB by comparing the frequency response (bode and sigma plots), the transient response (step and impulse response), the pole-and-zero plots and the Nyquist plots.

The models were compared with the open-loop identified models and not the models used in the simulation, because in the real world the open-loop identified model is all that is available for comparison.

Step 8: The following steps were followed in the indirect system identification:

- a model, $T(s)$ ($T(s)$ in the MIMO case), of each closed-loop system was needed and thus the entire closed-loop system was seen as an open-loop system and estimated as in step 3, with the input equal to r ($r1$ and $r2$) and the output equal to y ($y1$ and $y2$),
- the obtained models were converted to continuous time assuming a zero order hold on the inputs,
- the models were then converted to symbolic format,
- for the indirect case the controller models are required. It was therefore assumed that the controllers were known and they were also converted to symbolic format,
- the controllers, $K(s)$, were then symbolically "subtracted" from the identified closed-loop models, $T(s)$, by using matrix algebra and equation (2), to obtain the plant models, $G(s)$, in symbolic format,

$$G(s) = -T(s) * (K(s) * T(s) - K(s))^{-1} \quad (2)$$

- the plant models were then converted back to transfer function format, and
- the transient response of each identified plant was compared with that of the open-loop plant models.

Step 9: For the same input, the error in the output of each closed-loop identified model was determined by subtracting this output from the output of the open-loop identified model. The sums of the squared errors of the three direct identified models were compared. These sums for the different indirect and direct identified models were also compared.

4. OUTCOME OF THE SIMULATION

4.1 SISO 1

Direct Method: The direct method obtained a very good model for the plant. The open-loop identified plant model is compared with the closed-loop direct identified plant model in figures 5, 6, and 7. These figures show that the closed-loop identified model is very similar to the open-loop identified plant model, although there is a small steady-state-error as can be seen in figure 5.

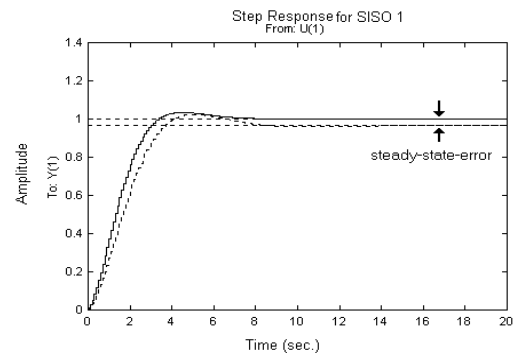


Fig. 5. The step response of the plant model in the SISO 1 system identified with the direct closed-loop method (dotted line) and the open-loop method (solid line).

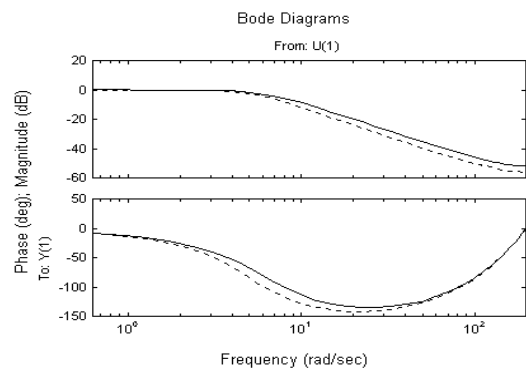


Fig. 6. The bode plot of the plant model in the SISO 1 system identified with the direct closed-loop method (dotted line) and the open-loop method (solid line).

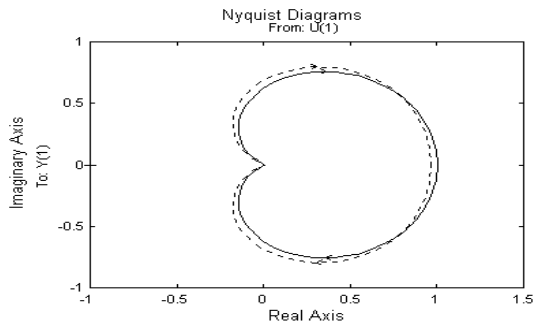


Fig. 7. The Nyquist plot of the plant model in the SISO 1 system identified with the direct closed-loop method (dotted) and the open-loop method.

All the other validation plots (impulse, sigma, pole-and-zero and Nyquist) showed very good agreement between the models.

The reason for the steady state-error is as follows: The data used for identification should be informative enough (Ljung, 1999). The information matrix for the estimated parameters depends only on the input-spectrum. In the case of the closed-loop experiment this would be the spectrum of u and not of r . According to equation 3, u depends on $S_{uo}(s)$, the nominal control sensitivity, and r (Goodwin, *et. al.*, 2001),

$$u(s) = S_{uo}(s)r(s) = \frac{T(s)}{G(s)}r(s) \quad (3)$$

For this system, u is an impulse when r is a step. For the steady state to be estimated, low frequency data is needed, but the impulse is not a low frequency signal and thus a steady-state-error result.

The residual analysis of the closed-loop data shows correlation between the error and the input, u , for negative lags. This is an indication that output feedback is present (Ljung, 1995).

Indirect Method: Comparing the step response of the indirect identified model, in figure 8, with the step response of the open-loop identified model, in figure 5, one can see that this model does not estimate the plant. This is because the closed-loop identified model, $T(s)$, is not accurate enough and the error in $T(s)$ is transported into $G(s)$.

The indirect method does however work when the true closed-loop model, determined mathematically from the simulated plant and controller models, is used. Thus, the success of the

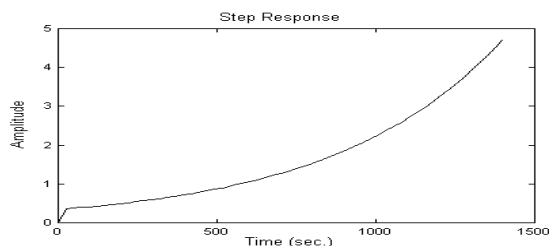


Fig.8. The step response of the indirect identified model of SISO 1.

indirect method depends on the accuracy of the identified closed-loop model, $T(s)$.

The obtained result illustrates to the students the difficulty in using this method.

4.2 SISO 2

The results of this system are very similar to those obtained for SISO 1, although the steady-state-error is a little bit worse in this case. This system will give the students additional experience in closed-loop system identification.

4.3 MIMO 1

The impulse, bode, Nyquist, sigma and pole-zero plots for the open-loop and direct closed-loop identified models showed satisfactory agreement. The only plot that did not show such good agreement was the step response. It showed that the direct identified models, $G11$, $G12$, $G21$ and $G22$, produce steady-state-errors. For $G11$ and $G22$ the offsets are small (20%), but for $G12$ and $G22$ the offsets are much bigger. The reason is, as before, that the input signals to the plant, $u1$ and $u2$, are not informative enough in regard to the low frequencies. Students are encouraged in this assignment to experiment with different reference signals, $r1$ and $r2$, to obtain better steady-state models.

Again the indirect method does not deliver good results, which confirms the difficulty of the method.

4.4 Comparison

The results indicate that the direct method of identification provides much better models than the indirect method. Ljung (1999) further states that the indirect method is not ideal for a non-linear controller and the controller has to be known as well. The direct method, however, only works when the input to the plant can be measured. Thus it seems that when the input to the plant can be measured, the direct method would be best.

5. EVALUATION OF THE SIMULATION ASSIGNMENT

5.1 Quality Requirements

According to Kheir, *et. al.* (1996) a good laboratory experiment should:

- demonstrate important theoretical ideas,
- reflect important real-life problems,
- give visual sensation,
- have a suitable timescale,
- be nonhazardous,
- be inexpensive, and
- be easy to understand and use.

The simulation assignment just outlined complies with all these requirements:

Theoretical Ideas: It demonstrates the following important ideas: modeling of a system (the distillation column), MIMO systems, PID control (for SISO systems) and decentralized PI control (for the distillation column), experiment design (for the identification experiments), simulation (in Simulink), and open-loop and closed-loop (direct and indirect) system identification.

Real-life Problem: The background information as in the introduction shows the importance of closed-loop system identification in the real world. The controlled distillation column gives an indication of how the theory can be applied in the real world.

Visual Sensation: The simulation in Simulink helps to visualize the identification process: One can see where to measure the output and supply the input and how the systems react to different inputs. One can also see how the feedback controllers influence the output of the systems and how the two loops of the MIMO system interact. With the GUI and LTI Viewer it is easy to visually verify and compare models.

Suitable Timescale: It will take about one hour for the lecturer to thoroughly explain and demonstrate how to identify and validate the SISO 1 system in MATLAB making use of the GUI, LTI Viewer and Simulink. It will then take the student about one hour to prepare (read through the assignment) for the simulation and a maximum of two hours (with knowledge of MATLAB) to do the simulation assignment. This is a suitable timescale.

Nonhazardous: Since the assignment is only a simulation, it is definitely safe.

Inexpensive: No equipment is needed and for educational purposes, MATLAB can be used at the university.

Easy to Understand and Use: The toolboxes used in MATLAB are user-friendly and with a good outline and demonstration of all the steps for the SISO 1 system, the students will be able to do and understand the assignment.

5.2 The ABET EC-2000 Outcomes

The desired outcomes of the simulation assignment is as follows (Besterfield-Sacre, *et. al.*, 2000):

- an ability to apply knowledge of system identification methods (a),
- an ability to design and conduct experiments, as well as to analyze and interpret data (b),
- an ability to identify, formulate and solve engineering problems (plant identification) (e), and

- an ability to use engineering tools (MATLAB) necessary for engineering practice (k).

6. CONCLUSION

This simulation assignment provides a good overview of closed-loop system identification. The simulation is good for a first acquaintance with closed-loop identification, since it removes many of the problems encountered in the real world, such as measurement noise, and enables the students to focus on the main issues. The aim is only to make students aware of the possibilities and difficulties.

A succeeding laboratory experiment is proposed in which a real plant is identified in closed-loop, since it is also important that students deal with measurement noise, friction, saturation, etc. (Kheir, *et. al.*, 1996).

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