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ADVANCED CONTROL COURSE TEACHING USING SOCCER-PLAYING ROBOTS

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Abstract: This paper presents our experience in integrated advanced control teaching with a final year undergraduate course taught by the authors in recent years at the University of Girona in Spain. The experimental framework consists of two main components: the soccer-playing robots and computer vision and control systems. By practicing in the Laboratory of Intelligent Systems, the students will achieve to consolidate, integrate and compare various learned advanced control techniques and thus will be able to select an appropriate technique for a real problem. Copyright © 2002 IFAC

Keywords: Control education, mobile robots, identification, Kalman filter, predictive control, robust control.

1. INTRODUCTION

A successful integrated lecture course and laboratory teaching of engineering students is an important way of both exemplifying sound engineering principles presented in formal lecture material as well as giving them opportunities to integrate and compare the different learned techniques about the "real life" practicalities not covered in the lecture. Advanced control teaching is no exception to this process. In general, the analysis and design of multi-input multi-output (MIMO) advanced control systems with parametric uncertainties, dynamic cross-coupling effects between inputs and outputs, sensing noises, actuator dynamics, external perturbations and nonlinearities is usually more problematic than those of single-input single-output (SISO) classical control systems. This is in part engendered by the perceived jump in mathematical sophistication required of students, the uneasy fit with prior learned classical control material and the lack of an appropriate framework to do experimental practices in order to make the students to consolidate the theoretic knowledge learned from the lecture course and to see what are the advantages and drawbacks of the each advanced control technique. The successful laboratory sessions should be organized in such a way that the students not only learn about the specific problems and techniques discussed but also acquire attitudes to know which technique is adequate for solving a real problem, what are the effectiveness and limitation of a given method, how can a method be combined with or complemented by another one, etc. Here, it arises a number of pedagogical issues, such as: i) the need of a framework that will characterize *a priori* the salient characteristics of the system in a transparent manner. ii) The same framework should suggest to the intending students the simplest and most economic control strategy possible. iii) If a control strategy is already in place, the framework should readily provide information as to whether and why the particular control strategy is appropriate or not and so on.

In this paper, we show our experience with the integrated advanced control teaching of a final year undergraduate course taught by the authors in recent years at the University of Girona in Spain. In order to give the students appropriate engineering training on their capability of solving a real problem by using the learned advanced control techniques we provide them an experimental framework that consists of the following main components: soccer-playing robots, ball, computer vision systems and remote computer control systems. By doing practices in the Laboratory of Intelligent Systems, the students will achieve to consolidate, integrate and compare different advanced control methodologies learned from the lecture course and thus will be able to select an appropriate technique or to combine various techniques for the solution of a real problem.

2. MOTIVATION

The motivation to find an appropriate framework for advanced control course teaching is largely attributed to the desire in modernizing the engineering students' perception of the subjects and their capacity in the integration and comparison of different advanced control techniques in order to find an adequate solution for a real problem. Some factors motivate a redefinition of the undergraduate course, such as: changes in the profile of students, new employment prospects, rapid advance in the computer and information technology, laboratory modernization, etc. Today's students expect to use the computer as a tool to understand the conceptual issues in any subject as well as to facilitate analysis and design of a controlled process. In the prospect of attracting students, a modernization of both the lecture course and the supporting laboratory is essential.

As a complementary part of the lecture course teaching, we consider that the soccer-playing robots based experimental framework as an ideal platform for the purpose of laboratory practices. Since soccer playing is a well-known and attractive problem to students, the robots can create enthusiasm among the students of present and future generations and the laboratory experience can stimulate their interest and participation in the lecture course. Every day, more students are involved in the world of gadgets and are more habituated to operate things through Internet A soccer-playing robot is constituted by mechanical systems, sensors, actuators and intelligent systems, etc. The construction of a good robot needs a successful collective collaboration of computer programmers, specialists in micromechanics and technicians specialized in electronics. The use of robots in the technical teaching will reinforce the multi-disciplinal work and permit the exchange of knowledge between all participated students. By working with a robot, a student will face a complex real system and has to solve a problem from a more critical point, to planning different experiments and to adopt an efficient solution to the problem. Also, it permits the students to take conscience in evaluating globally the quality of the solution by taking into account other aspects like the limited available resources (time, materials and money).

From the technical point of view, although the actuator's dynamics of the soccer-playing robots can be ignored due to the small size of two micro DC electric motors used, the experimental framework of soccer-playing robots nonetheless displays many of dynamic features to be found in all mobile robots. In general, the control of soccer-playing robots presents some difficulties due to the noises and time delays existed in the position sensing of the soccer-playing robots in the playing field via computer vision, irregular contact between the robots and the playing surface, dynamic cross-coupling between the inputs and outputs, variation of the gains of the process due to the change of the battery level, non-identical dynamic features for different soccer-playing robots, etc. Thus, the experimental framework will permit us to plan various laboratory practices related to the advanced control methodologies.

3. EXPERIMENTAL FRAMEWORK

The experimental framework consists of two main components: the soccer-playing robots and computer vision and control systems.

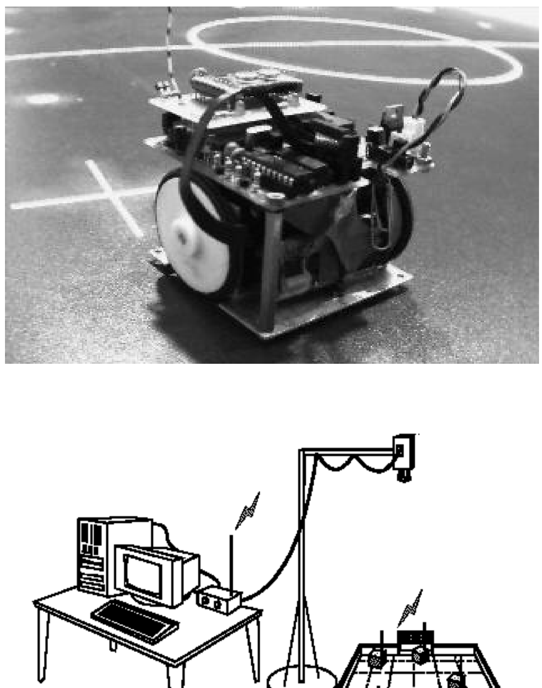

Fig. 1. Soccer-playing robot and supervisor system

The positions of the soccer-playing robots and the ball are detected by the computer vision system through a camera situated at 2m high above the playing surface. The soccer-playing robot also has its local measurement components: two photo-electronic sensors and two encoders on the axes of micro DC motors. The supervisor system, a PC with a radio transmitter connected to its output port, sends wefts to the soccer-playing robot in an autonomous way. A receiver integrated in the robot catches the wefts and then transform them into compatible signals by the micro controllers. The speed regulation of the DC motors is done by two PWMs in the micro controller. The maximal moving speed of a soccer-playing robot is about 80cm/s. Actually, there exist two soccer playing fields in the Laboratory of Intelligent Systems and each one is of a reduced size of a Ping-Pong table. There are also 10 personal computers that permit 20 students to do the experiment simultaneously.

4. COURSE DESIGN

Advanced Control is an elective course given to the students of specialty in Industrial (Electrical and Mechanical) Engineering in the final academic year. The students have acquired previously basic knowledge on the analysis and design of continuous-time and discrete-time classical control systems from two obligatory lecture courses: “Automatic Regulation” and “Industrial Automation”.

The objective of the course “Advanced Control” is to give the students an extension of the application field of automatic control to a wide class of industrial processes in which some “real” and “non-ideal” features should be taken into account during the analysis and design of control systems. For example, the state feedback control strategy might fail to work if a limited number of sensors are used, the practical results might be very different from those of computer simulation if the measurement noises and actuator’s dynamics had not been considered in the modeling and design of controlled processes, the degradation of control performance might occur due to the existence of parametric uncertainties and unmodelled high frequency dynamics, etc. In general, the solution to the above problems requires the use of some advanced control techniques. Due to the limited lecture hours, we can just make a “concentrated” selection of some typical and representative advanced control methodologies among an extensive source of successful teaching and research results. Finally, we include in our teaching program the following topics of advanced control: stochastic identification, Kalman filter, predictive control and robust control. In this way, the students will try to learn about how to find an adequate solution for a real process in which the parametric uncertainties, external perturbation, measurement noises, actuator’s dynamics, dynamic cross coupling between inputs and outputs and nonlinearities are involved.

The course is organized in an integrated educational way: sequential lecture teaching and concurrent laboratory practice. Concretely, the sequential lecture teaching will try to let the students to acquire the indispensable theoretical and technical disciplinary knowledge of the advanced control whilst the concurrent laboratory practices based on the proposed experimental framework of soccer-plying robots will give the students appropriate engineering training such that they can achieve to consolidate their knowledge and find an adequate solution for a real problem by making the integration and comparison of the different advanced control techniques.

The course is developed during a semester in an alternative manner of three hours twice-weekly for the lecture teaching and laboratory practices. Finally, feedback of the course is made at the end of the semester through a “modernized” exam (not on the paper), in which the students can use their familiarized advanced control techniques and computer software (MATLAB/SIMULINK) to solve a simulated real problem by computer.

5. INTEGRATED TEACHING APPROACH USING SOCCER-PLAYING ROBOTS

By keeping in mind that the course is given to the engineering students, the lecture course teaching will take a technical orientation towards the real problems existed in various controlled processes, the basic concepts and suitable methodologies for the solution of those problems, the usage of computer software in the analysis and design of control systems, the advantages and drawbacks of each advanced control technique, etc. Moreover, we will skip over the sophisticated mathematical developments and demonstrations by just providing some useful reference material to intending students for consulting the ignored details. In this way, we try to make the students being able to achieve a quick learning on the subjects of the process modeling, state observation, parameter estimation, system analysis, performance evaluation, controller design, numerical simulation and practical implementation. As a complementary part to the lecture teaching, we use the experimental framework with soccer-playing robots in the Laboratory of Intelligent Systems of the University of Girona in Spain to let the students to get a direct contact with a real problem and to consolidate their acquired knowledge on the advanced control. Instead of doing isolated exercises with one problem for each subject, the fact of being able to do various practices with a common experimental framework will give the students a great opportunity to make an integrated and comparative study on the advantages and drawbacks of the different advanced control techniques. Now, we describe in some detail our teaching experience with the topics covered in the course.

5.1. Stochastic Identification

Before seeking to control a system, it is very important to first characterize its dynamical behavior. In general, the system dynamics can be identified in parametric form (time response) or non-parametric form (frequency response). Although the later approach is usually sufficient to the advanced control strategy like the robust control, the former parametric approach is employed here to further the exposition of other advanced control methodologies like the predictive control.

In the lecture course, the students have concentrated themselves in a comprehensive and practical identification methodology such as the Least Square approach. Since the noisy environment can be generally considered as "white", an ARX model is usually used for modeling the real processes. We have presented the recursive algorithm of parameter estimation with forgetting factor, in which the sampling time should be properly chosen for capturing all the essential dynamics of the process. We have shown them the usage of the System Identification Toolbox for MATLAB (including the graphical library). The importance of designing adequately experimental excitation signals, in general, Pseudo Random Binary Signal (PRBS), has been emphasized to the students to guarantee the identifiability of the system.

In the Laboratory of Intelligent Systems, the students have tried to identify the dynamics of a soccer-playing robot with help of some script M-files in MATLAB codes developed by themselves and the graphical library of the System Identification Toolbox for MATLAB. Concretely, they are asked to obtain the models for linear velocity and angular velocity of the robot. In order to use the recursive algorithms of Least Square parameter estimation, they have studied the physical constitution of a soccer-playing robot to get an intuitive knowledge about order of the mathematical model for soccer-playing robots. As the first contact with the experimental framework, the students found immediately that the real environment is more complicated than expected in theory, for example, the measured data is greatly contaminated by the noise existed in computer vision as can be seen in the following figure. As consequence, it cannot be used directly in the recursive algorithm of Least Square parameter estimation.

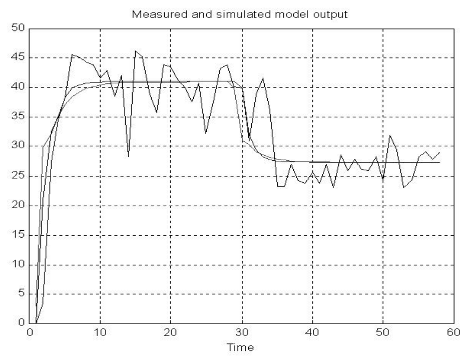

Fig.3. Dynamics of measured linear velocity

Soon, the students found a solution to it by making an arithmetic smoothing of the acquired data. Different experiments have been done by changing the reference velocities between 20cm/s and 50cm/s through the commands created by LabWindows. In this way, the students learned that the time constants and the gain of the model could not be kept in constants. In order to get a profound knowledge to usefulness of the least square identification algorithm in the identification of the robot model (a second order ARX model), the students have developed themselves off-line and recursive Matlab codes and then have compared the obtained results with those using the Matlab graphical library *Ident*. The coincidence of the results premises their confidence on the acquired advanced control theory. Finally, the students have got some experience with the influence of the excitation signal on the results of the identifiability of the system parameters. The students have seen that the identification algorithm might become singular when some non-persistent excitation signals were applied, concretely, when the robot goes straight with constant velocity. In this way, they have verified the theoretic counterpart. More experiments have been done by the students to observe the complex behavior exhibited by the soccer-playing robots in response to various reference signals (straight movement and rotation) of different magnitudes, such as the phenomena of variable gains under different operation conditions (one practical solution is to use different mathematical model for the corresponding velocity range to enhance the precision of the model), nonlinearities like time delay and saturation, asymmetric dynamics between the two wheels of the robots, etc.

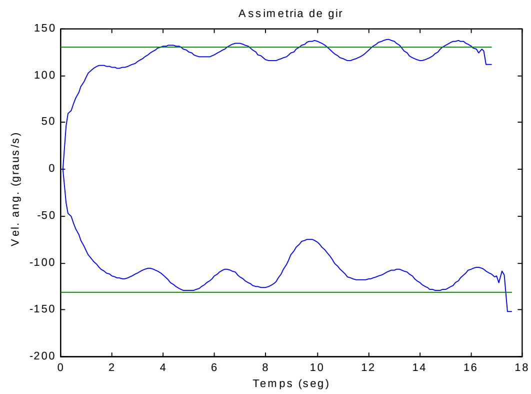

Fig. 4. Asymmetric dynamics between two wheels

5.2. Kalman filter

Excellent dynamic performance can be achieved usually by using a state feedback controller. In practice, full state information is rarely available due to the economic reason (limited number of sensors are installed) and the technical reason (some state variables are not physically interpretable). In this case, an observer can be used for reconstructing the unobservable states. However, if there exist significant noises in the sensor, the measurement data becomes "contaminated". In order to obtain the "true" measurement data, the state observer should be capable of working in the noisy environment. The well known Kalman filter (an optimal stochastic observer) will play an important role to solve this problem.

We start the lecture course by giving the students a brief review about the basic concept and practical significance of the observability and detectability of a controlled process. We present to the students the complete order, reduced order and optimal observers to provide them different manners for estimating the state variables when the system dynamics are deterministic and the parametric value is known. The separation principle that guarantees the simultaneous design of the estimated states based feedback controller and the state observer is also addressed. On the basis of different observer strategies, we take the students to a real world where the measured outputs and the applied control signals are contaminated by the noises. In this case, we present the students the technique of the Kalman filter that can be used to make the optimal state estimation of stochastic control systems. A brief description of the technique of Extended Kalman Filter is also given to the students in order to extend their knowledge to the nonlinear processes through some simple linearization of the system dynamics.

In order to verify the effectiveness of the Kalman filter, we made first an exhibition of the successful application of Kalman filter to another key piece of the proposed experimental framework: the "football" of the size of a tennis ball. The precise detection of the position of the ball in the playing field and the successful prediction of the moving trajectory of the ball in the near future instants are of high interest to the soccer-playing robots to make the best decision in order to win the soccer match. The students have observed the excellent results obtained. Then, the students have done some experiments in the Laboratory of Intelligent Systems with the soccer-playing robot. Based on the mathematical model obtained in the practice of stochastic identification, the students have learned first to evaluate the noise levels, then to use them in the solution of the algebraic Riccati equation and finally to obtain the optimal gain of Kalman filter. The students have applied the designed Kalman filter to the position detection of the soccer-playing robots with straight movements in the playing field by using the computer vision and have observed a wonderful improvement of the precision, e.g., the vibration of the imagine of the robots in the playing field is almost suppressed by using the Kalman filter in position sensing. Another interesting experience gained by the students is the prediction of the future movements of the robots by using Kalman filter. They have observed that the Kalman filter can predict successfully the moving trajectory of the robots in next instants by comparing the real and predicted trajectories on the screen of the computer.

5.3. Predictive control

As one of the practical and effective advanced control techniques, predictive control has been successfully applied to many industrial processes. It consists of calculating the control action that will make the predicted output equal to a conveniently selected desired output. The basic and extended strategies of predictive control imply the direct application of this principle in a single-step or multi-steps prediction, respectively.

In the lecture course, we have introduced to the students a simple manner for designing a predictive controller. We try to let them learn about which predictive model is suitable for controller design, how to generate a desired output trajectory based on the given reference signals, what is the reasonable prediction horizon for the prediction, etc, such that the closed-loop predictive control system is able to guide the process output to the setpoint in the desired way: rapidly, without overshoots and moreover, compatible with a bounded and smooth control action.

In the Laboratory of Intelligent Systems, the students have made some experiments on predictive control with the soccer-playing robots. The problem consists of: starting from the initial position (orientation should also be considered) the soccer-playing robot should reach the pre-assigned final position within the given time and, at the same time, the control action is of a reasonable level accepted by two micro DC motors. First, the students have tried to find an adequate manner to generate the desired output trajectory in order that the rapid system dynamics is achieved by a smooth control action. Here, the desired reference trajectory is not generated simply by choosing an asymptotic stable second order model but by using the path planning method. In this way, the generated trajectory can provide the correct orientation of the movements of the soccer-playing robots and thus achieve a rapid and smooth dynamics. Then, as a simple way, the students have taken the mathematical model obtained from the practice of stochastic identification as the predictive model for computing the predictive control law. Finally, the students have implemented the designed predictive control law on the PC to transmit the control signal by radio to the soccer-playing robot to be controlled and fed back the movements of the robot to the PC using computer vision. From a screen generated by the LabWindows codes on the PC, the students have observed the simulated and real trajectories of the controlled soccer-playing robot and found that in general the deviation between the two trajectories was small.

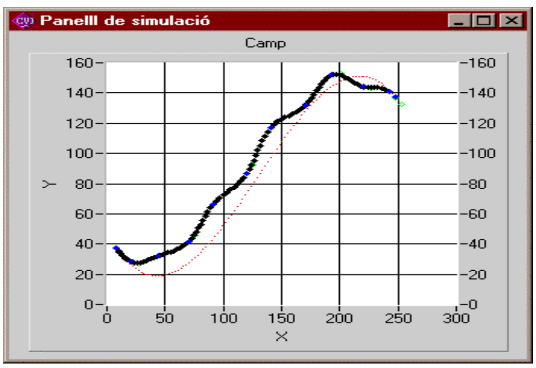

Fig.4. Simulated and real trajectories of the robot

5.4. Robust control

Much of modern control theory relies on a mathematical model of the plant to be controlled. In the real world, there is always uncertainty in any such model. Furthermore, the plant may change as it ages or as operating conditions vary. The objective of robust control is to develop feedback control laws that are robust in the presence of plant model uncertainties and changes in plant dynamics. Mostly, it has been concerned with fixed, non-adaptive linear control laws.

In the lecture course, we address two basic robust control problems: the analysis of a control law's robustness after it is designed and the original synthesis of robust control laws. We have introduced to the students the concepts of the robustness of systems with additive and multiplicative uncertainties and their corresponding robust stability margins. The students have learned about how to analyze the robustness of the closed-loop system in frequency domain by using singular value analysis. We have described the manner about how to get a description of the controlled process by using the two port diagram. Then, we have introduced the concept of H_∞ space and shown the procedure in designing a robust H_∞ controller by using the Robust Control Toolbox for MATLAB.

The students have done the practice on robust control by the computer simulation with the mathematical model for soccer-playing robots obtained from the laboratory practice on stochastic identification. This model has two inputs and two outputs and the matrix of transfer function is diagonally dominated. First, the students made some simplification of the model to transform the MIMO system into two SISO systems. Then, the students designed a robust H_∞ controller in order to track a given reference signal while maintaining the control action small and attenuating the negative influence of the measurement noise to the system dynamics. Up to today, the practice of the robust control is just limited in the computer simulation. In the next course, we will try to let the students to implement the designed H_∞ control law to the soccer-playing robots to see the effectiveness in trajectory tracking.

6. CONCLUSIONS

In this paper, we have exposed briefly, due to the limitation of the length of the paper, our experience with the integrated teaching of an undergraduate course on advanced control at the University of Girona in Spain. Although it is not possible to cover the whole content of a technical training with help of the soccer-playing robots, it could be a good complement to the traditional experimental frameworks, especially when the students have got some basic knowledge in several different areas. Our teaching experience has shown that the proposed experimental framework has permitted the students to receive appropriate engineering training from the laboratory practices and to consolidate their knowledge learned from the lecture course. Moreover, the use of a common experimental framework has given the students a great opportunity to make an integrated and comparative study on different advanced control techniques and thus to be able to know their advantages and drawbacks from the practical experiences obtained from a real problem.

As a promising future work, we will try to make a part of evaluation of the course by means of a competition between a pair of students. Since the objective of every student is to make his robot to carry out a predefined task, a well-designed robot, in the sense of advanced control, will obtain the better punctuation. Moreover, it is expected that this kind of competition will motivate the students to find their best solution to the real problem using the acquired knowledge on advanced control.

It is worthy of mention that the same framework has also been used for the teaching of two more elective course given at the University of Girona in Spain: “Artificial Intelligence Technique and Methods” and “Supervision System Design”, which permits the students to obtain a complete engineering training towards the practical industrial applications.

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