Design, simulation and implementation of a control system for the PeopleMover educational project

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Introduction

The PeopleMover project [1][2] is one of the first examples of project-based education at the Katholieke Universiteit Leuven, Belgium. Last-year bachelor students in electrical engineering perform this project to enhance their practical skills in subjects that are traditionally dealt with in purely theoretical courses. The project mimics all electronic and control aspects of a people mover, an autonomous but remotely supervised train that transports passengers between airport terminals. Student teams of about 4 students tackle the diverse tasks of speech recognition and acoustic noise reduction for the remote supervisor, wireless transmission by radio link, Finite State Machine (FSM) for main control, sensors (infrared, magnetic and solar cells), power electronics, and the speed control system. During initial brainstorming sessions, the students specify the layout of the entire system, the tasks facing each team, and the interfacing between different teams. Starting from these specifications, each team then designs and simulates an electronic circuit, which is implemented on a Printed Circuit Board (PCB). Finally, all PCBs are integrated into a small-scale model train, which can be seen in figure 1.

A multi-disciplinary design project has several advantages over traditional education, which consists of theoretical courses accompanied by exercise sessions. During the implementation of a 'real' application, practical problems arise that are typically masked in a simulation-only environment. Moreover, students learn to design something with many degrees of freedom, instead of following a fixed, tutorial-like path that is generally encountered in traditional exercise sessions. These degrees of freedom force reiteration in the design cycle, sometimes even backtracking to the first steps of the design, and redefining the original specifications. In addition, it requires a constant

collaboration between the different project teams, simulating an industrial environment. Finally, the focus on synthesizing instead of only analyzing early on leads to a better understanding in later advanced courses. Of course, there are also some disadvantages to this type of education. Since students have many degrees of freedom, multiple solutions may arise, resulting in an increased workload for the supervising staff, and necessitating the use of alternative assessment techniques. Instead of being only result-driven, assessment is focused on the abstract on innovative engineering students write (10%), presentation of progress and results (25%), team result (10%), global result (5%), documentation and communication (10%), and continuous evaluation with attention to contribution to team result, effort, efficiency, cooperation with other team members, and innovation (40%).

In this paper, the design of the speed control system will be investigated in detail. The complete design task can be divided into three parts. The *system design* team (two students) handles the modeling, the design, and the simulation of the control system. Simultaneously, the *analog design* team (two students) transforms the transfer functions generated by the system design team into an electronic circuit on PCB. The two teams then jointly perform the *testing* of the PCB, its *integration* into the model train and thus communication with other teams, and the final tuning of the system during normal operation of the model train. These three distinctive parts will be addressed below.

Modeling, design and simulation of the control system

The speed control system controls the voltage applied to the train motor such that the actual speed of the train tracks the desired speed imposed by the FSM. Challenges arise when the train encounters various disturbances such as riding up a slope of 10°. The system requirements specify that three speed levels should be attainable, being 0.2 m/s, 0.4 m/s and 0.8 m/. Furthermore, for the comfort of the passengers, the acceleration of the train should be in the range 0.5-1.0 m/s^2, without oscillations.

The task of the system design team consists of *modeling* the complete system, *designing* the parameters of the control system, and *simulating* the behavior of the train under various conditions and disturbances.

In order to *model the complete system*, the system design team needs to specify an appropriate control configuration, and obtain models for all components involved. Therefore models of the voltage-controlled train motor, the power driver and the current and speed measurement units are necessary. For didactical purposes, the control system is implemented as an analog PI-controller based feedback system [3][4][5]. The students are free to use 1 PI-controller for controlling the speed directly adjusting the voltage (cf. Figure 2), or 2 PI-controllers in a master-slave configuration. The master PI controls the speed by adjusting the requested current, while the slave controls the current manipulating the motor voltage. The master-slave configuration is known to be safer by avoiding power surges, at the expense of decreased tracking-speed and added complexity. The train with its permanent magnet DC-motor is modeled using a physical model [3]. The unknown parameters of this model can either easily be measured (for example mass, radius of wheels) or identified with a least-squares procedure using steady-state measurements of voltage, current and speed (for instance motor constant, resistance, and friction). In fact, a non-linear model is identified, since both static and dynamic friction components are taken into account, which overall can be modeled by means of a non-linear friction parameter. The power driver is modeled as a simple saturation and amplification. The speed of the train is measured using a shaft encoder attached to a train wheel, which generates a delay over a fixed distance since the measurement is only updated when a marking on the shaft is detected. Hence, a delay inversely proportional to the speed has to be taken into account in the feedback loop. Furthermore, low-pass filters are used to smooth the reference input signal from the FSM and for reducing measurement noise. The PI-controllers and the low-pass filters are modeled using the transfer functions

$$C(s) = P\left(1 + \frac{1}{T_i s}\right) \qquad F(s) = \frac{1}{\tau s + 1}.$$

The *design of the control system* consists of determining the 'optimal' parameters P, T_i for the PI-controllers and τ for the filters, such that all design specifications are satisfied. These specifications can be divided into three categories: time-domain specifications such as settling time and overshoot, frequency-domain stability specifications on gain and phase margin, and practical constraints avoiding clipping and windup. Moreover, robustness is taken into account by assuming model inaccuracies such as a change in mass, and considering a disturbance torque, caused by riding up and down a slope. Since the students are not familiar with designing control systems for non-linear systems, the complete system is first linearized. Therefore the friction and the delay are assumed independent of the speed. The design of this linear control system is performed using MATLAB.

In the second stage, the complete non-linear system is modeled using SIMULINK (see figure 2). Using this model, the influence of the non-linearities is analyzed, which can lead to a modification of the control system parameters. The behavior of the train is *simulated* for different conditions and disturbances. For example, figure 3 depicts the simulation of the speed and the current when the train accelerates from 0 m/s to 0.8 m/s at 0.5 m/s^2, and also shows the effect of a disturbance torque caused by riding up a slope of 10°.

Design and implementation of the electronic analog control circuitry

The analog design team works on the actual implementation of the control system. Whereas most undergraduate courses focus on analyzing electronic circuits, these students are now for the first time confronted with a real synthesis assignment. Therefore some basic principles of analog circuit design are taught. The students apply this knowledge to transform the system description generated by the system design team into an analog circuit implementation. This system description consists of a schematic overview, defining input and output signals, and including the transfer functions of all logical blocks (D/A converters, filters, PI-controllers), where certain parameters are still undecided and/or defined as tunable.

First, these transfer functions are converted to an operational amplifier feedback circuit design. This design is not yet realistic because it requires for instance capacitor sizes in the order of farads (F). The theoretical circuit is later refined into a practical circuit design, with realistic dimensions (so capacitors of μF to pF). During this design phase, teams modify their initial requirements to meet their needs. In order to guarantee that these modifications don't lead to conflicting specifications, the analog design team must regularly negotiate with other teams on the interface specifications. Finally, the system design team delivers the final values of the parameters for the filters and the PI-controllers, and defines ranges for all tunable parameters.

Once the circuit design is finished, it serves as the input for the PCB-design program CADSTAR. Some practical PCB design issues are taught to the students. For example, they learn about decoupling capacitors for all ICs. Next, the design scheme is entered, the components are placed and routed, and the final layout is transferred to a facility that delivers a soldered PCB.

Testing the PCB, integration into the train, and fine-tuning of the parameters

Once the design phase finishes, the two teams jointly test and validate the PCB. Testing is considered on functional and parametric levels. *Functional testing* in this context means ensuring the PCB is working correctly. Therefore students must verify that all components function properly, and that there are no incorrect or missing connections in the schematic entry. This aspect of testing is mostly electronic in nature. *Parametric testing* concerns validating the precise transformation of the system description into the electronic design. This testing involves measuring the cut-off frequency of the filters, and comparing the time-domain and the frequency-domain specifications of the PI-controllers with the simulations. These tests are formalized in a test plan, which details the requirements of the design, and proposes test benches that clearly show whether the specific requirements are fulfilled or not. All this testing is purely student work, with minimal assistance from supervising staff.

The *integration of the speed controller* into the miniature train follows the same pattern. Validation tests range from detecting whether the correct input signals are transmitted to the

controller, to whether the control system is able to correctly accelerate and maintain the speed of the PeopleMover, even on a slope. Typical problems include misinterpretation of ambiguities in the interface documentation, for instance where active high signals are considered active low by one team, or where most significant bits are interpreted as least significant bits. Also, this is the first time the control loop is closed, and differences between model and reality become apparent. Small non-linearities such as the hysteresis in the coupling between wagon and locomotive were not modeled, but have an impact on the oscillatory behavior of the control system. What at first sight is just a formality (plug the PCB in its foreseen slot, and the train will ride correctly), always turns out to be the most hectic, difficult, but rewarding job for the students. It is always extremely satisfying for the students to see the PeopleMover, which has been the topic of conversation and work for many weeks, running smoothly across the room.

Conclusion

The PeopleMover project, and the speed control system task within it, is highly regarded within the K.U.Leuven. Students and professors alike find the 'real' application a healthy change from courses with purely theoretical lectures and tutorial-like exercise sessions. The clear definition of a goal (let the train run within clear specifications), and working towards this goal is a thrilling experience for all the people involved, year after year. The aim of this project is applying theoretical courses in a practical application, learning how to do multi-disciplinary project work, and communication between teams. This goal is more then fulfilled. And above all, students learn in a playful way, since all these aspects naturally lead to their goal: to get the train gently riding along its tracks.

References

[1] W. Daems, B. De Smedt, P. Vanassche, G. Gielen, H. De Man, "PeopleMover: an Example of Interdisciplinary Project-based Education in Electrical Engineering," *IEEE Trans. on Education,* vol. 46, no. 1, pp. 157-167, Feb. 2003.

[2] PeopleMover Project: Department of Electrical Engineering, Katholieke Universiteit Leuven, Belgium. Available at http://www.esat.kuleuven.ac.be/~h838/index_en.html

[3] R.C. Dorf, R.H. Bishop, "Modern Control Systems", Prentice Hall, 9th edition, Aug. 2000.

[4] K. De Cock, B. De Moor, W. Minten, W. Van Brempt, H. Verrelst, “A tutorial on PID-control,” Internal Report 97-08, ESAT-SISTA, K.U.Leuven, Belgium, 1997. Available at ftp://ftp.esat.kuleuven.ac.be/pub/sista/minten/reports/pidcontrol.ps.gz

[5] G. Ysebaert, S. Doclo, "H838: Control system design in MATLAB and SIMULINK", Internal Report 04-67, ESAT-SISTA, K.U.Leuven, Belgium, 2004. Available at ftp://ftp.esat.kuleuven.ac.be/pub/sista/ysebaert/H838/04_67.ps.gz

Biographies

Steven Bex was born in Tongeren, Belgium, in 1974. He obtained the Master degree in Industrial Engineering from the Katholieke Hogeschool der Kempen, Geel, Belgium, in 1997, and the Advanced Master in Artificial Intelligence at the Katholieke Universiteit Leuven (K.U.Leuven), Belgium in 2001. From 1997 to 2001, he worked in METALogic NV, a spin-off company of the K.U.Leuven after which he started a PhD under supervision of Bart De Moor on the subject of Datamining in the Chemical Process Industry.

Simon Doclo was born in Wilrijk, Belgium, in 1974. He received the M.Sc. degree in electrical engineering and the Ph.D. degree in applied sciences from the K.U.Leuven, Belgium, in 1997 and 2003. Currently, he is a post-doctoral researcher with the Electrical Engineering Department of the K.U.Leuven. His research interests are in microphone array processing for speech enhancement, adaptive filtering, and hearing aid technology. Dr. Doclo received the first prize "KVIV-Studentenprijzen" for his M.Sc. thesis in 1997, and in 2001, he received a Best Student Paper Award at the International Workshop on Acoustic Echo and Noise Control.

Geert Ysebaert was born in Leuven, Belgium, in 1976. In 1999, he received the Master degree in electrical engineering from the K.U.Leuven, Belgium. In 2004, he received the Ph.D. degree at the Electrical Engineering Department (ESAT), K.U.Leuven, under the supervision of

Marc Moonen. His research interests are in the area of digital signal processing for DSL communications.

Georges G.E. Gielen received the MSc and PhD degrees in Electrical Engineering from the K.U.Leuven, Belgium, in 1986 and 1990, respectively. In 1993, he was appointed as a tenure research associate of the Belgian National Fund of Scientific Research and at the same time as an assistant professor at the K.U.Leuven, where he is now Full Professor. His research interests are in the design of analog and mixed-signal integrated circuits, and especially in analog and mixed-signal CAD tools and design automation (modeling, simulation and symbolic analysis, analog synthesis, analog layout generation, analog and mixed-signal testing). He has authored or coauthored two books and more than 200 papers in edited books, international journals and conference proceedings. He regularly is a member of the Program Committees of international conferences (DAC, ICCAD, ISCAS, DATE, CICC...).

Wim Dehaene was born in Nijmegen, The Netherlands, in 1967. He received the M. Sc. degree in electrical and mechanical engineering in 1991 from the K.U.Leuven. In 1996 he received the Ph. D degree at the K.U.Leuven. His research involved the design of novel CMOS building blocks for hard disk systems. In 1996 Wim Dehaene joined Alcatel Microelectronics, Belgium, as a senior project leader for the feasibility, design and development of mixed mode Systems on Chip. In 2002 Wim Dehaene joined the staff of the ESAT-MICAS laboratory of the K.U.Leuven where he is now associate professor.

Hugo De Man is professor in electrical engineering at the Katholieke Universiteit Leuven, Belgium since 1976. He was visiting associate professor at U.C.Berkeley in 1975 teaching semiconductor physics and VLSI design. His early research was devoted to the development of mixed-signal, switched capacitor and DSP simulation tools as well as new topologies for high-speed CMOS circuits, which led to the invention of NORA CMOS. In 1984 he was one of the cofounders of IMEC (Interuniversity Microelectronics Center).

Bart De Moor received his doctoral degree in applied sciences in 1988 from the K.U.Leuven, Belgium. He is Full Professor at the Department of Electrical Engineering, K.U.Leuven, in the research group SCD. His research interests include numerical linear algebra, system identification, control theory and datamining. He has more than 200 papers in international journals and conference proceedings, is the co-author of several books on system identification and neural nets.

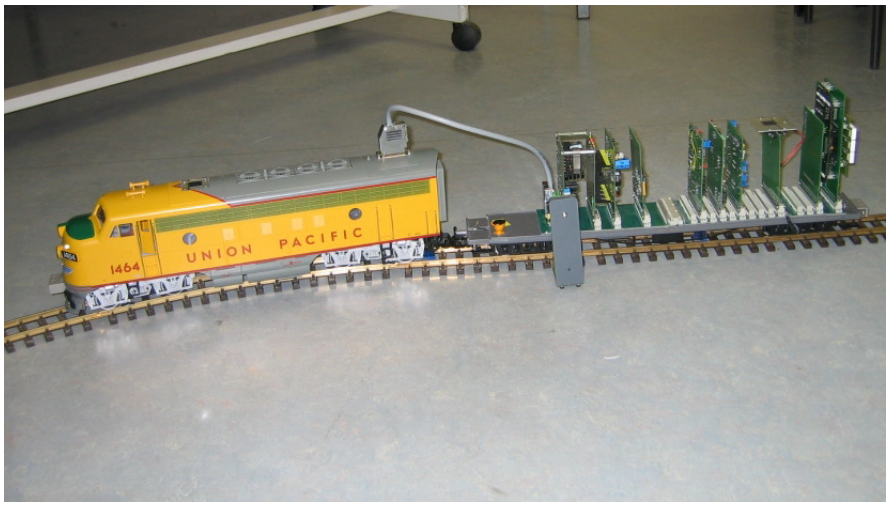

Figure 1: **The PeopleMover in its finished form. On the wagon the PCBs of the different teams are visible, one of which is the speed control system implementation as described in this paper.**

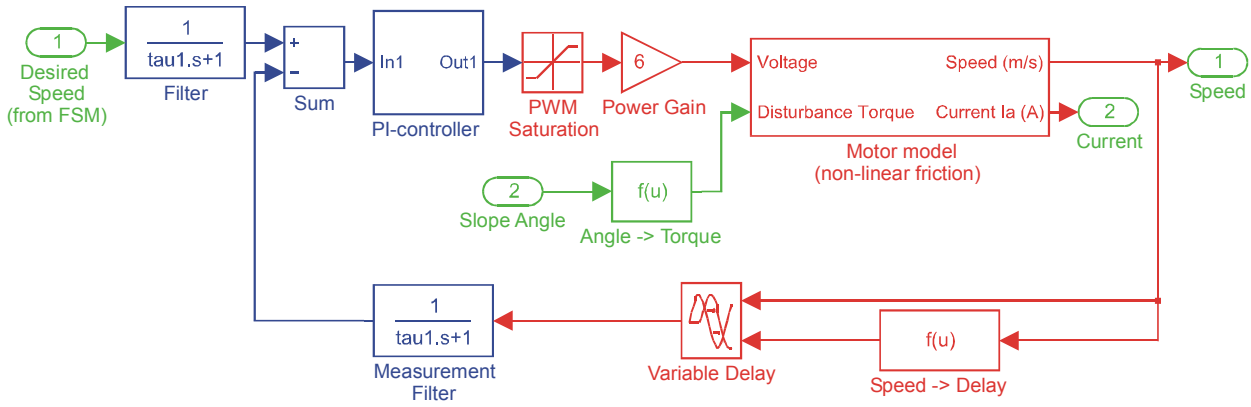

Figure 2: **Schematic overview of the complete speed control system in SIMULINK. This feedback control system consists of a non-linear model of the power driver and the train motor, the speed measurement unit and the actual control configuration (PI-controller) that needs to be designed. The input signal coming from the FSM is smoothed using a low-pass filter.**

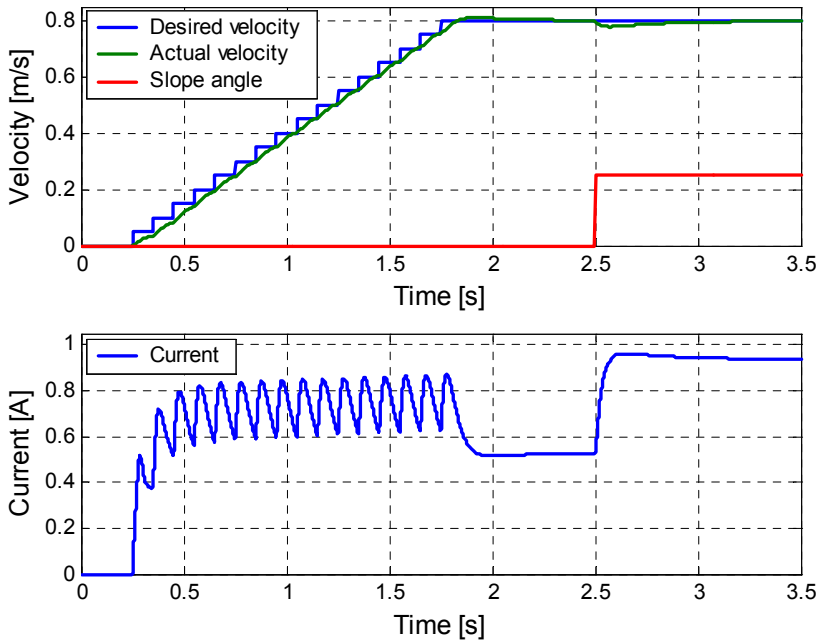

Figure 3: **Simulations results for the speed control system. This figure depicts the speed and the current when the train accelerates from 0 m/s to 0.8 m/s at 0.5 m/s^2, and the effect of a disturbance torque caused by a slope of 10°.**