DSPs for Real-time Sensing and Control of Automotive Systems

F. Salam, N. Xi, J. Yu, and W. Zuluaga
Department of Electrical and Computer Engineering
Michigan State University
East Lansing, Michigan 48824-1226, USA
Email: salam@egr.msu.edu; xin@egr.msu.edu
http://www.egr.msu.edu/autoweb/

Abstract:

This paper describes several on-going projects on the design, development, and prototyping of automotive control systems. These projects include both Senior Design Projects, as part of the automotive sensing and control curriculum development, as well as research-level projects on advanced control methodologies for automotive systems using Digital Signal Processors (DSPs). These projects have been sponsored in part by the National Science Foundation as well as co-sponsored by Ford and General Motors. It is our plan to expand this initial effort and engage more automotive industry manufacturers and suppliers in the future.

1 Introduction

Intelligent control devices and systems for real-time sensory-based processing and control of automotive systems are among the critical elements of emerging technologies identified by the U.S. Department of Commerce, with expected revenues exceeding 90 billion dollars in the U.S., and 120 billion dollars worldwide by the end of this decade.

Both education of new engineers as well as research in advanced digital control methodologies are critical to many major industries in the coming years. In particular, the automotive industry is witnessing new advances in vehicle technologies from the powertrain to the communication and entertainment devices. The precise and timely control of signals and information is becoming critical to the new vehicles of the future. Major investigations are currently being undertaken into the possibility of restructuring the power generation and distribution among the increasingly varied devices within a vehicle.

Moreover, to prepare the new graduate for the increasingly dynamic and innovative engineering markets, the undergraduate and graduate curricula should emphasize creativity, adaptability, teamwork, effective communication, and leadership. All are necessary talents for leading in the novel technology areas critical to our global competitiveness. Intelligent control devices and systems for *real-time* sensory-based processing and control, with emphasis on automotive systems, are among these emerging crucial technologies for the design of the next generation (smart) vehicles.

In this paper [1], we highlight sample activities in both the education of new graduates and in research using real-time sensing and control methodologies. We focus primarily on the DSP as a viable tool for real-time implementation of nonlinear and advanced estimation and control methodologies.

2 The Automotive Sensing and Control Project

A team of faculty, from the Department of Electrical and Computer Engineering and the Department of Mechanical Engineering at Michigan State University, have been collaborating with industry partners from Ford and GM to develop a 2-semester senior-level capstone engineering course in real-time sensing and (feedback) control computing with direct focus on automotive systems. This team of Michigan State University researchers is in a unique position to spearhead this timely effort because of their continuing close collaboration with researchers and engineers in the Big Three automotive producers as well as major automotive suppliers, including Eaton, United

Technologies, Johnson Controls, and others. Moreover, invited researchers from some of these industries have been participating directly: in research, course development, and in teaching. This course sequence has greatly benefited from and has incorporated the Continuous Quality Improvement (CQI) principles in the development of the proposed course [1].

2.1. Goals

The project brings the promising results of research conducted by the team members, their industry partners, and other leading researchers from academia and industry into the design of novel sensing and control computing systems. A two-semester senior-level capstone course is developed which integrates the curricula across the tow departments. The research being transferred to the classroom addresses a complete, project driven, course activities that span problem definition, modeling, simulation, and eventually real-time interfacing and control implementation. A host of advanced and novel feedback control algorithms addressing a variety of automotive systems are being incorporated. The class format simulates a micro-industrial research environment where the industry partners and other representatives assist in selecting the automotive systems and theme for the year. Then teams of MSU faculty and industry partners would supervise the class in expositions to the advanced tools, their proper usage, and underlying assumptions for the first semester. The second semester concentrates on projects by smaller teams of students coordinated through partnerships of MSU faculty and invited engineers from industry to focus on specific advanced approaches in real-time automotive control systems.

2.2. Description of Research to be Transferred to the Classroom

The team members of the project have conducted extensive and pioneering research in the analysis, design, development and hardware implementation of real-time dynamic and control systems. In collaboration with their industrial partners, the team members plan to develop the real-time sensing and control computing course with focus on automotive systems. It is hoped that this effort would help in enabling a generation of graduating engineers capable of inventive and creative approaches to developing the next generation "smart" vehicles and mobiles ([1-8]).

The current list of research areas include:

Adaptive, nonlinear control and dynamical systems

(i)model reference (ii) the cubic-modification update law (iii) the sigmoidal-modification update law
(iv) linearization, (v) feedback linearization, (vi) gain scheduling, (vii) Liapunov-based robust control,
(viii) variable structure control, (ix) multiple time scale techniques, (x) analysis and design of nonlinear
dynamic systems

Neural networks, optimal and Kalman filtering, and fuzzy logic

(i) real-time feedforward and recurrent networks, (ii) learning in neural networks using optimal control and Kalman filtering, (iii) extended optimal filtering techniques, (iv) basic fuzzy logic, (v) adaptive fuzzy logic, (v) fuzzy-neuro control

Hardware implementations and interface, sensors, and actuators

While algorithms for feedback control are essential, the completeness of the control efforts requires knowledge of sensing and actuating devices since their models must be well understood for a successful control. From an analysis view point the sensors and the actuators must be included as part of the model of the automotive system. Options of sensors and actuators are available, and the engineer must select sensors and actuators taking several factors into considerations. Some of these factors include the type of control algorithm selected, the type of automotive system addressed, the effectiveness and expense of the actuators vis-a-vis the automotive subsystem or component.

3 The DSP for Sensing and Control Laboratory

3.1 DSP environment

The automotive sensing and control lab has different DSP configurations, providing various resources. The more general configuration consists of a Windows NT platform with an LSI PC/C32 board, based on a TMS320C32 Texas Instruments floating point DSP [2]. The input/output interface is based on the Blue Wave Systems AM/D16SA daughter module, providing two analog input channels and two analog output channels. The most complete DSP system used in the laboratory has an additional daughter module synchronized with the first one, and an LSI PC/16IO8 Multi-channel board, for a total of 20 analog input channels and 12 analog output channels. This configuration is complete enough to implement a wide variety of automotive controls. An appropriate interface (e.g. power amplification stage) are designed in-house to enable direct application to a DC motor or a PWM controlled device.

3.2 Matlab/Simulink Interface

In this domain, the user is able to take advantage of the design and simulation capabilities of Matlab's Simulink tool, along with the Real-Time Workshop (RTW). By using the libraries and drivers provided by the manufacturer, a control design is directly implementable via the Simulink interface. Although some considerations have to be taken into account in the design, e.g., maximum sampling rate, the process is straightforward and provides a way for rapid design and testing. Also, in external mode, RTW allows the user to modify the control parameters, and therefore control fine-tuning can be easily achieved. Finally, data logging provides the user the opportunity to view the signals in the Matlab command window and process them, e.g. applying FFT or filtering. Two platform choices are available using DSPs: (I) LSI boards [3] and (ii) dSpace boards [4].

3.3 C++ Interface

Another option available is to build the DSP control tool from scratch, giving the users more flexibility to design their own code, make any changes to the most common implementations and optimize the programs to suit the objectives of the particular project. A program was implemented in C++ where the user can select a control system representation. For example, the state space provides state variables, inputs, and outputs (based on the DSP configuration). For systems with one input and one output, either the state space, transfer function or PID control representations can be used.

Additionally, the user can create his own functions for the DSP, by implementing them in ANSI C and invoking the compiler. By identifying the necessary parts for a general program (i.e. interruptions, daughter modules configuration, data interface), all the functions are stored in a main file where no further modification is needed (except for the headers for the new functions). The new code to be implemented is stored in a different C file, compiled, linked and downloaded to the DSP. While the program is running, specific regions of the DPRAM are allocated to send and receive the user's data, along with previously defined variables, that also allow for plotting the input and output signals of the DSP directly on the screen. However, the user may change any part of the code (including the main program).

3.4 Test configuration

The DSP environment is being tested with two different single input/single output automotive systems. The test setup consists of using a DC motor. The motor speed is fedback to the DSP through a tachometer, then sampled and applied to the control algorithm. The output of the controller can not be applied directly to the motor, since the output power is not high enough. Power amplification is obtained through a pair of BJTs, that set the right level for both current and voltage.

4 Educational Projects: Example Student projects sponsored by Ford and GM

We will briefly describe 3 example Senior Projects which have been conducted this Spring Semester 1999. Further information about the projects and the activities are available through http://www.egr.msu.edu/autoweb/

4.1 Project 1: DETC: Digital Electronic Throttle Control

Student Team: Anthony Christie, Laura Hudy, Keith Lui and Parag Wadhawan

The objective of the project has been to design a Digital Electronic Throttle Control (DETC) System for electronic engine control operation using classical control methods. The function of the DETC is to control a standard throttle plate using a remote digital signal. The DETC system consists of a pedal position sensor (PPS), a throttle position sensor (TPS), an actuator, and a processor or a controller. The team's focus has been to develop the control system for a specific throttle body, provided by Ford, which has been used in Ford vehicles. The control module monitors the opening and closing of the throttle plate. The project is a proof of concept and is merely a stepping stone for further research.

4.2 Project 2: Intelligent Automotive Mirror System

Student Team: Chee-Kuang Kok (ME), Michael McAlpine (ECE), and Nathan Radcliffe (ME)

This senior design project entails the development of an electro-mechanical automotive mirror system for Lincoln Continental that will adjust the side-view mirror position based on the position of the rearview mirror and build a prototype of the design. The design team had identified the design specifications of the mirror system and came up with different conceptual designs to accomplish the task. Design alternatives were evaluated and the best design selected, implemented, and tested.

4.3 Project 3: Powering 12-Volt Components with 36-volt batteries

Student Team: Brennan Sicks (ME), Brian Cunningham (ECE), and Jennifer Walker (ECE)

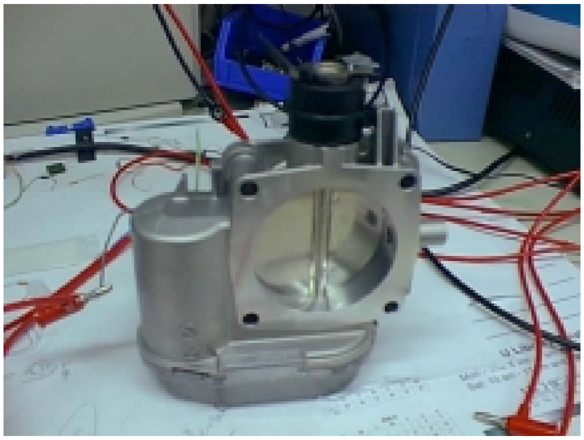
Today, innovations in electronic automobile components are creating the need for higher voltage power supplies. A proposed 12/36Volt dual power supply would allow for the implementation of advantageous components like electronic brakes and electronic power steering. This project uses 12V components and the development of a system, which enables these components to be powered by a 36V power supply/battry. The strategy was to produce a cost effective and reliable solution, which would produce minimal noise. Following investigation and evaluation of various ideas, three circuits were found to produce the desired results. The final design choice was a circuit utilizing a LM317T Voltage Regulator. This circuit produced the desired output voltage of 12V and was below the maximum heat generation specification. It was the optimum design because it is the least expensive and most compact. The circuit successfully ran a 12V power mirror and door lock actuators with a 36V battery.

5 Research Component

Example projects include research in developing nonlinear observers using optimal and adaptive control to provide real-time estimates of a system's states from available sensory measurements.

5.1 Project 1: DETC using DPS

We have developed a DSP-based controller for the automotive Electronic Throttle Control (ETC) system.
A conventional throttle system consists of a pull cable that connects the gas pedal and the throttle body.



The system being used is a Generation Two (Gen 2) model of the digital electronic throttle body. Fig. 1 on the left depicts the throttle system used in this experiment of real-time control to meet a set of specification. The throttle is composed of a DC brushless motor, four gears, and two sensors. A Pulse Width Modulated (PWM) signal is sent to the motor, moving the throttle to the desired position. This position is read and sent back to estimate the error from the reference (command) signal. For this system, it is required to convert the output of the DSP to a PWM signal with the correct specifications in order to control the motor. Moreover, the controller output also has to be amplified to provide sufficient power to drive the throttle.

The novel “control-by-wire” would use digital control to actuate the motor of the Electronic Throttle Control (ETC). The advantages of this approach are to reduce the number of needed actuators, easier packaging, and better traction control performance. A conventional system has a separate actuator for the idle air control and the cruise control. With the ETC system the Powertrain Control Module (PCM) could accomplish these functions with the throttle actuator alone. This paper describes the design, development, and building of an Electronic Throttle Control system. A throttle body was fitted with an actuator and a digital DSP-based controller is used.

5.2 Project 2: Nonlinear Optimal Estimators and Observers

Due the difficulty of having reliable models of many (necessarily nonlinear) automotive systems, including, e.g., the engine model, the emission model, etc., we have developed optimal nonlinear estimators that require input and output measurements and identify parameters in nonlinear structures (see[8] for details). This nonlinear estimator uses optimization approaches but computes state and co-state dynamics forward in time, adapts parameters in a given structure to track and/or estimate states on-line. In this experiment, we test the performance and robustness of the estimator on physical system with an approximate structure but unknown parameters. The physical system is approximately represented in each case by a linear system equation.

Let $$\begin{bmatrix} \dot{x}_2 \\ \dot{x}_1 \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{C_1R_1} & 0 \\ \dfrac{1}{C_2R_2} & -\dfrac{1}{C_2R_2} \end{bmatrix} \begin{bmatrix} x_2 \\ x_1 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_1R_1} \\ 0 \end{bmatrix} u_d \qquad = Ax + Bu$$

and $Y = x_1$

Case 1: An optimal adaptive tracking experiment :

Physical system approximate equation : $\dfrac{u_d - x_2}{R_1} = C_1 \dfrac{dx_2}{dt} = C_1 \dot{x}_2 \qquad Y = x_2$

Consider the estimator model to be : $\dot{\hat{x}}_2 = \tanh(a\hat{x}_2 + bu_d) \quad \hat{y} = \hat{x}_2$ with $u_d, x_2 \in R$

and the tracking error is : $e = Y - \hat{y} = x_2 - \hat{x}_2$

The criterion to be minimized is : $J(t_0, t_1) = \int_{t_0}^{t_1} \bar{L}(e, \lambda, a, b)dt$ with $t_1 \to \infty$

where λ represent the co-state, e represents the error, $\bar{L}$ is the modified performance index given by [8] :

$$\bar{L}(e,\lambda,a,b)=\frac{1}{2}\alpha e^2+\frac{1}{2}\beta(a^2+b^2)+\frac{1}{2}\gamma\lambda^2$$

and the corresponding Hamiltonian is:

$$\bar{H}=\bar{L}(e,\lambda,a,b)+\lambda\tanh(a\hat{x}_2+bu_d)$$

Thus one obtains the equations for the extended dynamics as :

$$\dot{\hat{x}}_2=\frac{\partial\bar{H}}{\partial\lambda}\qquad \dot{\lambda}=-\frac{\partial\bar{H}}{\partial\hat{x}_2}\qquad \dot{a}=-\eta\frac{\partial\bar{H}}{\partial a},\dot{b}=-\eta\frac{\partial\bar{H}}{\partial b}$$

which are :

$$\begin{aligned}
&\dot{\hat{x}}_2=\tanh(a\hat{x}_2+bu_d)+\gamma\lambda\\
&\dot{\lambda}=-(-\alpha(x_2-\hat{x}_2)+\lambda(1-\tanh^2(a\hat{x}_2+bu_d))a\\
&\dot{a}=-\eta(\varepsilon a+\lambda(1-\tanh^2(a\hat{x}_2+bu_d))\hat{x}_2)\\
&\dot{b}=-\eta(\varepsilon b+\lambda(1-\tanh^2(a\hat{x}_2+bu_d))u)
\end{aligned}$$

Figure 1 depicts the experiment results provided by the DSP system in real-time tracking of the output of the physical system.

Case 2: An optimal adaptive observer experiment:

For this case the physical system has two states. One measures the state x_1, and the observer would track this state and moreover provide and estimate or a prediction of the other state should estimate the second state x_2. The observer model is chosen (which is different from the physical plant to test its robustness to unmodeled dynamics) is:

$$\begin{aligned}
&\dot{\hat{x}}_1=-\hat{x}_2\\
&\dot{\hat{x}}_2=\gamma_3\tanh(a\hat{x}_2+bu)\\
&\hat{y}=\hat{x}_1
\end{aligned}$$

and the observation error is : $e=Y-\hat{y}=x_1-\hat{x}_1$

The criterion to be minimized is : $J(t_0,t_1)=\int_{t_0}^{t_1}\bar{L}(e,\lambda_1,\lambda_2,a,b)dt$ with $t_1\to\infty$

where λ_1 and λ_2 represent respectively the co-states associated with x_1 and x_2, e represents the error, $\bar{L}$ is the modified performance index given by [8]:

$$\bar{L}(e,\lambda_1,\lambda_2,a,b)=\frac{1}{2}\alpha e^2+\frac{1}{2}\varepsilon_1 a^2+\frac{1}{2}\varepsilon_2 b^2+\frac{1}{2}\gamma_1{\lambda_1}^2+\frac{1}{2}\gamma_2{\lambda_2}^2$$

and the corresponding Hamiltonian is :

$$\bar{H}=\bar{L}(e,\lambda_1,\lambda_2,a,b)-\lambda_1\hat{x}_2+\lambda_2\tanh(a\hat{x}_2+bu)$$

The dynamic equations of the augmented system are :

$$\dot{\hat{x}}_1=\frac{\partial\bar{H}}{\partial\lambda_1},\dot{\hat{x}}_2=\frac{\partial\bar{H}}{\partial\lambda_2}\qquad \dot{\lambda}_1=-\frac{\partial\bar{H}}{\partial\hat{x}_1},\dot{\lambda}_2=-\frac{\partial\bar{H}}{\partial\hat{x}_2}\qquad \dot{a}=-\eta_1\frac{\partial\bar{H}}{\partial a},\dot{b}=-\eta_2\frac{\partial\bar{H}}{\partial b}$$

All the dynamics are executed forward in time [8]. These dynamics now specialize to:

$$
\begin{aligned}
\dot{\hat{x}}_1 &= -\hat{x}_2 + \gamma_1 \lambda_1 \\
\dot{\hat{x}}_2 &= \gamma_3 \tanh(a\hat{x}_2 + bu) + \gamma_2 \lambda_2 \\
\dot{\lambda}_1 &= \alpha(x_1 - \hat{x}_1) \\
\dot{\lambda}_2 &= -\lambda_1 - \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))a \\
\dot{a} &= -\eta_1(\varepsilon_1 a + \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))\hat{x}_2) \\
\dot{b} &= -\eta_2(\varepsilon_2 b + \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))u)
\end{aligned}
\tag{0.1}
$$

Figure 2 depicts the experimental DSP results. It should be noted that in this case the observer model is different from the structure of the physical system. If we assume two other different physical system dynamic structures,

$$
\text{(Structure 1)} \qquad
\begin{aligned}
\dot{\hat{x}}_1 &= -\hat{x}_2 \\
\dot{\hat{x}}_2 &= -\gamma_3 \tanh(a\hat{x}_2 + bu) \\
\hat{y} &= \hat{x}_1
\end{aligned}
$$

The observer is now

$$
\begin{aligned}
\dot{\hat{x}}_1 &= -\hat{x}_2 + \gamma_1 \lambda_1 \\
\dot{\hat{x}}_2 &= -\gamma_3 \tanh(a\hat{x}_2 + bu) + \gamma_2 \lambda_2 \\
\dot{\lambda}_1 &= \alpha(x_1 - \hat{x}_1) \\
\dot{\lambda}_2 &= -\lambda_1 + \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))a \\
\dot{a} &= -\eta_1(\varepsilon_1 a - \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))\hat{x}_2) \\
\dot{b} &= -\eta_2(\varepsilon_2 b - \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))u)
\end{aligned}
\tag{0.2}
$$

And

$$
\text{(Structure 2)} \qquad
\begin{aligned}
\dot{\hat{x}}_1 &= -\hat{x}_2 - \hat{x}_1 \\
\dot{\hat{x}}_2 &= -\gamma_3 \tanh(a\hat{x}_2 + bu) \\
\hat{y} &= \hat{x}_1
\end{aligned}
$$

The observer now becomes

$$
\begin{aligned}
\dot{\hat{x}}_1 &= -\hat{x}_2 - \hat{x}_1 + \gamma_1 \lambda_1 \\
\dot{\hat{x}}_2 &= -\gamma_3 \tanh(a\hat{x}_2 + bu) + \gamma_2 \lambda_2 \\
\dot{\lambda}_1 &= \alpha(x_1 - \hat{x}_1) + \lambda_1 \\
\dot{\lambda}_2 &= -\lambda_1 + \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))a \\
\dot{a} &= -\eta_1(\varepsilon_1 a - \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))\hat{x}_2) \\
\dot{b} &= -\eta_2(\varepsilon_2 b - \lambda_2 \gamma_3 (1 - \tanh^2(a\hat{x}_2 + bu))u)
\end{aligned}
\tag{0.3}
$$

the model (1.2) gives similar result to Figure 2, and model (1.3) gives the experimental result in Figure 3.

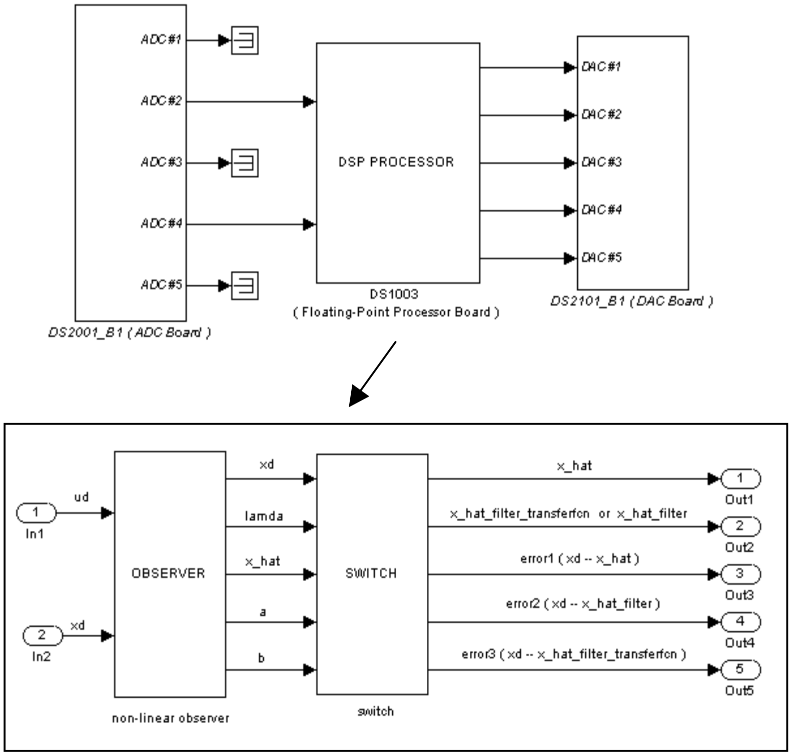


Figure 2a structure for experiment 1

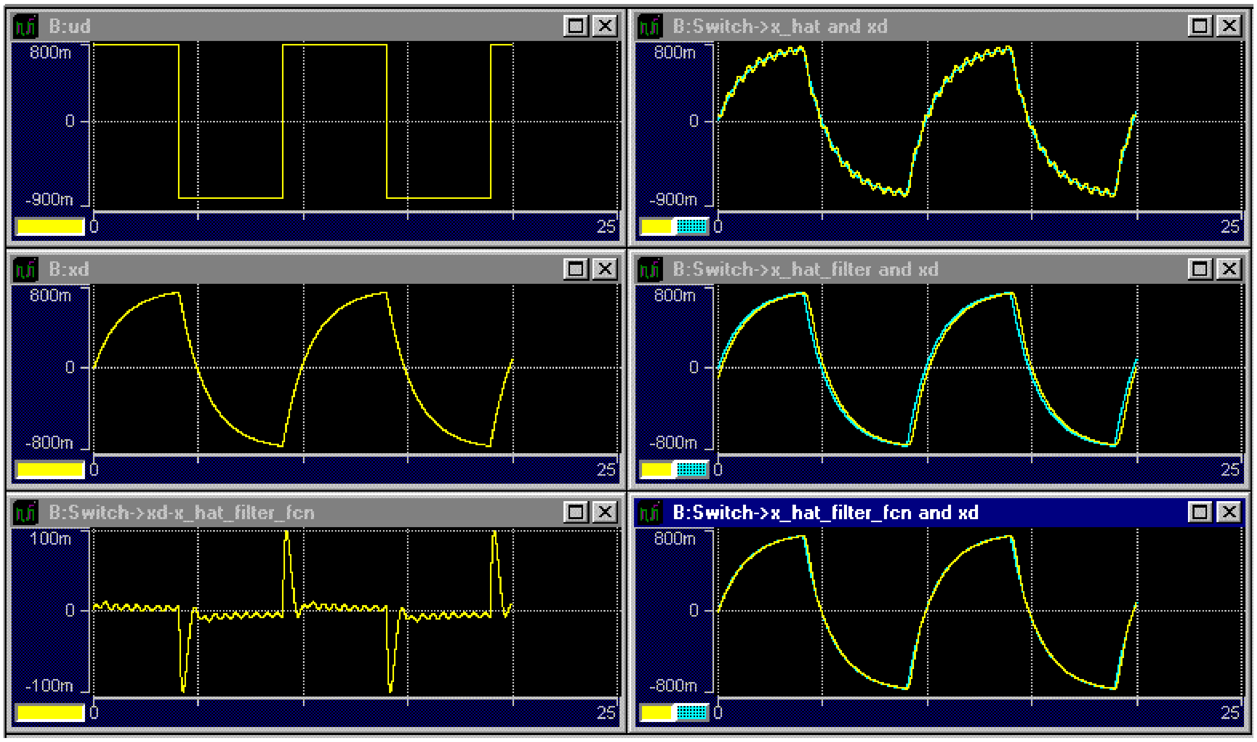


Figure 2b. tracking results for Experiment 1

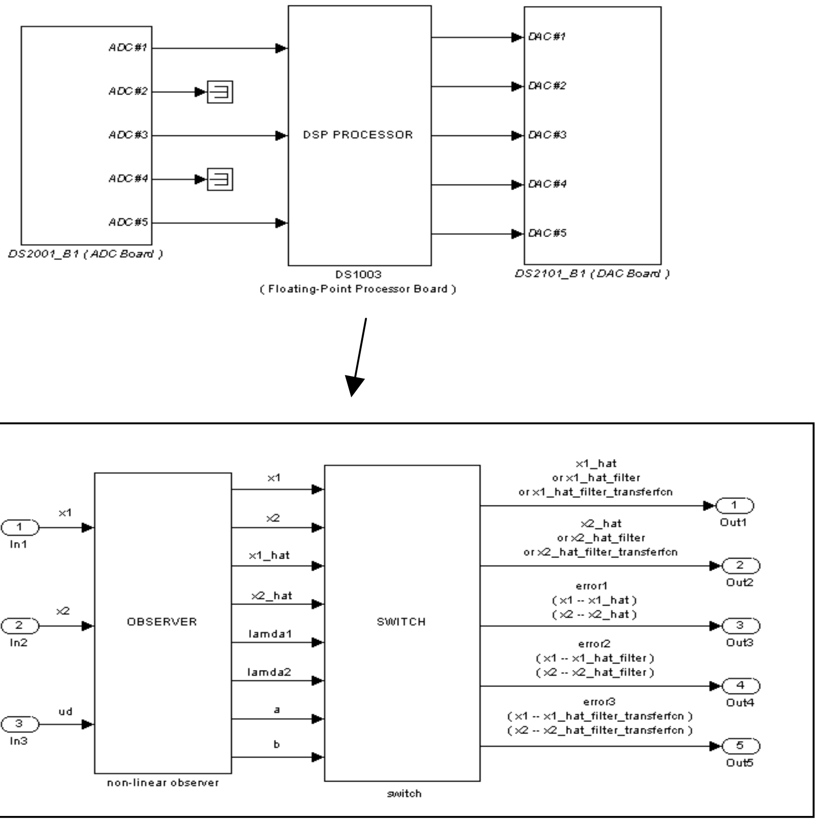


Figure 3a. structure for experiment 2

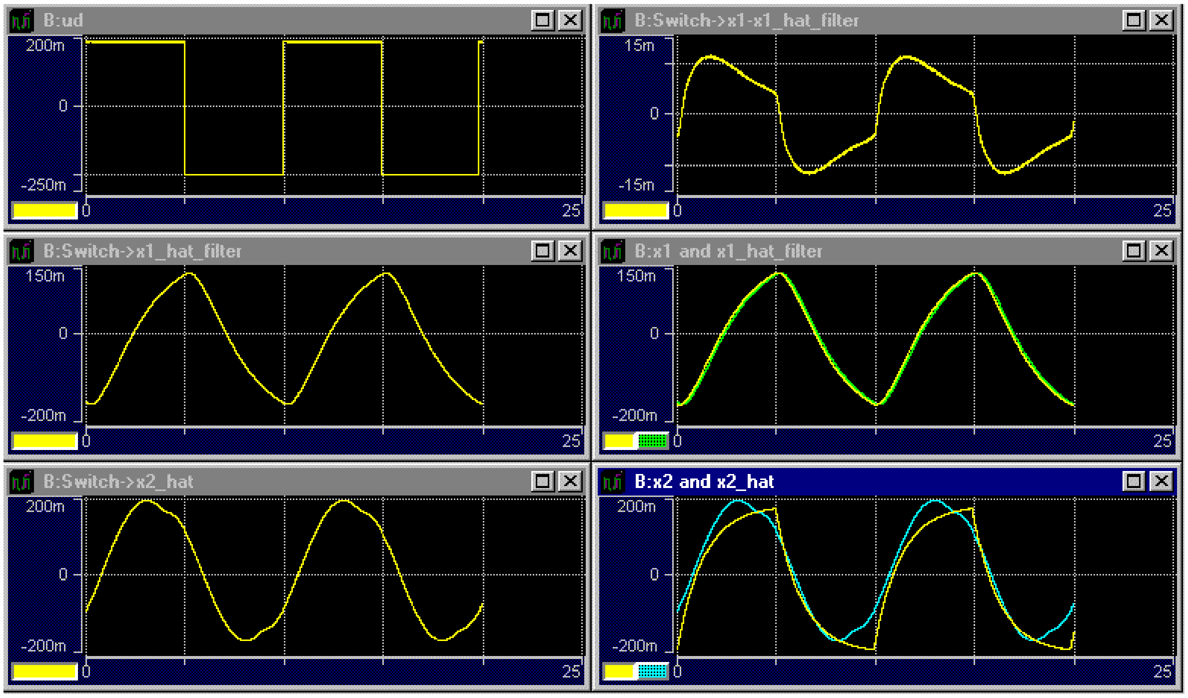


Figure 3b. the results for experiment 2 with the dynamics model (1.3). State 1 is tracked, state 2 is crudely estimated due to the un-modeled dynamics in the physical system (plant). Note that in matching structures full state estimated is realized in simulations.

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