Experimental Comparison of Nonlinear Control Strategies for Vehicle Speed Control

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Abstract

This paper describes an experimental comparison of two alternative nonlinear automotive speed control systems. The first approach is based on interpolation of multiple linear controllers designed using multiple local linear models. The second approach is based upon geometric nonlinear control theory and utilises feedback linearisation. This paper focuses on engineering aspects and experimental comparison in a test vehicle. The controllers are tested in a range of speed-profile tracking tasks, and in a disturbance rejection task (the vehicle is driven up a 10% slope). For comparison, linear PI/PID controllers are implemented.

1. Introduction

The demands of the new generation of intelligent cruise control systems provide motivation for the design of a high-precision speed controller. The first approach implemented here, which is based on interpolation of multiple linear controllers, is a generalised form of gain scheduling since the models and controllers take explicit account of both stationary and non-stationary (off-equilibrium) operating points. Further, the local models and controllers need not have the same structure (they can, for example, have different orders). Finally, the control input (throttle) is used for scheduling together with the output (speed) and an auxiliary input (gear). This approach is in contrast to the traditional gain scheduling approach. The second approach is based upon geometric nonlinear control theory and utilises feedback linearisation. For comparison, linear PI/PID controllers are also implemented.

This paper gives only a small selection of experimental results; full details can be found in [1, 2]. Background material relating to the theoretical properties of the approaches can be found in the following references: the Local Model Network (LMN) approach to nonlinear modelling is described fully by Johansen *et al* [3, 4]; the generalised gain scheduling approach, called a Local Controller Network (LCN), was developed by Hunt and Johansen [5] (stability issues are investigated in this reference); a detailed discussion of off-equilibrium modelling and control design is given by Johansen *et al* [6].

A description of the software environment used for the LMN/LCN approach can be found in [7]. Further details of the test vehicle employed are given in the references [8, 9], and the results of longitudinal dynamics modelling with LMNs and FEM approaches are presented in Hunt *et al* [10] and Kalkkuhl *et al* [11], respectively. Alternative nonlinear (neural network) controllers are evaluated for this application by Fritz [12, 13, 14].

Figure 1: The experimental vehicle OTTO.

2. Definition of the Speed Control Application

The results in the paper were obtained using the experimental vehicle shown in figure 1. This is a

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medium-sized Mercedes-Benz 8-tonne truck of type LN814D (8 tons, 140 PS, diesel engine) with a 4-gear automatic gearbox.

The principal components of the drivetrain are shown in figure 2. The nonlinearities are due mainly to the engine characteristics, the torque converter, and the gearbox (a switching element). To a large extent the nonlinearities can be characterised by a number of measurable quantities: vehicle speed v; throttle angle α (or throttle command α^c); gear, denoted as g. This information can be used in the construction of models and in the design of controllers.

In addition to the nonlinearities, limitations to control performance are caused by the throttle actuator (it has a deadtime and high-frequency oscillatory mode), and the speed sensor (which suffers from noise at low speeds). The primary goals of control design are to achieve fast command response over the complete operational range, together with good disturbance rejection. The feedback system should be insensitive to unmodelled actuator dynamics and sensor noise.

3. Controller Parameterisation

3.1. LMN/LCN

Full details of the LMN/LCN control design are given in [1]. Based on measurements carried out on the test vehicle, a number of empirical LMN models were identified. These combine a set of local linear models via switching (based on measured gear) and smooth interpolation (using speed and throttle). Each local controller in the corresponding LCN is designed by solving a linear pole assignment problem (with observer) for each local model. This meets a nominal time-domain performance specification in each operating point.

For design of the LCN, the fact that the engine performance varies depending on gear can be directly accomodated by using different specifications in each gear. Within each gear the same specification was used for each local controller.

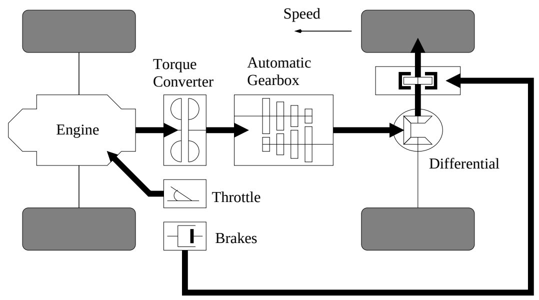

Figure 2: Principal drivetrain components.

3.2. Geometric Nonlinear Controller

Full details of the geometric nonlinear controller design are given in [2]. The geometric nonlinear controller uses an internal model of the plant. FEM models were used as internal models for the geometric controller experiments [11]. These models allow the direct on-line computation of the corresponding dynamic inverse. Two first-order FEM models were identified from the same experimental data that were used for the LMN models. Different discretisation schemes with a total of 48 and 81 meshpoints were employed.

Besides the internal nonlinear plant model, the parameterisation for the geometric nonlinear controller is based on shaping a fourth-order regulating filter which directly represents the desired complementary sensitivity function of the control system for each gear.

3.3. PI/PID controller

Two conventional controllers of PI- and PID-type were experimentally evaluated. The PID controller was designed on the basis of one local model from 1st gear, and the PI controller used one linear local model from 3rd gear. These models were validated for small-signal performance at the corresponding operating points.

4. Experimental Results: test vehicle implementation

Extensive experimentation showed that speed-measurement noise and unmodelled high-frequency dynamics in the actuator are the primary engineering constraints in this application. Further, a linear PID controller is very sensitive to measurement noise; in first gear very strong oscillations in the throttle position occur, and the controller must be detuned to maintain stability.

A set of standard speed profiles was defined (one for each gear). The controllers have the task of following the profiles in a specified way (i.e. through specification of risetime and damping). The profiles were designed in such a way that both small-signal and large-signal performance could be evaluated over the complete operational range. Thus, in each gear the profile consists of small steps in the low-throttle region, small steps in the mid-range, and small steps in the high-throttle region. In addition, the profile includes a large step from the high to low throttle region, and a large step from low to high. This section gives a small selection of typical experimental results. These are mainly from the 1st gear, which is the most challenging operating region.

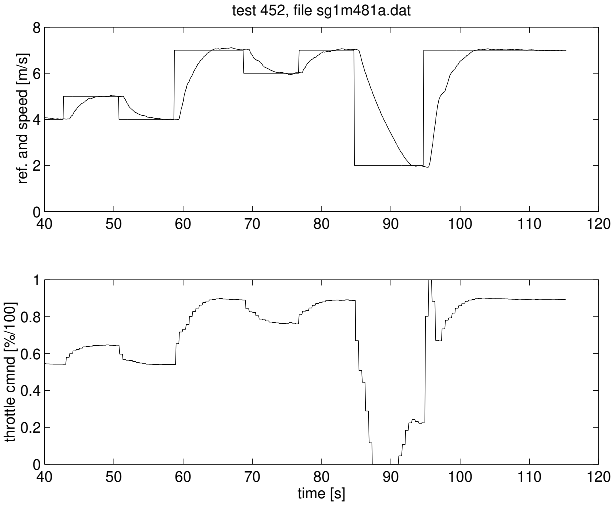

Figure 3: LCN: tracking result in 1st gear. (Experimental result with the test vehicle.)

4.1. LMN/LCN results

A representative experimental tracking result with the LCN for the 1st gear profile is shown in figure 3. The controller gives fast, stable performance. Small-signal behaviour is excellent in the medium- and high-range throttle regions. The large upward step is also excellent, with no overshoot.

The large-signal performance for this controller in 3rd gear is shown in figure 4. This is a good result with no overshoot. Linear controllers typically gave a large overshoot on this test (see figure 7).

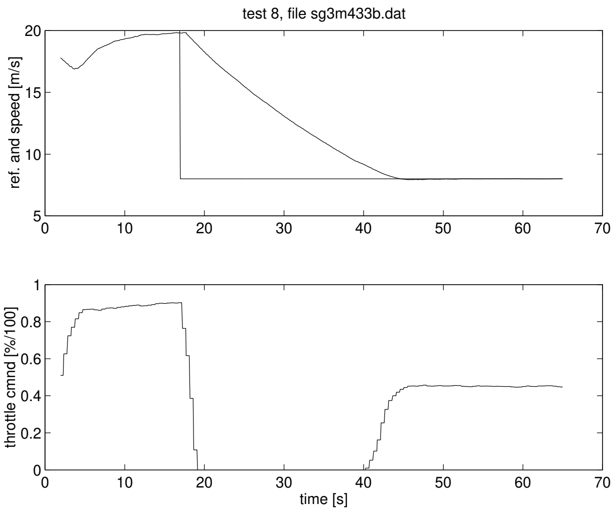

Figure 4: LCN: tracking results in 3rd gear. (Experimental results with the test vehicle.)

4.2. Geometric nonlinear controller results

An experimental tracking result with the geometric controller in the first gear is shown in figure 5.

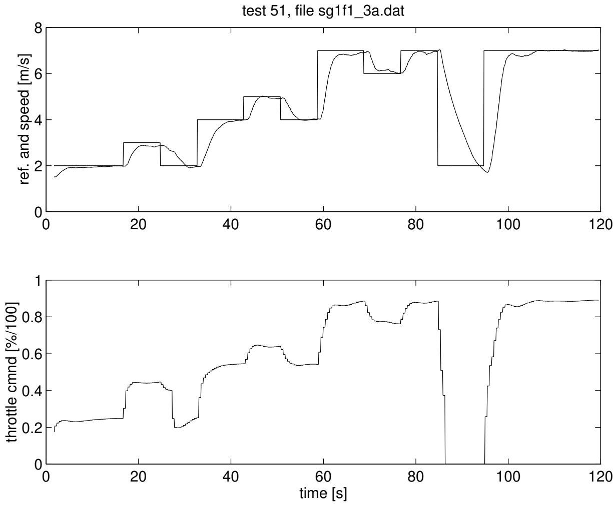

Figure 5: Geometric Nonlinear Controller: tracking result in 1st gear. (Experimental result with the test vehicle.)

The response of the control system is satisfactorily fast. A comparison with the LCN result in figure 3 shows that the initial response of the geometric controller is actually faster. The control signal is smooth indicating that no excessively high gain is used. However, close to the setpoints the response of the geometric controller becomes somewhat sluggish indicating that the bandwidth of the control system is much too low at these points. Note that the designed (nominal) bandwidth is determined by the regulating filter under the condition that the internal model represents the plant dynamics with sufficient accuracy. Thus, it is suspected that the accuracy of the FEM model in the neighbourhood of the equilibrium curve is poor. The result is a slightly inferior overall performance of the geometric controller in comparison to the LCN. It can be anticipated that a different discretisation scheme for the internal FEM model will improve the control performance of the geometric controller. In particular, a sufficient number of elements should be aligned along the equilibrium curve. Also, using a second order FEM model can be considered.

4.3. Conventional controller: linear PI

As mentioned above, a tightly tuned PI controller leads to large oscillations at low speeds. This was found to be due to excitation of the high-frequency unmodelled actuator dynamics by the sensor noise [1].

The results of using a suitably detuned PI controller with the 1st gear profile are shown in figure 6. Clearly,

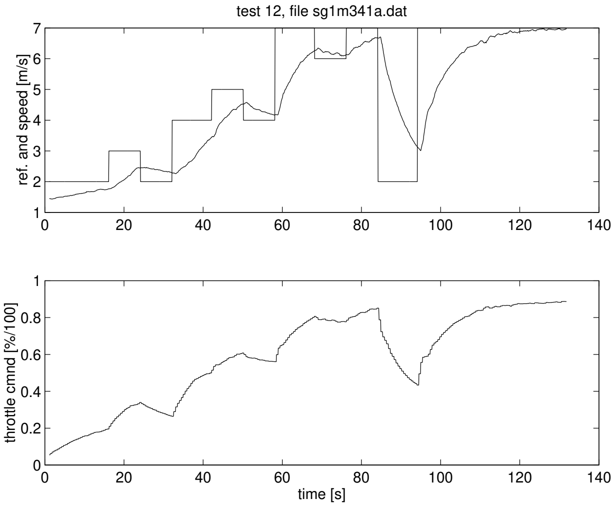

Figure 6: PI control: tracking result in 1st gear. (Experimental result with the test vehicle.)

the PI controller gives unacceptable performance in this gear.

The results of one large-signal tracking test in 3rd gear with the PI controller are shown in figure 7. The large signal responses are not satisfactory. The

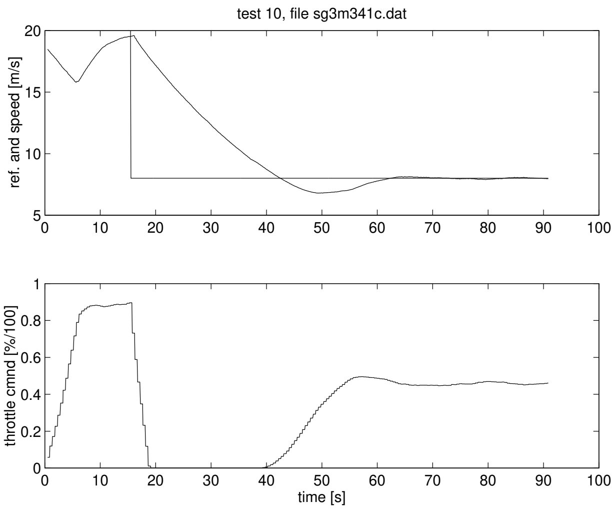

Figure 7: PI control: tracking result in 3rd gear. (Experimental results with the test vehicle.)

response on the step down has a large overshoot. This results from the inability of the PI controller to respond to significantly different off-equilibrium dynamics. (Note that the PI controller was implemented with antiwindup [15].) The nonlinear controllers coped well with this test, i.e. there was no overshoot (see figure 4).

5. Discussion of Results

The experimental results showed that the combination of measurement noise and oscillatory actuator dynamics presents the key engineering constraint in the experimental vehicle. The other main challenge is the very strong nonlinearity in the dynamics.

The LCN controller gave very good tracking performance over the whole range of vehicle operation (both large- and small-signal behaviour). Selection of the LCN design parameters was straightforward based on the servo specifications, and on knowledge of the engineering constraints. Proper selection of the observer polynomials made the controller insensitive to the measurement noise and unmodelled high-frequency dynamics. The LCN controller also gave good disturbance rejection in the challenging 10% slope test, for a variety of operating conditions (results not shown in this paper - see [1]).

The geometric nonlinear controller gives stable and smooth performance over the operational range, from 1st to 4th gear. The controller displays no sensitivity to measurement noise; this is a result of the transparent and direct tuning of the key closed-loop sensitivity functions (this is done in the same way as in the LCN, and experience from tuning the local LCN controllers was indeed exploited for the geometric controller). The disturbance rejection performance is reasonable [2].

The measurement noise, actuator performance constraints and plant nonlinearities place a basic limitation on the application of the conventional PI/PID controller. In order to avoid controller oscillations in 1st gear, a significantly 'detuned' controller must be implemented, e.g. a controller designed for 3rd gear. Such a controller has good small-signal performance in 3rd gear. However, large-signal performance of the PI controller is not tight, with significant overshoot. Clearly, it is crucial to account for the off-equilibrium behaviour of the plant. Performance of this controller in 1st gear, while stable, is extremely sluggish, and therefore unacceptable for the demands of the application.

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