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Robust $\mathscr{H}_2$ static output feedback to control an automotive throttle valve

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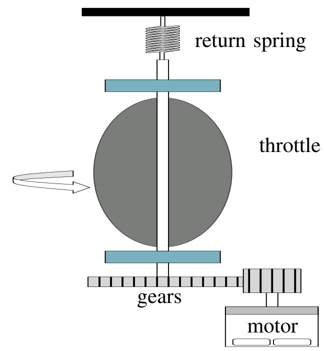
***Abstract*— The paper presents a control strategy for an automotive electronic throttle body, a device largely used into vehicles to increase the efficiency of the combustion engines. The synthesis of the proposed controller is based on a linear matrix inequality (LMI) formulation, which allows us to deal with uncertainties on the measurements of the position of the throttle valve. The LMI approach generates a suboptimal solution for the robust $\mathscr{H}_2$ static output feedback control problem, and the corresponding suboptimal control gain was evaluated in practice to control the valve position of the throttle. The usefulness of the approach has been verified not only by numerical simulations but also by real experiments taken in a laboratory prototype.**

I. Introduction

The electronic throttle body is a mechatronic device mounted in combustion engines (Fig. 1), and its role is to control a throttle valve that regulates the amount of air that inflows into the engine [1]–[10]. By adjusting the position of the throttle valve, one can control the amount of combustion inside the engine and hence the velocity and acceleration of the vehicle. When a person driving the vehicle activates the gas pedal, the corresponding pressure made on the pedal generates a signal command that must be interpreted as a reference for the aperture of the throttle. Thus, the gas pedal generates continuously a reference for the position of the throttle, and a control strategy should be able to make the position of the throttle to follow the reference as close as possible. In this setup, we aim to design a control law using the static output feedback structure, as detailed next.

Dating back to the beggining of the 70's, the static output feedback is a challenging control problem yet open in the literature. In the seminal work [11], Levine and Athans presented the problem for continuous-time linear systems and suggested an algorithm to calculate a static output feedback gain satisfying necessary conditions of optimality. However, it is well-known that this algorithm may produce unstable solutions (see Table I for an example). Many authors proposed modifications to the original Levine-Athans algorithm [12]–[15, Sec. 10.4], for both continuous and discrete time systems, seeking for improvements on the convergence. Despite of these efforts, the convergence problems persist and the necessity of starting the algorithms with a stabilizing static output feedback gain turns this scenario even more complicated [16, p. 631]. In particular, if the sensor providing the signal measurements is subject to deterioration during the process operation, then the output parameter may become uncertain and so the difficulty of obtaining an efficient control solution increases drastically.

The automotive innovation unveiled by our approach



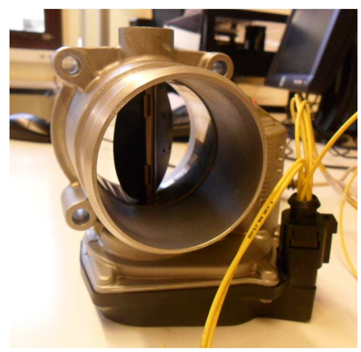


Fig. 1. Upper: throttle schematic. Lower: picture of the automotive electronic throttle body used in the experiments described in Section III.

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exploits the potential of a linear matrix inequality (LMI) formulation to design a robust controller that can cope with possibly deterioration of the sensor that measures the position of the throttle, and that drives the throttle to track an arbitrary reference signal generated by the gas pedal. In fact, such a real-time controller for the automotive throttle body represents a key component in the so-called drive-by-wire technology [1], [2]. Thus, our approach can be seen as a contribution towards the technological development of automotive systems.

Even though based on a simple idea, the design of a tracking controller for the throttle is a very difficult task, basically due to the builted-in nonlinear behaviour generated by backlash, high friction on the components, limp-home effects, and non-linear force provoked by the security return spring [4], [17], [18]. Moreover, a specific control technique useful for one throttle may be useless for another [3]. These difficulties motivated us to design a simpler but practical linear controller, based on the static output feedback derived from the minimization of an upper bound to the $\mathscr{H}_2$-norm via an LMI formulation, proved to be useful for controlling the position of a throttle device when it operates over a programmed range of interest from 30 to 40 degree. Indeed, although being nonlinear, the throttle body presents linearity in the interval of operation from 30 to 40 degrees, see Section III.

The controller implemented in our setup uses a static output feedback gain provided by the LMI formulation (designed off-line), which provides a suboptimal solution for the control problem. Though being suboptimal, the LMI formulation presented here improves the results obtained with other methods available in the literature.

The experimental outcome presented here was obtained due to two distinct controllers, as follows. We derived a controller for the nominal model (i.e., there are no uncertainties on the model), and another for the uncertain model (i.e., there are uncertainties on the measurements from the sensor of the position of the throttle). The experiments indicate that the nominal controller is effective for the system with no uncertainties, but it becomes deteriorated when uncertainties appear. In the uncertain case, the robust controller presents a much better response (see Section III-B).

II. Notation, definitions, and main result

The r-th dimensional Euclidean space is represented by $\mathscr{R}^r$ and $\|\cdot\|$ stands for the corresponding norm. The linear space made up by all $r\times s$ ($r\times r$) real matrices is denoted by $\mathscr{M}^{r,s}$ ($\mathscr{M}^r$). The trace operator is denoted by $\mathrm{Tr}\{\cdot\}$ and the identity matrix is denoted by I. Let Λ_N denote the unit simplex of N elements, i.e.,

$$\Lambda_N = \Big\{\xi \in \mathscr{R}^N : \sum_{i=1}^N \xi_i = 1 \ \text{ with } \ \xi_i \geq 0\Big\}.$$

The problem under investigation is represented by the discrete-time linear system

$$x_{k+1} = Ax_k + Bu_k + Ew_k, \quad \forall k \geq 0,\ x_0 \in \mathscr{R}^n, \tag{1}$$

where $x_k \in \mathscr{R}^n$ denotes the state vector, $u_k \in \mathscr{R}^m$ the control input, and $w_k \in \mathscr{R}^r$ the exogenous input. The system matrices $A \in \mathscr{M}^n$, $B \in \mathscr{M}^{n,m}$, and $E \in \mathscr{M}^{n,r}$ are precisely known. We assume that the system state x_k is not measured directly, but it is done indirectly via the uncertain output

$$y_k = C(\alpha)x_k, \quad \forall k \geq 0, \tag{2}$$

where matrix $C(\alpha) \in \mathscr{M}^{q,n}$ belongs to the polytope

$$\mathscr{C} := \Big\{C(\alpha) : C(\alpha) = \sum_{i=1}^N \alpha_i C_i,\ \alpha \in \Lambda_N\Big\}.$$

For sake of simplicity, we consider the control law in the static output feedback form as in (1), i.e., with $K \in \mathscr{M}^{m,q}$ as a gain matrix,

$$u_k = Ky_k, \quad \forall k \geq 0. \tag{3}$$

If we let

$$A_K(\alpha) := A + BKC(\alpha), \quad \forall \alpha \in \Lambda_N, \tag{4}$$

system (1) reads as

$$x_{k+1} = A_K(\alpha)x_k + Ew_k, \quad \forall k \geq 0,\ x_0 \in \mathscr{R}^n. \tag{5}$$

Let us now associate the closed-loop system (5) with the k-th cost by stage vector

$$z(k) = Qx(k) + Ru(k), \quad \forall k \geq 0,$$

where $Q \in \mathscr{M}^{p,n}$ and $R \in \mathscr{M}^{p,m}$ are given matrices. The transfer function from the input sequence $\{w_k\}$ to the cost by stage sequence $\{z_k\}$ is defined as $H_{wz}(\xi) = Q(\xi\mathrm{I} - A_K(\alpha))^{-1}E$, with ξ denoting the time-shift operator. The $\mathscr{H}_2$-norm of the closed-loop system (5) can be evaluated as follows.

Proposition 2.1: ([19, Lem. 1], [20, Lem. 1]). The inequality $\|H_{wz}(\xi)\|_2^2 < \mu^2$ holds for all $\alpha \in \Lambda_N$, with $A_K(\alpha)$ being a robustly stable matrix, if and only if there exist symmetric positive-definite parameter-dependent matrices $P(\alpha) \in \mathscr{M}^n$ and $W(\alpha) \in \mathscr{M}^r$ such that

$$\begin{aligned} &\mathrm{trace}(W(\alpha)) < \mu^2, \quad E'P(\alpha)E - W(\alpha) < 0, \\ &\text{and} \quad A_K(\alpha)'P(\alpha)A_K(\alpha) - P(\alpha) + Q'Q < 0, \end{aligned} \tag{6}$$

hold for all $\alpha \in \Lambda_N$.

In the sequence, the constant μ in (6) will be minimized with respect to K to compute a guaranteed $\mathscr{H}_2$-norm for the static output feedback control problem.

Before proceeding with this analysis, let us recall a stability concept for uncertain linear systems.

Definition 2.1: We say the matrix $K \in \mathscr{M}^{m,q}$ is a *robust static output feedback stabilizing gain* if all eigenvalues of the matrix $A_K(\alpha)$ as in (4) lie strictly inside the unit circle for all $\alpha \in \Lambda_N$.

A. Main result

The LMI formulation to be presented below is evaluated in two steps. It requires any state-feedback stabilizing gain as a starting point, and in particular the usual Riccati gain satisfies this property [12, p. 54]. This state-feedback gain is used into the LMIs to produce both a robust static output feedback stabilizing gain and a suboptimal solution for the corresponding $\mathscr{H}_2$ control problem. This two-step procedure represents a direct adaptation of the result from [20, Th. 2], which was inspired by the results from [21]–[23].

Theorem 2.1: Let $Z \in \mathscr{M}^{m,n}$ be some given state feedback stabilizing gain. If there exist symmetric matrices $P_i \in \mathscr{M}^n$, $W_i \in \mathscr{M}^m$, $i = 1,\ldots,N$, and matrices $F \in \mathscr{M}^n$, $H \in \mathscr{M}^p$, $M \in \mathscr{M}^m$, and $L \in \mathscr{M}^{m,q}$ such that the next LMIs hold

$$\operatorname{trace}(W_i) < \mu^2, \quad i = 1,\ldots,N, \tag{7}$$

$$E'P_iE - W_i < \mathbf{0}, \quad i = 1,\ldots,N, \tag{8}$$

$$\begin{bmatrix} -P_i & A'F + Z'B'F & Q'H + Z'R'H & C_i'L' - Z'M' \\ \star & P_i - F - F' & \mathbf{0} & F'B \\ \star & \star & \mathrm{I} - H - H' & H'R \\ \star & \star & \star & -M - M' \end{bmatrix} < \mathbf{0}, \quad i = 1,\ldots,N, \tag{9}$$

then $K = M^{-1}L$ is a static output feedback stabilizing gain, and μ is an upper bound (guaranteed cost) for the $\mathscr{H}_2$-norm of the system (1).

Proof: By multiplying (7), (8), and (9) by α_i, and summing up for $i = 1,\ldots,N$, we have

$$\operatorname{trace}(W(\alpha)) < \mu^2, \tag{10}$$

$$E'P(\alpha)E - W(\alpha) < \mathbf{0}, \tag{11}$$

$$\begin{bmatrix} -P(\alpha) & A'F + Z'B'F & Q'H + Z'R'H & C(\alpha)'L' - Z'M' \\ \star & P(\alpha) - F - F' & \mathbf{0} & F'B \\ \star & \star & \mathrm{I} - H - H' & H'R \\ \star & \star & \star & -M - M' \end{bmatrix} < \mathbf{0}, \tag{12}$$

Setting

$$U(\alpha) = \begin{bmatrix} \mathrm{I} & \mathbf{0} & \mathbf{0} & (M^{-1}LC(\alpha) - Z)' \\ \mathbf{0} & \mathrm{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathrm{I} & \mathbf{0} \end{bmatrix},$$

and multiplying (12) on the left by $U(\alpha)$ and on the right by $U(\alpha)'$, we obtain

$$\begin{bmatrix} -P(\alpha) & A_{cl}(\alpha)'F & C_{cl}(\alpha)'H \\ \star & P(\alpha) - F - F' & \mathbf{0} \\ \star & \star & \mathrm{I} - H - H' \end{bmatrix} < \mathbf{0}, \tag{13}$$

with

$$A_{cl}(\alpha) = A + BM^{-1}LC(\alpha), \quad C_{cl}(\alpha) = Q + RM^{-1}LC(\alpha).$$

Now by multiplying (13) on the left by $\begin{bmatrix} \mathrm{I} & A_{cl}(\alpha)' & C_{cl}(\alpha)' \end{bmatrix}$ and on the right by the transpose, we obtain

$$A_{cl}(\alpha)'P(\alpha)A_{cl}(\alpha) - P(\alpha) + C_{cl}(\alpha)'C_{cl}(\alpha) < \mathbf{0}, \tag{14}$$

which together with (10) and (11) assures that the closed-loop system (5) is robust static output feedback stabilizing, and μ provides an upper bound for the $\mathscr{H}_2$ cost (c.f. Proposition 2.1). ■

Remark 2.1: As the method proposed in [24, Sec. III.B, p. 1934], the LMI conditions proposed in Theorem 2.1 are specially adequated to cope with $\mathscr{H}_2$ robust static output feedback when the output matrix $C(\alpha)$ is affected by uncertainties. Uncertain output matrices can be used to represent sensor failures, which may arise due to changes in enviroment conditions, deterioration of mechanical components, etc. By means of an automotive application, presented in the next section (see Table I for an immediate comparison), we show that the conditions of Theorem 2.1 are able to generate control gains that assure a better $\mathscr{H}_2$ performance when compared to the method in [24, Sec. III.B, p. 1934].

III. Control of an Automotive Electronic Throttle Body

The aim of the project described in this section is to design two controllers for an automotive electronic throttle body using static output feedback gains obtained from Theorem 2.1. The two cases consider the output matrix with and without uncertainty, reflecting whether the existence or not of the possibility of partial failures in the sensor of the throttle imposes changes in the response of the system. Our findings corroborate that the LMI formulation of Theorem 2.1 is useful and produces better results than other approaches from the literature.

In the experimental front, we wish to control the angle of aperture (position) of the throttle valve in such a manner that it tracks a reference signal. To reach this goal, we mounted the laboratory testbed, as depicted in Fig. 2, with a Quanser Q4 Real-Time Control Board to integrate the Matlab/Simulink in the experimental setup, a Quanser UPM180-25-B-PWM Power Amplifier to supply the voltage and electrical current consumed by the equipments, and a brand new unity of the automotive electronic throttle body made up by Continental Siemens VDO, Model A2C59511705, P.N. 06F133062J, used into many vehicles. The electronic throttle body has a sensor for the position of the throttle, and it generates a proportional voltage ranging from $0V$ (completely closed) to $+5V$ (completely opened). The Quanser Q4 board sets the operation clock of the equipments at a fixed sample rate of 1 *ms*.

As discussed in the introduction, the electronic throttle body is a device subject to many nonlinear phenomena. However, when constrained to operate with position ranging from 30 to 40 degrees, it can be represented by a linear model. The nonlinearities are collected as the exogenous external perturbation to the system. This linear representation is advantageous, because it enables us to design not only a practical but also a simple controller, which generates promising results, as illustrated in the sequel.

The idea of the experiment is to assure that the throttle tracks a reference square wave oscillating between 30 and 40 degrees. To achieve this goal, we programmed the experimental setup to implement the proportional-integrative (PI) scheme as in [25, Sec. 1.8.2, p. 56], see the block representation in Fig. 3. Notice that the PI scheme is useful to minimize the steady-state error, and it can be incorporated into the system dynamics by augmenting the system state, as detailed next.

The electronic throttle system can be represented with accuracy by three states [2], [6], [26]. The first state represents the angular position of the throttle valve, denoted here by θ_k, being measured in degrees and, for sake of simplicity, resized by a scale factor of 0.1 (i.e., $\theta_k = \delta$ signifies $10 \times \delta$ degrees).

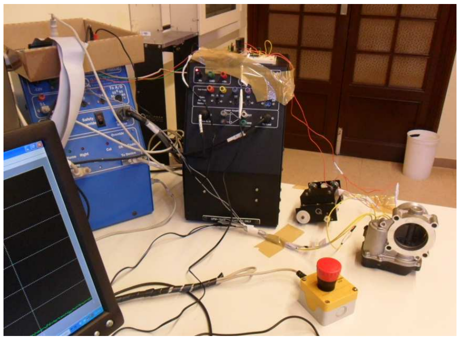


Fig. 2. Real-time laboratory testbed used to control the valve position of the electronic throttle body, according to the experimental setup described in Section III.

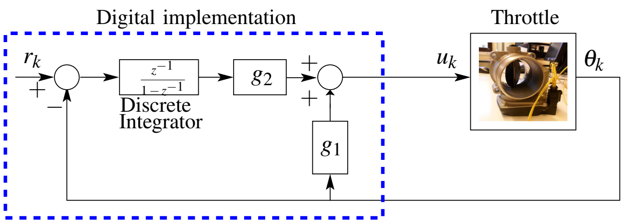


Fig. 3. Block representation of PI strategy used to control the angular position of the automotive electronic throttle body.

The other two remaining variables are non-measurables ones: the angular velocity and the electrical current consumed by the DC motor that actuates internally on the throttle device. A fourth state is included to cope with the integrator term from the PI scheme (c.f. [25, Sec. 1.8.2]) that depends on the desired position. Thus, our system state $x_k \in \mathscr{R}^4$ reads as $x_k \equiv [\theta_k\ x_{1,k}\ x_{2,k}\ x_{3,k}]'$, and this representation enabled us to obtain the following discrete-time linear system for the electronic throttle body:

$$x_{k+1} = Ax_k + Bu_k + \Gamma r_k, \quad x_0 \in \mathscr{R}^4, \tag{15}$$

with matrices

$$A = \begin{bmatrix} 0.994683 & 0.360013 & 0 & 0 \\ 0.015725 & 0.945758 & -0.142769 & 0 \\ 0 & 0.577739 & 0.876635 & 0 \\ -1 & 0 & 0 & 1 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 \\ 0 \\ -0.120648 \\ 0 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix},$$

being identified via excitation signals that were used in the testbed to vary the angular position of the throttle between 30 and 40 degrees. The input $\{r_k\}$ represents the reference tracking signal and it oscillates between the values 3 and 4.

In the sequence, we present two distinct situations regarding the sensor, one for a perfect measurement and the other for measurements with failures.

A. Control with perfect measurements on the sensor

Let us consider the electronic throttle body with perfect measurements on the sensor. In this case, the output is in the form

$$y_k = \begin{bmatrix} 1.000687 & 0 & 0 & 0 \\ 0 & 0 & 0 & 8.31 \times 10^{-4} \end{bmatrix} x_k, \quad \forall k \geq 0. \tag{16}$$

Notice that all the parameters of the system (15) and (16) are precisely known.

Taking the control in the static output feedback form

$$u_k = Gy_k, \quad \forall k \geq 0, \tag{17}$$

we aim to design the gain $G \in \mathscr{M}^{1,2}$ by minimizing the $\mathscr{H}_2$-norm for the regulator problem corresponding to (15) and (16) (i.e., assuming $r_k \equiv 0$).

Let us consider the $\mathscr{H}_2$-norm with the weight matrices

$$Q = \begin{bmatrix} 0.031623 & 0 & 0 & 0 \\ 0 & 0.031623 & 0 & 0 \\ 0 & 0 & 0.031623 & 0 \\ 0 & 0 & 0 & 0.031623 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

and $R = [0\ 0\ 0\ 0\ 23.452]'$.

In an effort to find out a solution for the $\mathscr{H}_2$ problem, we evaluated the discrete-time version of the Levine-Athans algorithm [11], [14]. The algorithm requests any static output feedback stabilizing gain as a starting point. After initializing the algorithm with the stabilizing gain $G_0 = [-0.95\ 12.5]$, we verified the algorithm converged to the unstable gain $G = [0.1961\ 1.6712]$. Seeking instead for a suboptimal solution, we evaluated the LMI formulations from [24, Sec. III.B, p. 1934] and [19, Sec. 4.2], and both did not produce a feasible solution.

Using the LMI formulation from Theorem 2.1 with Z identical to the Riccati gain [12, p. 54] and minimizing μ^2, we obtained a suboptimal solution for the problem. In addition, when the static output gain obtained from Theorem 2.1 is taken to initialize the discrete-time Levine-Athans algorithm, then it rapidly converges, indicating that the necessary conditions of optimality were attained. See Table I for a detailed comparison.

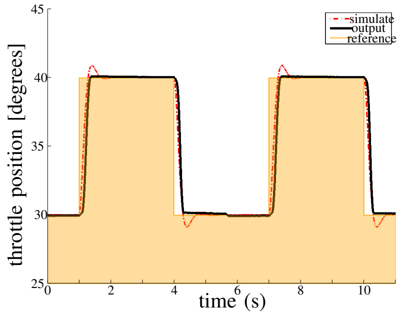
To evaluate the experimental response of the throttle, we applied in the reference input a square wave signal oscillating from 30 to 40 degrees, for four different frequencies, see Fig. 4. By increasing the frequency, the response tends to deteriorate, a normal ocurrence due to the mechanical limitations as already investigated in [10, p. 3904].

TABLE I

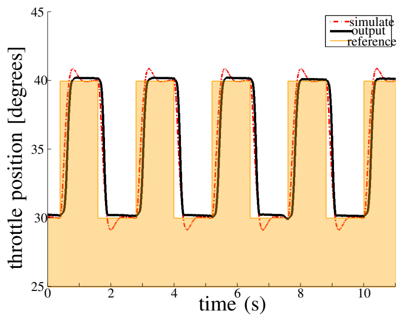
COMPARISON OF THE $\mathscr{H}_2$-COST DUE TO DIFFERENT METHODS.

Method	$\mathscr{H}_2$-cost	Gain
[24, Sec. III.B, p. 1934]	–	–
[19, Sec. 4.2]	–	–
Theorem 2.1	58.8597	$G = [-0.2003\ 1.5460]$
Levine-Athans [11][a]	$+\infty$	$G = [0.1961\ 1.6712]$[c]
Levine-Athans [11][b]	58.8500	$G = [-0.2004\ 1.5460]$

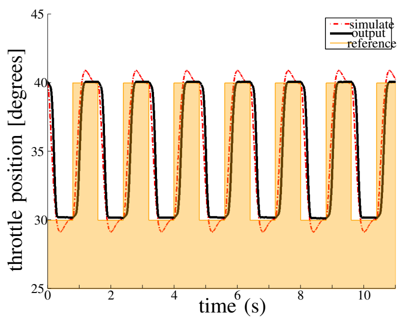
[a] Initiated with the stabilizing output gain $G_0 = [-0.95\ 12.5]$.
[b] Initiated with the stabilizing output gain $G_0 = G$ from Theorem 2.1.
[c] Unstable gain.



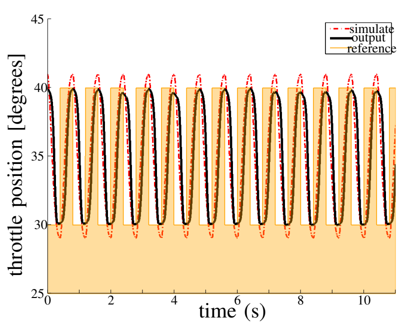
(a) Square wave at 0.167 Hz.



(b) Square wave at 0.417 Hz.



(c) Square wave at 0.625 Hz.



(d) Square wave at 1.250 Hz.

Fig. 4. Real-time throttle position (in black) obtained from the experimental testbed due to four distinct square wave references (in orange) and their simulated counterparts (in red). The controller was designed according to the $\mathscr{H}_2$ static output feedback control law of Theorem 2.1.

B. Robust control for sensor with failures

Over the life-time of a vehicle, it is expected that the electrical contacts that connect the electronic throttle body and the controller deteriorate, in the sense that some phenomena such as fretting corrosion may induce severe fluctuations of the contact resistance [27]. These facts can be interpreted as partial failures of the sensor because they alter the quality of the measurements. In particular, the controller must rely on this sensor, even though it may be influenced by some sort of deterioration. In fact, as illustrated in the sequence, a robust controller designed to take this deterioration into account may produce better results than the nominal one. This interesting behaviour was verified in our laboratory testbed, in which the equipments were modified to generate deteriorated measurements for the position, and a robust controller designed by Theorem 2.1 was implemented to deal with such situation.

It is assumed that the sensor may lose 50% of the intensity of its signal, and to include this characteristic into the model, we associate the system (15) with the uncertain output

$$y_k = \begin{bmatrix} 0.500343(\alpha+1) & 0 & 0 & 0 \\ 0 & 0 & 0 & 8.31\times 10^{-4} \end{bmatrix} x_k, \quad 0 \le \alpha \le 1, \quad \forall k \ge 0. \quad (18)$$

We say the output sensor is deteriorated when $0 \le \alpha < 1$, and, in particular, when $\alpha = 1$ we recover the nominal output matrix given in (16).

By evaluating Theorem 2.1 for the uncertain (18), we obtain the guaranteed $\mathscr{H}_2$-cost with value 61.9835 and the corresponding robust controller is given by

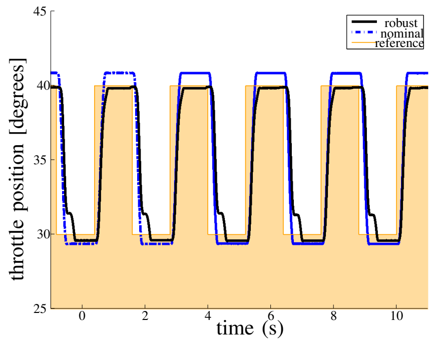
$$G_{rob} = [-0.2842 \ 1.5379].$$

Fig. 5 shows the real-time response of the system due to both the robust controller G_{rob} and the nominal one G from Table I, collected for the degradated values $\alpha = 0.2$ and $\alpha = 0$. Fig. 5 indicates that the robust controller presents a better response in comparison with the nominal one. This experiment suggests that degradated measurements make the nominal controller produce unsatisfactory responses, and a robust controller can be a reasonable alternative when the sensor of the throttle is subject to such kind of failures.

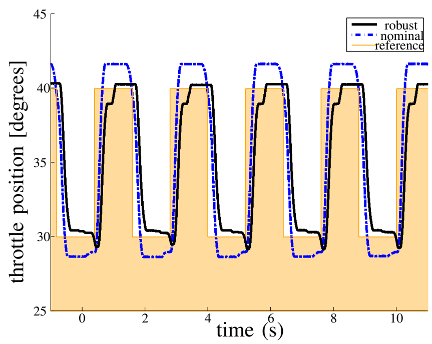
IV. Concluding Remarks

The paper presented an LMI formulation (Theorem 2.1), useful to control in practice the position of an automotive electronic throttle body. In fact, we designed a suboptimal solution to the $\mathscr{H}_2$ static output feedback control of the throttle device. An advantage of our approach, for the nominal case in which the output sensor works perfectly, is that it was helpful for finding a solution satisfying the necessary conditions of optimality, as exemplified in Table I.

Under partial failures on the sensor, which has accuracy varying from 100% to 50% of its signal intensity and incorporated into the model through the variation of α, we designed an appropriate robust controller to the throttle that was able to handle this practical situation. Experiments were taken in a laboratory testbed to compare the response of the



(a) Sensor with degradation at $\alpha = 0.2$.



(b) Sensor with degradation at $\alpha = 0$.

Fig. 5. Real-time position of the throttle, evaluated to both nominal and robust controllers, when the sensor becomes deteriorated. It can be seen that the robust controller (in black) produces a better response than the nominal one (in dotted blue).

throttle by using both the nominal and robust controllers, and the robust one presented a superior performance when the output sensor becomes deteriorated due to some partial failures. Further investigation is under way to consider the full range of operation for this equipment.

References

[1] C. Rossi, A. Tilli, and A. Tonielli, "Robust control of a throttle body for drive by wire operation of automotive engines," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 6, pp. 993–1002, 2000.

[2] R. Conatser, J. Wagner, S. Ganta, and I. Walker, "Diagnosis of automotive electronic throttle control systems," *Control Engineering Practice*, vol. 12, no. 1, pp. 23–30, 2004.

[3] G. Panzani, M. Corno, and S. M. Savaresi, "On adaptive electronic throttle control for sport motorcycles," *Control Engineering Practice*, vol. 21, no. 1, pp. 42–53, 2013.

[4] J. Deur, D. Pavković, N. Perić, M. Jansz, and D. Hrovat, "An electronic throttle control strategy including compensation of friction and limp-home effects," *IEEE Trans. Industry Appl.*, vol. 40, no. 3, pp. 821–834, 2004.

[5] M. Vasak, M. Baotic, I. Petrovic, and N. Peric, "Hybrid theory-based time-optimal control of an electronic throttle," *IEEE Trans. Industrial Electronics*, vol. 54, no. 3, pp. 1483–1494, 2007.

[6] P. Mercorelli, "Robust feedback linearization using an adaptive PD regulator for a sensorless control of a throttle valve," *Mechatronics*, vol. 19, no. 8, pp. 1334–1345, 2009.

[7] X. Yuan and Y. Wang, "A novel electronic-throttle-valve controller based on approximate model method," *IEEE Trans. Industrial Electronics*, vol. 56, no. 3, pp. 883–890, 2009.

[8] M. di Bernardo, A. di Gaeta, U. Montanaro, and S. Santini, "Synthesis and experimental validation of the novel LQ-NEMCSI adaptive strategy on an electronic throttle valve," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 6, pp. 1325–1337, 2010.

[9] M. Reichhartinger and M. Horn, "Application of higher order sliding-mode concepts to a throttle actuator for gasoline engines," *IEEE Trans. Industrial Electronics*, vol. 56, no. 9, pp. 3322–3329, 2009.

[10] Y. Pan, U. Ozguner, and O. H. Dagci, "Variable-structure control of electronic throttle valve," *IEEE Trans. Industrial Electronics*, vol. 55, no. 11, pp. 3899–3907, 2008.

[11] W. Levine and M. Athans, "On the determination of the optimal constant output feedback gains for linear multivariable systems," *IEEE Trans. Automat. Control*, vol. 15, no. 1, pp. 44–48, 1970.

[12] B. D. O. Anderson and J. B. Moore, *Optimal Control: Linear Quadratic Methods*. Prentice-Hall, Inc., 1989.

[13] P. Makila, "On the Anderson-Moore method for solving the optimal output feedback problem," *IEEE Trans. Automat. Control*, vol. 29, no. 9, pp. 834–836, 1984.

[14] P. Makila and H. T. Toivonen, "Computational methods for parametric LQ problems – A survey," *IEEE Trans. Automat. Control*, vol. 32, no. 8, pp. 658–671, 1987.

[15] V. Syrmos, C. Abdallah, P. Dorato, and K. Grigoriadis, "Static output feedback: a survey," *Automatica*, vol. 33, pp. 125–137, 1997.

[16] J. Gadewadikar, F. L. Lewis, K. Subbarao, K. Peng, and B. M. Chen, "H-infinity static output-feedback control for rotorcraft." *Journal of Intelligent and Robotic Systems*, vol. 54, no. 4, pp. 629–646, 2009.

[17] D. Pavković, J. Deur, M. Janszb, and N. Perić, "Adaptive control of automotive electronic throttle," *Control Engineering Practice*, vol. 14, no. 2, pp. 121–136, 2006.

[18] U. Montanaro, A. di Gaeta, and V. Giglio, "Robust discrete-time MRAC with minimal controller synthesis of an electronic throttle body," *IEEE/ASME Trans. Mechatronics*, vol. 19, no. 2, pp. 524–537, 2014.

[19] M. C. de Oliveira, J. C. Geromel, and J. Bernussou, "Extended H_2 and H_∞ norm characterizations and controller parametrizations for discrete-time systems," *Internat. J. Control*, vol. 75, no. 9, pp. 666–679, 2002.

[20] H. R. Moreira, R. C. L. F. Oliveira, and P. L. D. Peres, "Robust H_2 static output feedback design starting from a parameter-dependent state feedback controller for time-invariant discrete-time polytopic systems," *Optim. Control Appl. Meth.*, vol. 32, no. 1, pp. 1–13, 2011.

[21] D. Mehdi, E. K. Boukas, and O. Bachelier, "Static output feedback design for uncertain linear discrete time systems," *IMA J. Math. Control Inform.*, vol. 21, pp. 1–13, 2004.

[22] D. Arzelier, D. Peaucelle, and S. Salhi, "Robust static output feedback stabilization for polytopic uncertain systems: improving the guaranteed performance bound," in *4th IFAC Symp. Robust Control Design (ROCOND 2003), Milan, Italy*, 2003.

[23] D. Peaucelle and D. Arzelier, "An efficient numerical solution for H_2 static output feedback synthesis," in *European Control Conf. 2001, Porto, Portugal*, 2001.

[24] J. Dong and G. Yang, "Static output feedback control synthesis for linear systems with time-invariant parametric uncertainties," *IEEE Trans. Automat. Control*, vol. 52, no. 10, pp. 1930–1936, 2007.

[25] E. Ostertag, *Mono- and Multivariable Control and Estimation: Linear, Quadratic and LMI Methods*. New York, USA: Springer-Verlag, 2011.

[26] X. Yuan, S. Li, Y. Wang, W. Sun, and L. Wu, "Parameter identification of electronic throttle using a hybrid optimization algorithm," *Nonlinear Dynamics*, vol. 63, pp. 549–557, 2011.

[27] M. Braunovic, N. K. Myshkin, and V. V. Konchits, *Electrical Contacts: Fundamentals, Applications and Technology*. Boca Raton, FL, USA: CRC Press, 2007.