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ECOPACE: Estimation and control of delayed periodic systems: Application to engine optimization

Young Teams Project
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PI: Zs. Lendek
Technical University of Cluj-Napoca, România

Objectives and results of the 2019 phase

The 2019 phase was entitled *Estimation and control*. The deliverables of this phase were 1) a conference paper on the analysis and 2) a submitted journal paper on the design of observers. The project website is online at `http://lendek.net/TE11`.

In the sequel, after a short summary of the previous activities, we describe the activities in the project this year, and how they correspond to the deliverables and to the objectives of the project.

Some technical background on air-fuel ratio control is important to understand the remainder of the report. The latest trends in the control of engines are directed towards the design of increasingly economic and less polluting cars and thus the need for advanced strategies to reduce resource consumption and emissions rises. Current control algorithms rely heavily on experimental calibration techniques, which often achieve suboptimal performance. Cylinder-to-cylinder air-fuel ratio (AFR) control in internal combustion engines with multiple cylinders is one of the technologies developed to satisfy emission regulations. Because modern engines use separate fuel injectors for each cylinder, the fueling system can in principle be controlled independently for each cylinder. However, the variables required cannot be measured and controllers are not readily available. Thus, development of algorithms beyond existing concepts has become critical.

First-principle models have been developed for most engine parts. However, these models are usually simplified by reducing the model order and by linearizing it. The resulting control-oriented model commonly contains parameters which vary as a function of the operating conditions (e.g. engine speed). The controllers designed based on these models often use gain scheduling methods to match the parameters used in the model, but the performance may not be adequate as the cumulative emissions predictions can have extremely large errors due to the experimentally chosen and verified controller gains. To improve the efficiency, one should take into account the cyclic behavior and study the phenomena involved at the level of each cylinder. Advanced control formulations require sensors and are developed using overly simplified plant models. Adding a sensor cannot be a general option and many of the variables cannot be measured. Thus, before developing controller design methods for realistic models that are nonlinear, periodic, and delayed, observer design methods to estimate the variables of interest are necessary. A prerequisite of this is the analysis of the models.

Analysis

The air-fuel ratio (AFR) represents the ratio between the amount of air and the amount of fuel that have been injected in the cylinder during the intake phase. The AFR is measured by the lambda sensor. The main issue when controlling the AFR is the variable transport delay due to the position of the lambda sensor. The performance of the controller may be improved by taking into account this delay. Looking at the bigger picture, the delay is in fact a variable transport delay, i.e., it does not depend directly on time, but on a time-varying variable. In the literature, the variable transport delay has been considered as fixed, obtained by approximation or by mapping. Variations have also been proposed as PI + Smith controllers or a Smith predictor structure combined with a PID controller.

Most air-fuel ratio models are nonlinear and we use the Takagi-Sugeno (TS) fuzzy representation is used to handle the nonlinearities [1]. TS models can provide an exact representation of the nonlinear system and have been used in the literature for several applications [2].

An original transformation to the crank-angle domain allows fixing the variable transport delay [3] which becomes equal to a number of samples. However, the methodology to design the controller presented in [3] is too conservative and it is not possible to include an integral action for reference tracking and external disturbance rejection. Results suggest that by including the constant delay in the augmented state, this problem may be overcome.

A publication on this topic has been submitted to a journal.

Approach

TS models are nonlinear, convex combinations of local linear models, and are able to exactly represent large class of nonlinear systems in a compact set of the state-space [4]. For TS models, well-established methods and algorithms have already been developed to design controllers and observers. In general, Lyapunov synthesis is used, employing common quadratic, piecewise quadratic, or, recently, nonquadratic [5, 6] Lyapunov functions. The analysis and design conditions are generally in the form of linear matrix inequalities (LMIs), which can be solved using convex optimization methods [7].

In the discrete-time case, since the variation of the Lyapunov function does not involve any derivatives and thus further conditions, non-quadratic Lyapunov functions have shown a real improvement [5, 8, 9, 10, 11, 6] for developing global stability and design conditions. The solutions obtained by non-quadratic Lyapunov functions include and extend the set of solutions obtained using the quadratic framework.

Observer design

State estimation is an important problem, either because it is physically not possible to measure some of the states or because the sensors are too expensive. For this reason, starting from [12, 13], much research has been done to design state estimators. The model of a dynamic system usually contains a set of nonlinear terms, which needs to be taken into consideration for observer design. Linear approximations provide local, but nonlinear observers may be able to satisfy global performances.

An important nonlinear observer design approach was presented in [14] for continuous-time state estimation, and extended in e.g., [15, 16]. This approach assumes that the unmeasured-state nonlinear terms satisfies a slope-restricted condition. A drawback of this condition is that the rest of the error dynamics are considered linear.

Starting from this idea, we have considered observer design for nonlinear systems represented by TS fuzzy models. TS fuzzy models can be used to design nonlinear observers. However, although in the case when the premise variables are measured the observer can easily be designed, in many applications the premise variables depend on unmeasured states. This problem is usually solved by including a Lipschitz condition on the membership functions. However the Lipschitz condition is very conservative. The method of [14] has been developed for linear systems, where all the nonlinearities are compressed into a nonlinear vector function. We have extended the approach for nonlinear systems represented by TS models, where that part of the nonlinearities that depends only on measured variables is considered in the polytopic model, while the part that depends on unmeasured variables is included in the nonlinearities that are handled with the approach of [14]. We have developed conditions both in the continuous and in the discrete-time case. The results in the continuous-time case have been published in

- Z. Nagy, Zs. Lendek, Observer-based controller design for Takagi-Sugeno fuzzy systems with local nonlinearities. In Proceedings of the 2019 IEEE International Conference on Fuzzy Systems, pages 1-6, New Orleans, USA, June 2019.

while for the discrete-time case a publication has been submitted to the 2020 European Control Conference.

Controller design

While most of the enumerated results require the full state information to be available, in general this is not possible. Thus several output feedback controller design methods have been developed, but – due to the computational complexity – these rely on conservative Lyapunov functions. To reduce this conservativeness, we have proposed to use nonquadratic Lyapunov functions and non-PDC controllers, thus providing an alternative output feedback controller design.

This research was developed in an international collaboration between the project members, the University of Valenciennes, France, and the Sonora Institute of Technology, Mexico. Resulting publication:

- V. Estrada-Manzo, Zs. Lendek, T.M. Guerra, An alternative LMI static output feedback control design for discrete-time nonlinear systems represented by Takagi-Sugeno models, ISA Transactions, vol. 84, pages 104-110, 2019

Further, we have considered a similar setup as for observer design, i.e., handling some of the nonlinearities by a slope-restricted conditions. First, we developed results for the linear case, where all the nonlinearities are compressed in a vector function that satisfies such a condition and the stability of the closed-loop system has to be ensured. Second, we have extended the result for polytopic models, where some of the nonlinearities are separated in the membership functions, while others satisfy the conditions that their slope is restricted. Both continuous and discrete time systems have been considered. For the continuous-time case, we have also developed conditions for observer-based controller design. These results have been published in

- Z. Nagy, Zs. Lendek, Observer-based controller design for Takagi-Sugeno fuzzy systems with local nonlinearities. In Proceedings of the 2019 IEEE International Conference on Fuzzy Systems, pages 1-6, New Orleans, USA, June 2019.

while for the discrete-time case a journal publication is being prepared.

Next, we have considered time-delay nonlinear systems, with delay both in the states and in the input. Note that although the case when the input is delayed is quite common in real systems, it is rarely considered in the literature. Similarly to the previous results, the nonlinearities were handled on the one hand by the membership functions and on the other hand by a slope-restricted condition. Using a simple Lyapunov function, we have developed conditions for the stabilization of the system. The results have been submitted for possible publication in the 2020 IFAC World Congress.

All the developed results, both for controller and observer design have been thoroughly tested on numerical examples.

Others

In the linear case, where all the nonlinearities are compressed in a vector function that satisfies a slope-restricted condition, we have also considered the setup of tracking a dynamic target. The results obtained have been submitted for possible publication in the 2020 American Control Conference.

We have co-organized a special session at the 5th IFAC Conference on Intelligent Control and Automation Sciences and are organizing an Invited Open track on this and related research at the 2020 IFAC World Congress, Berlin, Germany and a special session at the 2020 IEEE World Congress on Computational Intelligence. In our talks we outline the research undertaken in this project.

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