Control of the NASA Langley 16-Foot Transonic Tunnel with the Self-Organizing Map

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Abstract

A predictive, multiple model control strategy is developed based on an ensemble of local linear models of the nonlinear system dynamics for a transonic wind tunnel. The local linear models are estimated directly from the weights of a self-organizing map (SOM). Multiple self-organizing maps collectively model the global response of the wind tunnel to a finite set of representative prototype controls. These prototype controls partition the control space and incorporate experiential knowledge gained from decades of operation. Each SOM models the combination of the tunnel with one of the representative controls, over the entire range of operation. The SOM based linear models are used to predict the tunnel response to a larger family of control sequences which are clustered on the representative prototypes. The control sequence which corresponds to the prediction that best satisfies the requirements on the system output is applied as the external driving signal.

Each SOM provides a codebook representation of the tunnel dynamics corresponding to a prototype control. Different dynamic regimes are organized into topological neighborhoods where the adjacent entries in the codebook represent the minimization of a similarity metric which is the essence of the self organizing feature of the map. Thus, the SOM is additionally employed to identify the local dynamical regime, and consequently implements a switching scheme that selects the best available model for the applied control.

Experimental results of controlling the wind tunnel, with the proposed method, during operational runs where strict research requirements on the control of the Mach number were met, are presented. Comparison to similar runs under the same conditions with the tunnel controlled by either the existing controller or an expert operator indicate the superiority of the method.

Introduction

Many modern approaches to the control of complex industrial process are quite naturally based on a model which accurately describes the evolution of the process as a function of its current state and the application of control inputs over a reasonable interval into the future. Multiple models of the process may provide a convenient means of providing this description under a wide variety of conditions [2]. The use of multiple models necessitates a means of switching among the available models to the one that best describes the current operating environment. In a multiple model predictive controller framework, the control signals are generated by first switching to the model of the process that best matches the recently observed input-output behavior, then determining the best control signal by predicting what the process will do, while either implicitly or explicitly observing known constraints on the state of the system and the control. When a finite number of models are used to cover a broad range of system dynamics, coverage of the full dynamical space becomes an issue.

The Kohonen self-organizing map (SOM) [1], is employed as the basis for dynamic modeling and extended to a control framework, where the modeled system is nonautonomous [4]. The idea here is that the SOM , trained with responses from the full operating range, provides a basis for local dynamic models that fully cover the dynamical space corresponding to a *representative* or *prototype* control. For the application, we were able to cluster the inputs onto a small set of prototypes. Local dynamic models which are linear in the control are derived from the SOM, enabling computationally efficient prediction of the system response to a larger set of pre-defined control inputs. We exploit the advantage of an approximate local model that is linear in the control input in contrast to an exact model which has a nonlinear dependence on the control as established by Narendra [3].

Switching Controller

The experimental framework that evolved was essentially a predictive control scheme that used multiple models of the plant with *switching*. The controller switches between multiple, SOM-based models which, collectively, describe the global input-output behavior of the tunnel. The tunnel response to a set of candidate controls is predicted p steps ahead, using the currently selected model. The overall system, referred to as the PMMSC, for **P**redictive **M**ultiple **M**odel **S**witching **C**ontroller, is shown in Figure 1. It is composed of the following major functions:

1) The recent control input, $u(k-1), u(k-2), \ldots, u(k-m)$, is clustered on a set of prototype control inputs which will choose one of the Kohonen self-organizing maps (SOM);

2) The selected SOM identifies the local dynamics of the tunnel based on the past $n+1$ Mach number measurements, $\mathbf{M} = M(k), M(k-1),..., M(k-n)$, and chooses a winning processing element (PE);

3) A linear predictor associated with each PE predicts the Mach number response *p* steps into the future for each of the candidate controls;

4) The predicted effectiveness of the candidate control inputs is evaluated over the last $(p-l)$ steps of the *p* steps-ahead predictions;

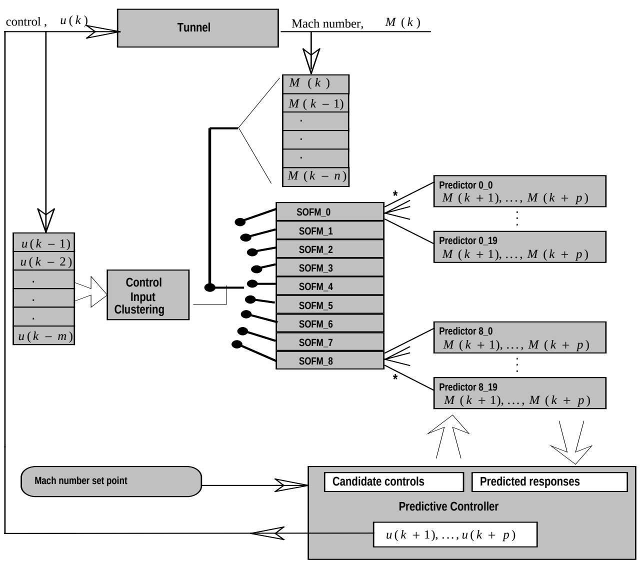

Figure 1. Predictive, Multiple Model Switching Controller

5) The control input that provides the best response with respect to the Mach number set point is chosen as the next control, *u(k)*.

Experimental Results

Figure 2 compares the results of controlling the Mach number to several different set points over a nominal 28 minute interval. Mach number set points of 0.95, 0.9, and 0.6 are common to all three controllers. The PMMSC controls the Mach number to 0.85 versus 0.8 for the operator and existing controller. This difference is minimal and still provides a reasonable basis for comparison of the controllers. The test article angle-of-attack was varied extensively during all three runs.

Derived metrics to quantify the comparisons between the three cases are the *time out of tolerance* and the $L1$ norm of the control input, *u*. The *time out of tolerance* is cumulative sum of time that the measured Mach number deviates beyond the required tolerance of 0.003.

Conclusion

Significant improvements in controlling the Mach number in a transonic wind tunnel have been obtained experimentally with the PMMSC. The use of self-organizing maps to discretize the state space, to identify the local dynamic models and predict responses to similar control inputs has been shown to be a viable method of obtaining an error minimizing control.

References

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Criteria	Existing	Operator	PMMSC	%
Out of tol	329 s	310 s	266 s	19 / 17
L1 [u]	424	466	374	12 / 20

Table 1. Comparison for controlling to several set points

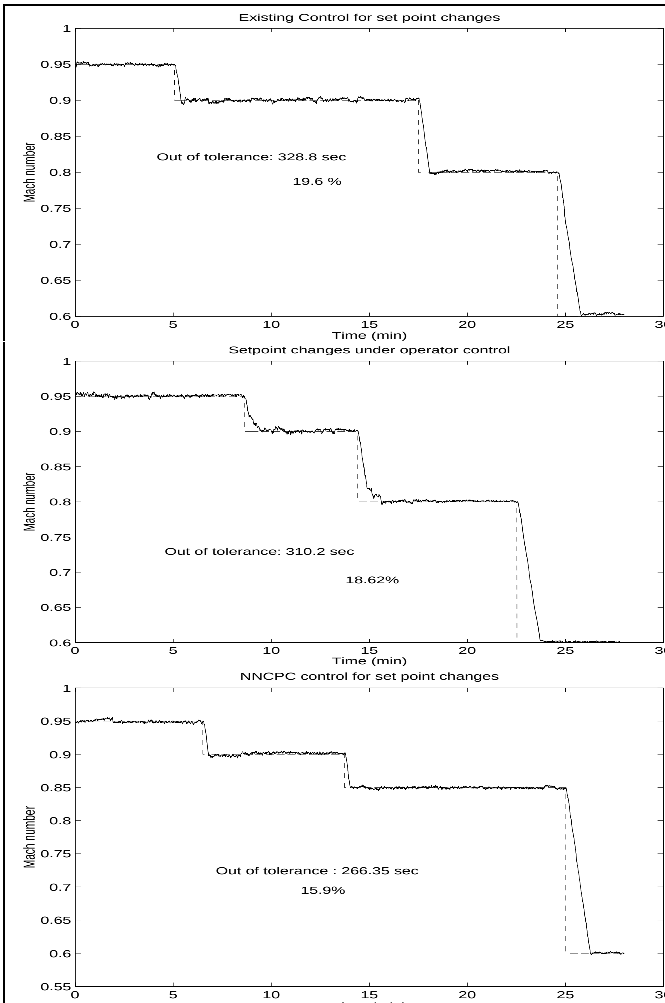

Figure 2. Mach number while controlling to several set points with existing , operator, and PMMSC control