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From model-based control to data-driven control: Survey, classification and perspective

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ABSTRACT

This paper is a brief survey on the existing problems and challenges inherent in model-based control (MBC) theory, and some important issues in the analysis and design of data-driven control (DDC) methods are here reviewed and addressed. The necessity of data-driven control is discussed from the aspects of the history, the present, and the future of control theories and applications. The state of the art of the existing DDC methods and applications are presented with appropriate classifications and insights. The relationship between the MBC method and the DDC method, the differences among different DDC methods, and relevant topics in data-driven optimization and modeling are also highlighted. Finally, the perspective of DDC and associated research topics are briefly explored and discussed.

1. Model based control theory

Since the late 1960s, modern control theory has been fully grown and developed. Its main branches, system identification, adaptive control, robust control, optimal control, variable structure control, and stochastic system theory, have been extensively used in industrial processes, aerospace, traffic systems, and other applications. However, the field of modern control theory still holds many challenging topics from both theoretical aspects and practical perspectives.

1.1. Modeling and identification

The introduction of the parametric state-space model by Kalman in 1960 and together with optimal control gave birth to the modern control theory, which is also called model-based control (MBC) [70,71]. Successful applications abounded, particularly in aerospace, where accurate models were available.

Modern control theory includes control theory for both linear and nonlinear systems. Typical linear control systems design methodologies include zero-pole assignment, LQR design, and robust control. For nonlinear systems, typical controller design methods include *Lyapunov*-based controller designs, backstepping controller design, and feedback linearization, etc. All these controller design methodologies are regarded as typical MBC system design. In applications of MBC theory, the first step is modeling the plant, or identifying the plant model, and then designing the controller based on the plant model obtained using the certainty equivalence principle with the faith that the plant model represents the true system. Therefore, the modeling and identification of the plant is necessary to MBC theory.

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Modeling a plant using first principles requires that the parameters be calibrated on-line or off-line using measured data. Identification theory may be used to develop a plant model within a model set that either covers the true system or approximates it in terms of bias and variance error on the identified model. Modeling, whether by the first principles or by identification from data, is an approximation of the true system, and some error is inevitable. Unmodeled dynamics always exist in the modeling process. Consequently, the closed loop control system, designed on MBC approaches which are thought to be unalterable, is inherently less safe and less robust because of these unmodeled dynamics [5–8].

In order to preserve the obvious advantages of MBC design while increasing robustness against model errors, much effort has been expended toward the development of robust control theory. Various ways of describing model errors in the configuration of closed loop systems have been considered. These include additive and multiplicative descriptions and the assumption on *priori* bounds on noise or modeling errors or uncertainties. However, the model uncertainty descriptions upon which robust control design methods have been based are not consistent with the methods delivered by physical mathematical modeling and identification modeling [86]. Modeling by first principles and by identification from data have very little to offer in terms of explicit quantification of errors. The main stumbling block in the application of model-based robust control design techniques is the lack of adequate, practical uncertainty descriptions [40].

It is very natural that, first spending a significant amount of efforts to obtain a very accurate model (including a model uncertainty set) for the unknown system by mechanism modeling or identification techniques, then computing a model based robust controller from this model and its uncertainty set. However, there are both practical and theoretical obstacles for the researchers who want to establish the perfect control theory. First, unmodeled dynamics and the robustness are a pair of inevitable twinborn problems and they cannot be solved simultaneously within the conventional MBC theoretical framework. Second, the more accurate the model is, the more effort or cost must be spent on the design of the control system. Until now, there has been no efficient way of producing an accurate plant model. Accurate modeling can be more difficult than control system design. Furthermore, there is no well-recognized means of addressing certain types of complexity, such as that observed in plants whose parameters vary quickly or whose structures change over time. If the system dynamics is of too high order, we cannot use it as a control system design model. Even if it were used as a model for control system design, this would typically lead to a controller with too high order. High-order controllers are not suitable to use in practice and reduction of model or controller order must be performed. Modeling an accurate high-order model to target high performance for a control system design, then having to perform a controller order reduction or model simplification for a low order controller, seems paradoxical. The last but not least is the persistence of excitation or persistently exciting inputs condition for modeling. Without the persistently exciting inputs, an accurate model cannot be produced. Without an accurate model, most model-based theoretical results of a closed loop control system scheme, such as stability and convergence, cannot be guaranteed as what they are claimed when they are used in practice [6–8,40].

1.2. Model based controller design

The certainty equivalence principle is a fundamental assumption in MBC theory. Model-based controller design may not work well if the plant model does not fall into the assumed model set. For this reason, designing a controller using an inaccurate model could leads to either bad performance or an unstable closed-loop system. Arbitrarily small modeling errors can lead to arbitrarily bad closed-loop performance [121]. For adaptive control, Rohr's counterexample has demonstrated that reported stable adaptive control systems based on some assumptions made about the system model may show certain unexpected behavior in the presence of unmodeled dynamics [108,109]. Rohr's counterexample is a wake-up call for researchers, who began to contemplate robustness issues in adaptive control.

Even when the model is accurate enough, the results of theoretical analysis, such as those covering stability, convergence and the robustness of a closed loop control system, proven by beautifully rigorous mathematical processes, are not always valuable if the additional assumptions made about the system are not correct. The architecture of MBC theory is shown in Fig. 1. This diagram shows that the system model and assumptions are the starting point for controller design, and also the destination of the MBC control system analysis. The key issue is that there exists a gap between the controlled plant and the system model built using assumptions, and this gap seems to cease to exist in controller design and control system analysis.

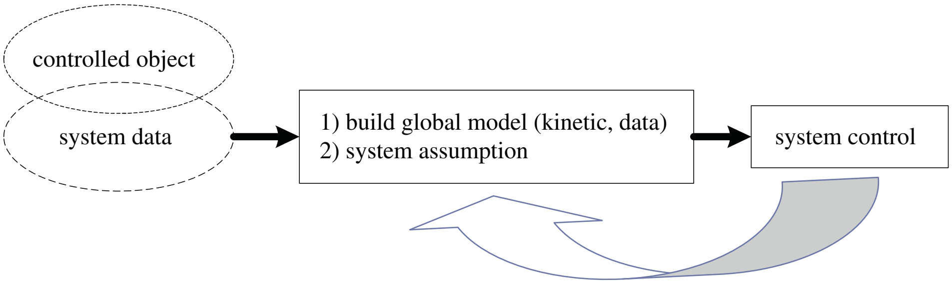

Fig. 1. Architecture of MBC theory.