بسم الله الرحمان الرحیم
و صلی الله علیکم یا اهل البیت النبوه

Introduction to Data-Driven Control Systems: From Model-Based to Data-Driven Control

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"In God we trust, all others must bring data."
W. Edwards Deming

Introductory Remarks

- Model-based control system design has been the dominant paradigm in control system education and design. Nearly all courses in control theory deal with different aspects of model-based analysis and design techniques. However, in the past two decades, there has been a tremendous interest in **data-driven control systems**. The exponentially increasing number of research papers in this field and the growing number of courses offered in universities worldwide on the subject show this trend.

- Kalman's state-space concept in 1960 and the notion of optimality in control systems resulted in remarkable model-based control design methods. Prior to this, most control designs were based on transfer function models (Bode, Nyquist plots or the root-locus and Nichols charts). The data-driven technique of Ziegler and Nichols PID parameter tuning was also the most widely used control technique, considered *the first data-driven control approach*.
- Later adaptive and robust control methodologies were developed to tackle the time-varying and uncertainty problems and successfully controlled many real-world and industrial plants. However, both strategies require mathematical models and prior plant assumptions mandated by the theory.

- An alternative approach to control system design has re-emerged to circumvent the necessity of deriving off-line or online plant models: The **data-driven approach**.

- Many plants regularly generate and store huge amounts of operating data at specific instants of time. Such data encompasses all the relevant plant information required for control, estimation, performance assessment, decision-making, and fault diagnosis. This data availability has facilitated the design of data-driven control systems.

Model-Based Control System Design Approach

- The seminal paper of Maxwell: *On Governers*

The following communications were read :—

I. "On Governors." By J. Clerk Maxwell, M.A., F.R.SS.L. & E. Received Feb. 20, 1868.

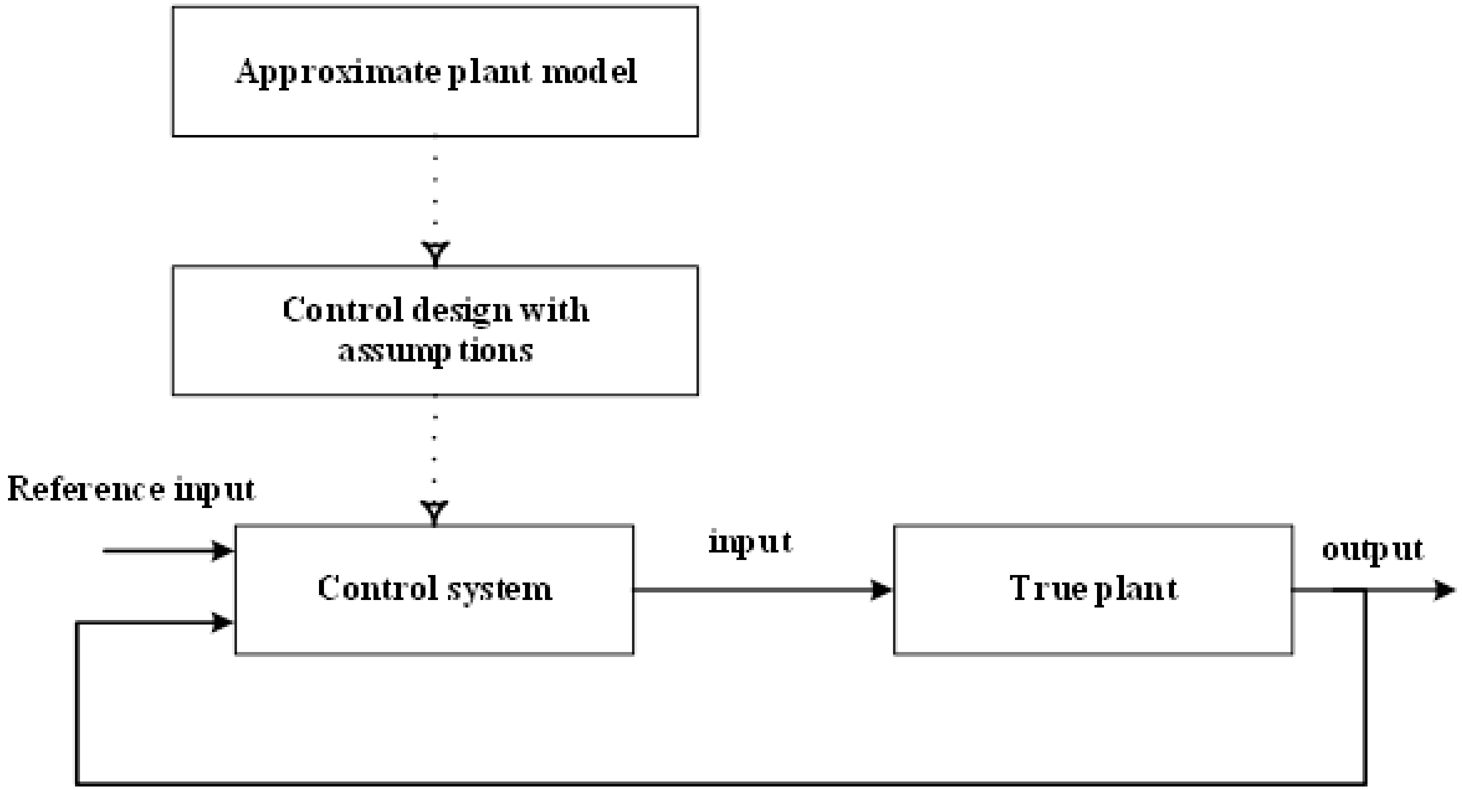
A Governor is a part of a machine by means of which the velocity of the machine is kept nearly uniform, notwithstanding variations in the driving-power or the resistance.

- Modelling A Philosophical Paradigm in Science and Engineering

- The early twentieth-century control system design methodologies: The *classical control* techniques initiated by Bode, Nyquist, Evans, and Nichols

- In the 1960s, Kalman introduced the *model-based state-space* approach that was more detailed and mathematical

Model-Based Control System Status Quo



Challenges of Models in Control Systems Design

- Reliable models are unavailable, or the in the case of varying parameters and changing operating conditions, the application of the model-based control is severely limited.
- In the mid-1960s, the system identification strategy evolved. The proposed Maximum Likelihood framework for the identification of input-output models resulted in the prediction error type identifiers. The advent of identification theory solved the problem of the control of complex time-varying plants using model-based control design methodologies.

- The elusive goal of converging to the *true system* under the assumption that the *true system* was in the defined model set.
- The theory could best achieve an approximation of the true system and characterized this approximation in terms of bias and variance error on the identified models.
- Identification was guided towards a control-oriented identification.
- *Modelling errors* are unescapable, and *explicit quantification* of modelling errors is practically impossible.
- Arbitrarily small modelling errors can lead to arbitrarily bad closed-loop performance.
- *Certainty equivalence principle*.
- The model-based approaches of fixed-parameter *robust control* and *adaptive control* system design

The mathematical models derived from the physical laws have been effectively used in practical applications provided that:

- Accurately model the actual plant.
- Priori bounds on the noise and modelling errors are available.

The identification models have been employed in many practical applications, provided that:

- Compatibility of the selected model structure and parameterization with the actual plant's characteristics is assumed.
- The experiment design is appropriate.

IF

- An accurate model is unavailable, or
- The assumptions regarding the plant do not hold

The designed mode-based controller, validated by simulations, can lead to an unstable closed-loop plant or poor closed-loop performance.

Adaptive and Robust Control Methodologies

- Adaptive and robust control has successfully controlled many real-world and industrial plants.
- Both strategies require many prior plant assumptions mandated by the theory.
- The key questions are the closed-loop robust stability and robust performance issues in practical implementations.
- The assessment of these specifications is not possible a priori, as unforeseen events may occur in practice.

- Hence, *ad hoc* methods for a safe and reliable closed-loop operation: By performing many tests for various variations of uncertainties and operating scenarios in the Monte Carlo simulations: Limitations inherent in the adaptive and robust controllers.

- Parameter adjustments and robust control and their synergistic design packages are the ultimate solutions of the model-based control scientists for the utmost guarantee of safe and reliable closed-loop control.

Data-Driven Control System Design Approach

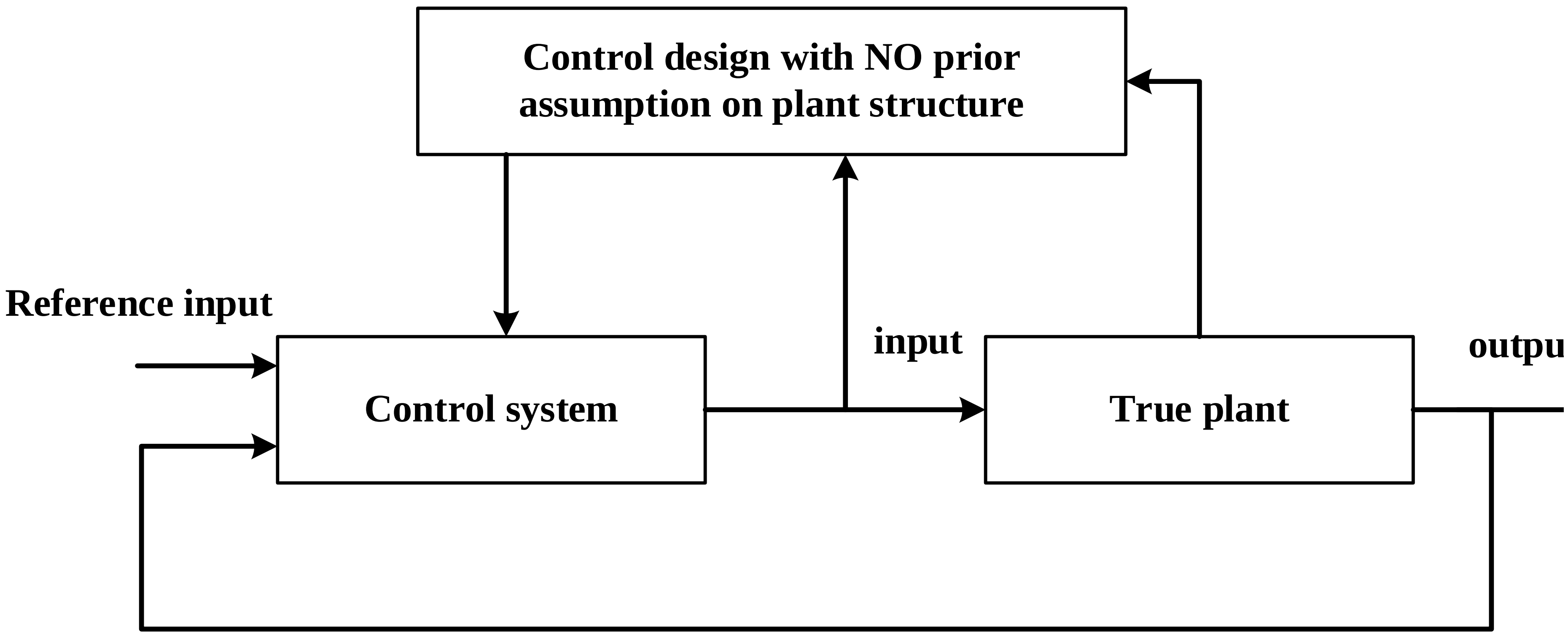
“Data-driven control only refers to a closed loop control that starting point and destination are both data. Data-based control is then a more general term that controllers are designed without directly making use of parametric models, but based on knowledge of the plant input-output data. Sorted according to the relationship between the control strategy and the measurements, data -based control can be summarized as four types: post-identification control, direct data-driven control, learning control, and observer integrated control.”

J.-W. Huang and J.-W. Gao, "**How could data integrate with control? A review on data-based control strategy**," International Journal of Dynamics and Control, vol. 8, no. 4, pp. 1189-1199, 2020

Main Features of DDC Approaches

- Control system design and analysis employ only the measured plant input-output data. Such data are the controller design's starting point and end criteria for control system performance.
- No priori information and assumption on the plant's dynamics or structure is required.
- The controller structure can be predetermined.
- The closed-loop stability, convergence, and safe operation issues should be addressed in a data-driven context.
- A designer-specified cost function is minimized using the measured data to derive the controller parameters.

Structure of a Data-Driven Control System



Definition

Data-driven control includes all control theories and methods in which the controller is designed by directly using online or offline input-output data of the controlled system or knowledge from the data processing but not any explicit information from a mathematical model of the controlled process and whose stability, convergence, and robustness can be guaranteed by rigorous mathematical analysis under certain reasonable assumptions.

Model-based or Data-driven control?

- *Class* 1. In this class of simple plants, it is possible to derive accurate mathematical models from the first principles or the identification-based schemes, and it can be anticipated that the theoretically indispensable plant assumptions hold. This is also, to some extent, possible for certain complicated systems.

model-based control strategies
calassical and modern control

- *Class* 2. In this class, for some even simple plants, many complicated systems, and few complex systems, models derived from the first principles or the identification-based schemes are crudely accurate, but uncertainties can be used to compensate for the modelling error with known bounds, and it can be anticipated that the theoretically indispensable plant assumptions hold.

Adaptive and robust control strategies

- *Class* **3**. In this class, conditions are similar to class 2, but with the difference that the theoretically indispensable plant assumptions may not be guaranteed to hold.

  adaptive and robust control??

- *Class* **4**. In this class, for some complicated systems and most complex systems, models derived from the first principles or the identification-based schemes models are crudely accurate, and the uncertainties used to describe the modelling errors are difficult to obtain accurately, and it can be anticipated that the theoretically indispensable plant assumptions may not hold.

  Data-driven is recommended and adaptive and robust control??

- *Class* **5**. In this class, for a few complicated, some complex, and complex adaptive systems, derivation of models first form the principles or the identification-based schemes, and reliable uncertainty descriptions are difficult or practically unavailable, and it can be anticipated that the theoretically indispensable plant assumptions do not hold.

  Data-Driven Control

Summary

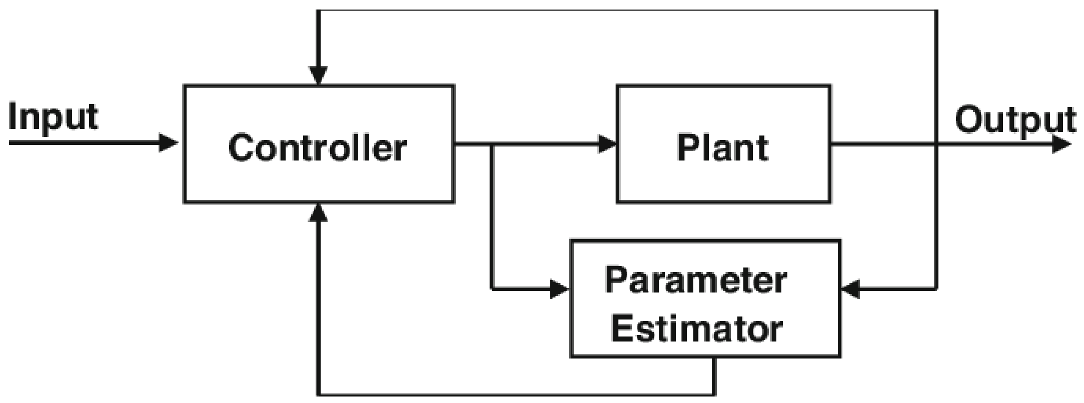
- In the data-driven control approaches, the design methodologies do not explicitly include any parts or the whole of the plant model or are not restricted by the assumptions following the traditional modellings. Hence, they are basically *model-free* designs.

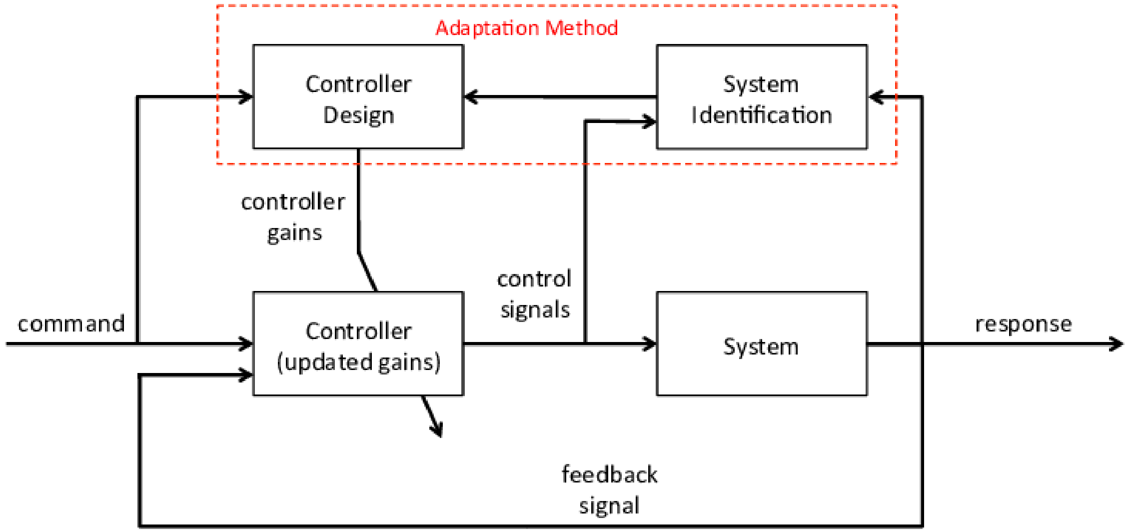
- The stability and convergence derivations of the data-driven approach do not depend on the model and uncertainty modelling accuracy.

- In the data-driven control framework, the inherently born concepts of un-modelled dynamics and robustness in the model-based control methodologies are non-applicable.

Some Technical Remarks

A Note on Adaptive Control Strategies





The Direct Approach

The Indirect Approach

- What is an Adaptive Control System?
- Is it Data-Based or Data-Driven?
- An old confusion about Adaptation (1957):

"The authors define an adaptive control system as one which monitors its own performance and adjusts some of its own parameters in the direction of better performance. However, any feedback control system may be said to monitor its own output or outputs and to adjust something in the system in such a way as to decrease the discrepancy between what the performance is and what it ought to be. To call one system adaptive because it varies parameters, and to exclude another system from this category because it only varies signals, seems to be an undue restriction of the meaning of the word adaptive."

- What about Data-Driven? All Controllers work with Data!

R. Drenick and R. Shahbender, ***Adaptive servomechanisms***, Transactions of the American Institute of Electrical Engineers, Part II: Applications and Industry, vol. 76, no. 5, pp. 286-292, 1957.

- *Remark 1*. Control design techniques that *implicitly* utilise the plant model, such as direct adaptive control, are sometimes categorised as data-driven control. However, their design, stability, and convergence analysis are fundamentally model-based and require strong assumptions on different model characteristics such as the model order, relative degree, time delay, noise, uncertainty characteristics, and bounds. Hence, we categorised them as model-based rather than data-driven.

- *Remark 2.* In dealing with mathematical models, issues such as nonlinearity, time-varying parameters, and time-varying model structures cause serious limitations and require complex theoretical handling. However, such issues at the input-output data level are non-existent. A truly data-driven control approach should be able to deal with the above control problems.

- *Remark 3.* New definitions and frameworks are necessary to pursue system design concepts in the data-driven control context.

- *Remark 4.* The theory-practice gap is greatly alleviated in the data-driven approach.

- *Remark 5.* It is not desirable or wise to ignore valuable model-based information. Hence, cooperation of data-driven control with other control theories and methods is recommended. Effective employment of existing accurate information about the plant by the data-driven approach is an open problem for further research.

- *Remark 6.* Data-driven control is predicted to be the dominant paradigm of control design science, complementing and substituting the present model-based paradigm.

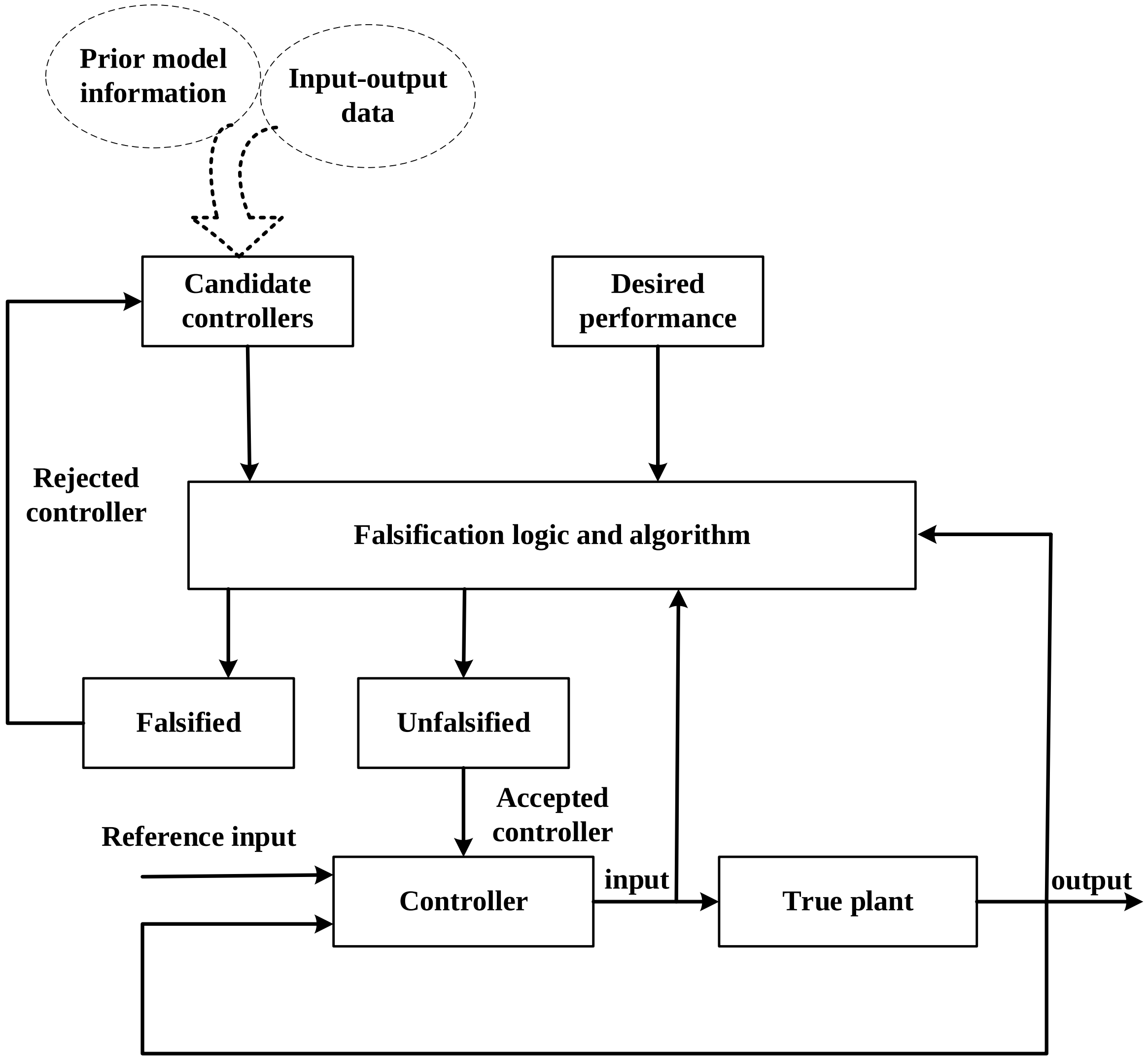
(Classical) Data-driven control schemes

Unfalsified adaptive control

The three elements that form the unfalsified control problem are:

- Plant input-output data
- The bank of candidate controllers
- Desired closed-loop performance specification denoted by T_{spec} consisting of the 3-tuples of the reference input, output, and input signals

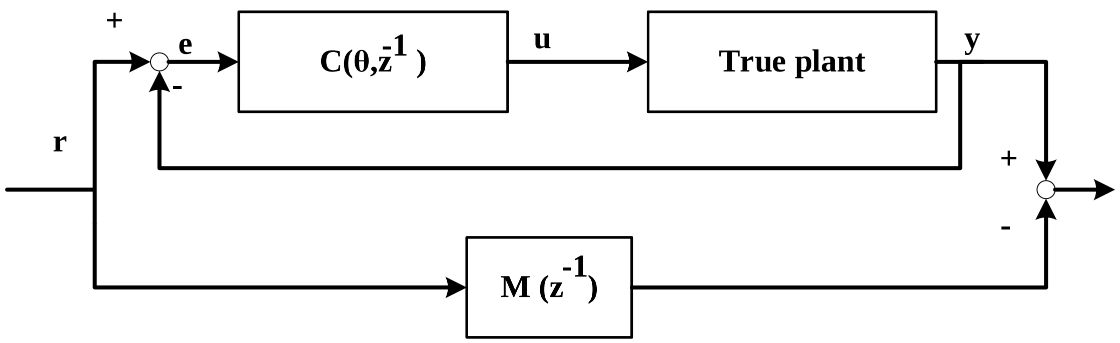
Unfalsified Control Structure



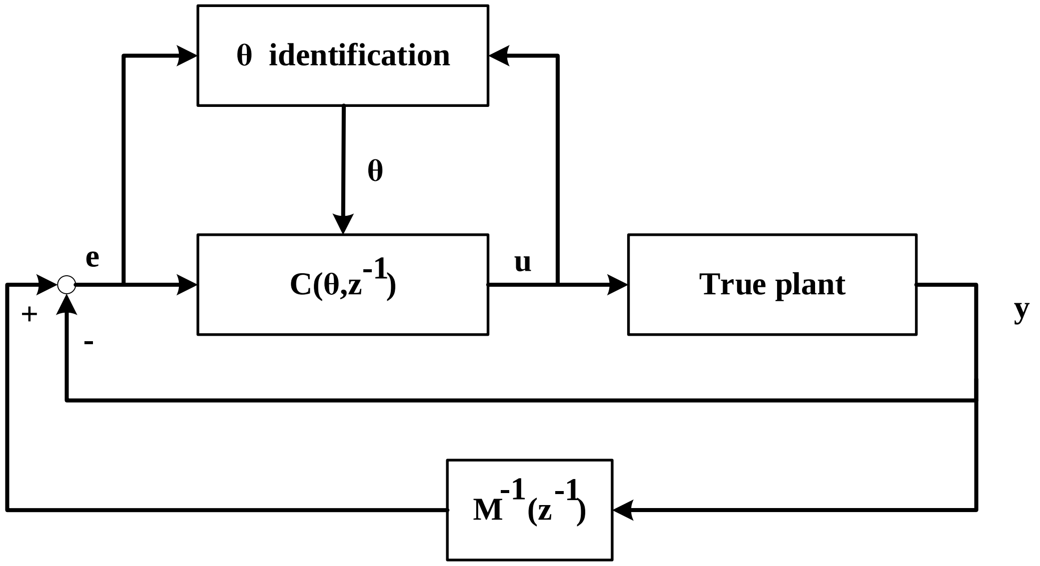
Virtual Reference Feedback Tuning (VRFT)

- VRFT is a general methodology for the controller design of a plant with no available mathematical model. It is a non-iterative or one-shot direct method that minimizes a control cost using a batch of input-output data collected from the plant, where the optimization variables are the controller parameters.
- VRFT formulates the controller tuning problem as a controller parameter identification problem by introducing a virtual reference signal.
- VRFT is an adaptive method where the adaptation is performed offline.
- In VRFT, a controller class is selected, and a specific controller is chosen based on the collected data.
- The designed controller is verified for stability and performance requirements prior to its placement in the loop.

The VRFT General Structure



(a)

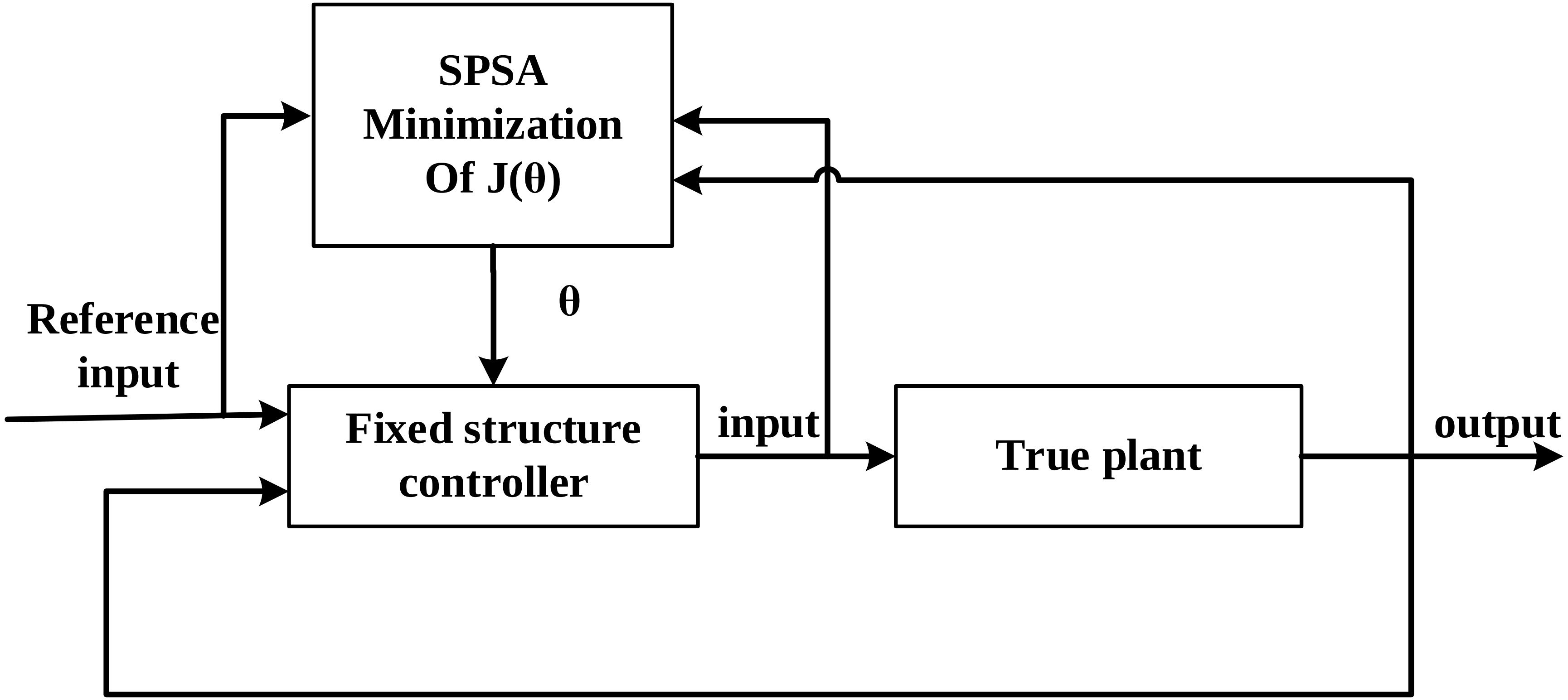


(b)

Simultaneous Perturbation Stochastic Approximation (SPSA)

- SPSA was introduced as a SA algorithm that is based on a simultaneous perturbation gradient approximation. SPSA has recently attracted considerable attention in data-driven control designs.
- SPSA uses only input-output measurements of the plant in contrast to the gradient-based optimization algorithms that are widely employed in the model-based control theory.
- A general nonlinear control problem with NO plant model and applied fixed structure control (PID or a neural network). $J(\boldsymbol{\theta})$ is defined with the weighted square error of the outputs and inputs, $\boldsymbol{\theta}$ contains the controller parameters. The design problem is, therefore to minimize $J(\boldsymbol{\theta})$ with respect to $\boldsymbol{\theta}$. SPSA is utilised for this optimisation problem since the classical techniques require a plant model for the mathematical calculations.

An SPSA-Based Data-Driven Control System



The Willems Fundamental Lemma

- Model-based control systems analysis and design techniques: A dynamical system is associated with a mathematical input-output or state-space model.
- The behavioural approach to system theory: A system theoric platform that separates the plant from its many representations by defining it as a set of trajectories. These techniques are unsupervised; they directly utilize measured plant data. They do not involve a parametric transfer function or state-space model of the plant and are therefore classified as non-parametric methods.
- For a given trajectory of an LTI plant, it is possible to derive a representation. Derive a desirable representation of the plant by employing a sufficiently rich trajectory: Willems Fundamental Lemma.
- The fundamental lemma provides a framework to identify the data-generating plant from the measured data.

The design of data-driven control methodologies based on the Fundamental Lemma can be summarised in the following general steps:

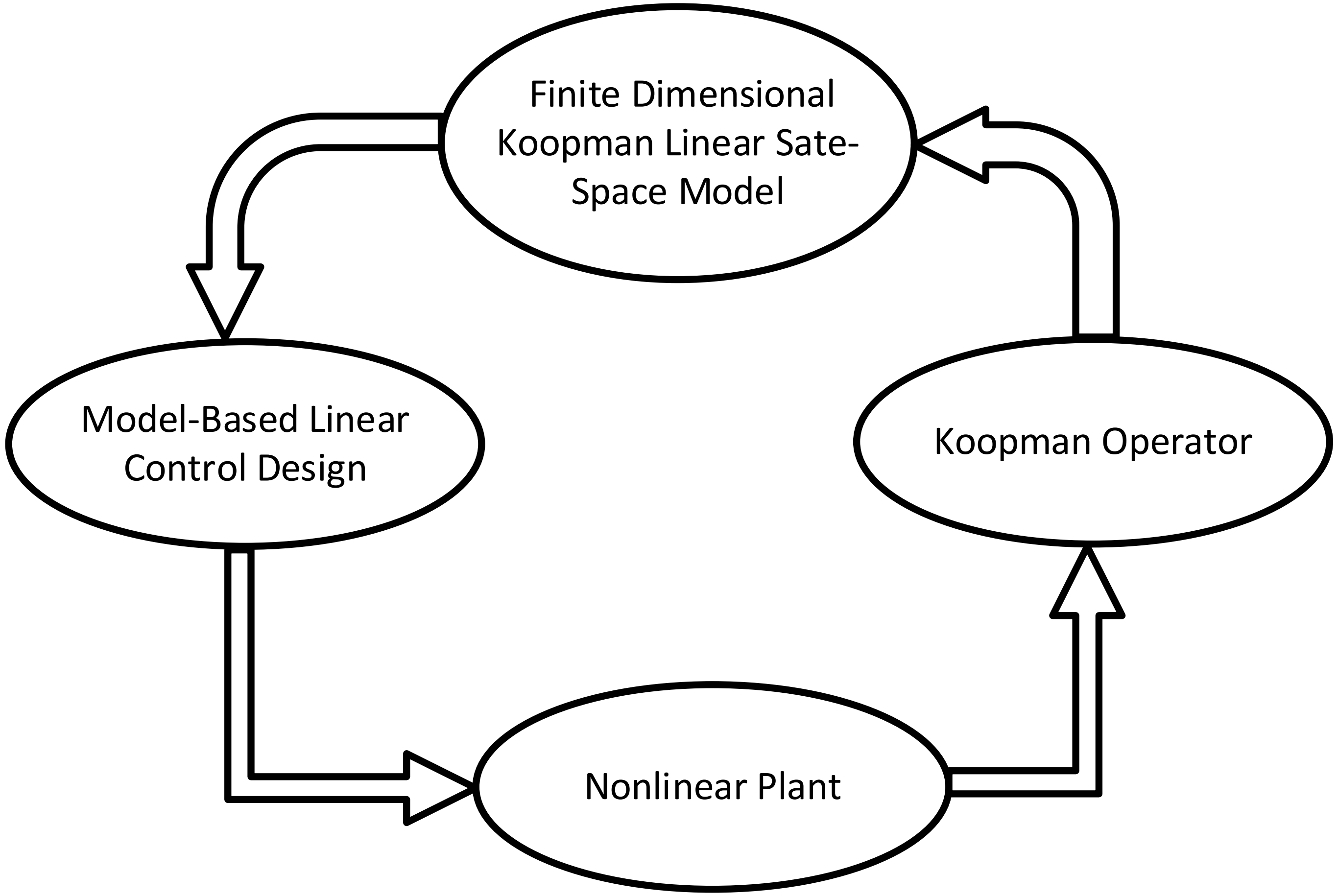
- Sufficiently rich input-output data is collected from the unknown (linear) plant.
- State estimation, input-output predictions, or necessary algebraic equations (whichever is applicable) are derived or solved by utilising non-parametric representations based on the Fundamental Lemma.
- Control signals are produced by solving the required equations or an optimisation problem (whichever is applicable).

Data-driven control system design based on Koopman theory

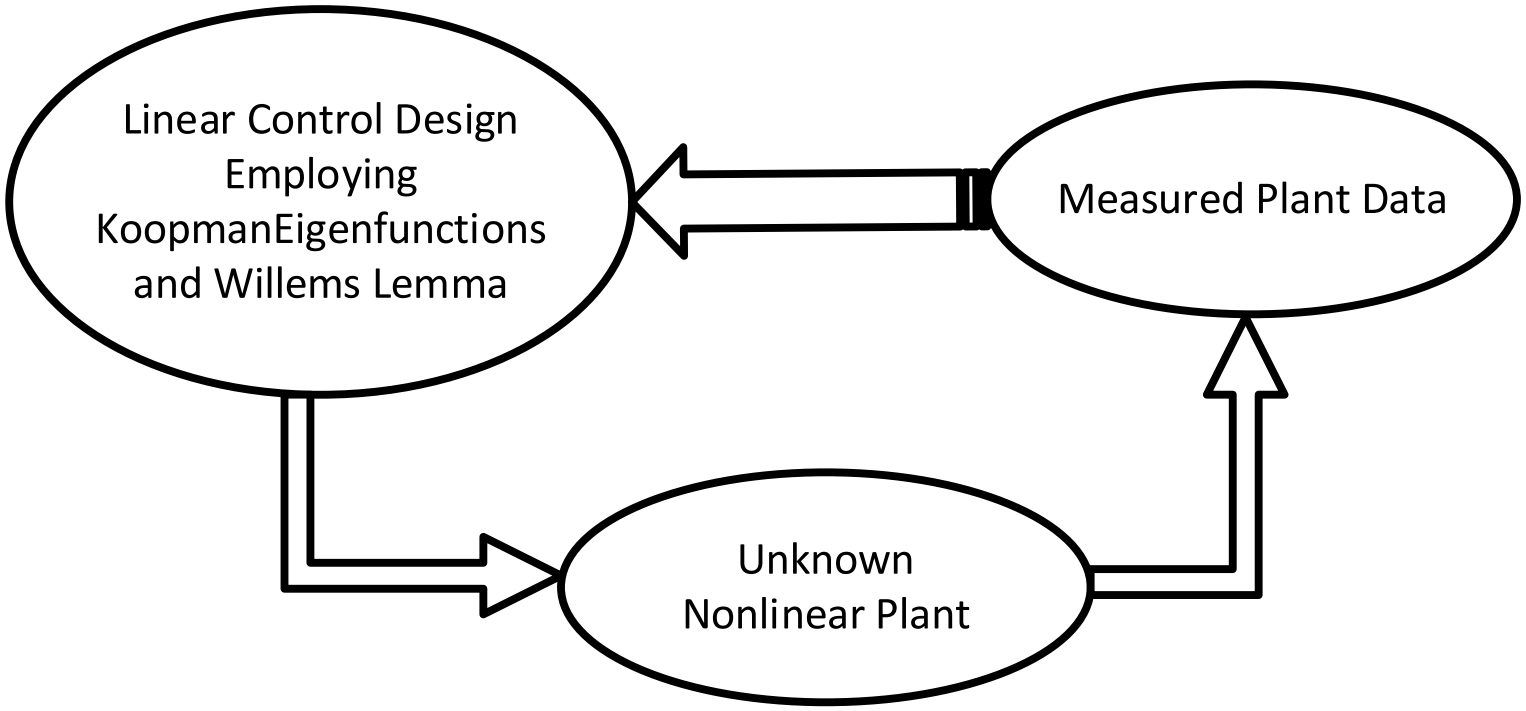
- Linear control systems analysis and design methodologies are applied to nonlinear systems by linearising the nonlinear system at its operating points.
- The Koopman operators provide a fundamentally different approach to nonlinear dynamical systems by providing linear representations for even strongly nonlinear dynamics.
- Their application in control design was not taken seriously due to their infinite-dimensional nature, making them difficult to work with in practice. This has changed for Koopman operators by obtaining low-dimensional matrix approximations of the Koopman operators through dynamic mode decomposition techniques.

- In principle, the Koopman operator provides a linear embedding of nonlinear dynamics and enables the application of linear control methods to the nonlinear system.
- Koopman has recently gained attention with its application in data-driven control.
- The data-driven application is facilitated by the application of Willems' Fundamental Lemma, and a class of data-driven control methods are developed for unknown systems.

The model-based cycle of the Koopman-based linear controller design for general nonlinear plants



The data-driven design cycle of the Koopman-based linear controller design for general nonlinear plants

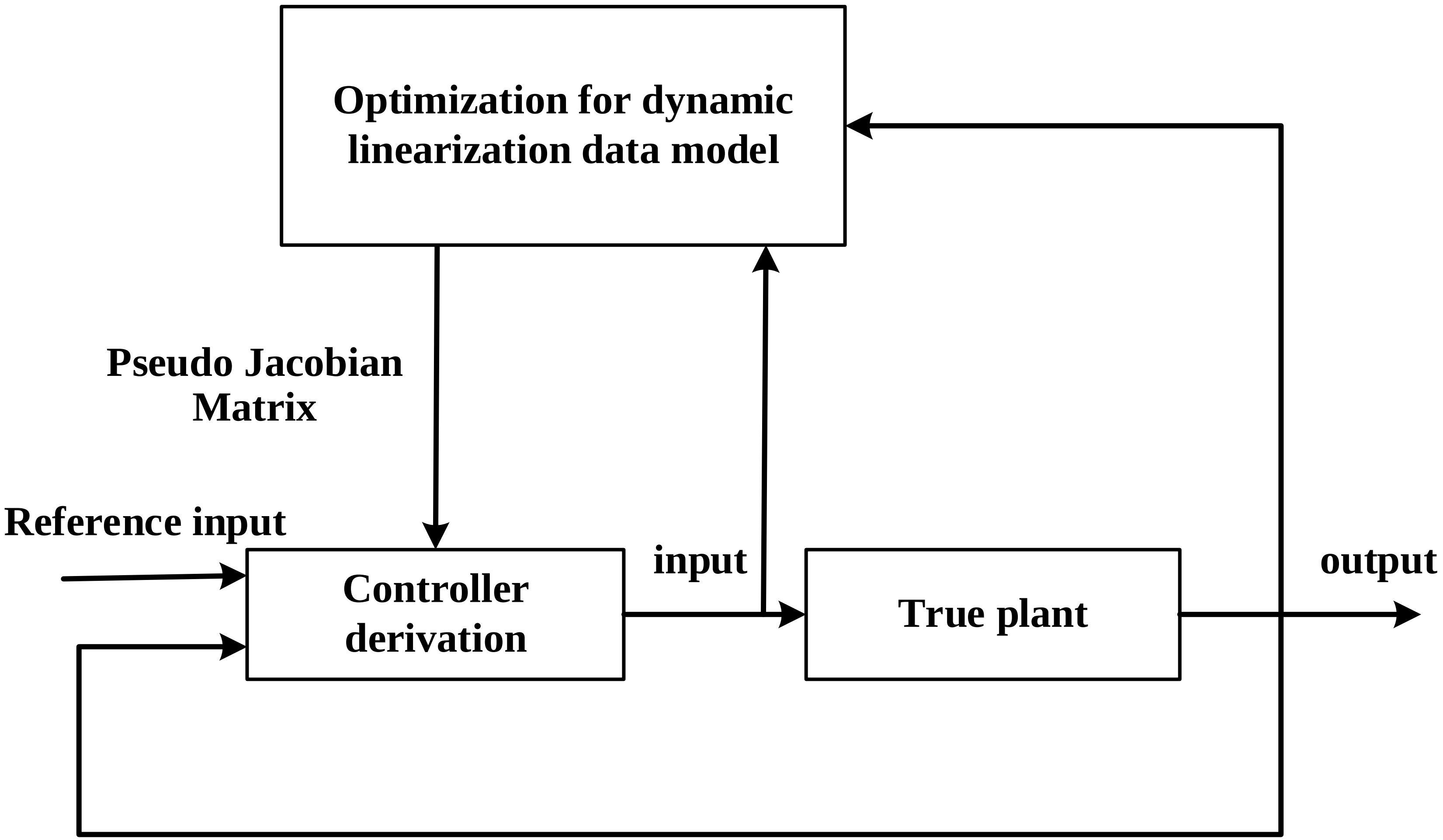


Model-Free Adaptive Control (MFAC)

- MFAC is a data-driven control method initially proposed in 1994 for a class of general discrete-time nonlinear systems.
- Contrary to the classical adaptive control techniques that identify a linear or nonlinear model of the plant, a virtual equivalent dynamical linearisation data model is derived at each closed-loop operating point.
- Classical linearisation: Feedback linearisation requires an accurate mathematical model; Taylor's linearisation approach uses Taylor expansion around the operating point and neglects high-order terms. The orthogonal function-approximation-based linearization is based on a carefully selected set of orthogonal basis functions to approximate the nonlinear model of a controlled plant and has a heavy computational burden.

- To overcome the problems of model-assumptions-complexity, the dynamic linearization technique is based on the concepts of pseudo partial derivative (PPD), the pseudo gradient (PG) or the pseudo-Jacobian matrix (PJM), using the plant input-output data. The various dynamic linearization data models are: The compact-form dynamic linearization (CFDL) data model, the partial-form dynamic linearization (PFDL) data model, and the full-form dynamic linearization (FFDL) data model.
- MFAC is formed using the equivalent virtual data model and a proposed controller. MFAC approach is a data-driven control method, and no priori model information is required. MFAC does not require external testing signals or training processes.
- Under certain practical assumptions, the monotonic convergence and BIBO stability of the CFDL, PFDL, and FFDL data model-based MFAC can be guaranteed.

The MFAC General Structure



Course Syllabus

PART A Data-Driven Control System Design Methodologies

1. Introduction to data-driven control system design approaches (2 hours)
2. Unfalsified Adaptive Switching Supervisory Control (5 hours)
3. Multi-Model Unfalsified Adaptive Switching Supervisory Control (4 hours)
4. Data-Driven Control System Design Based on the Virtual Reference Feedback Tuning (VRFT) Approach (4 hours)
5. The Simultaneous Perturbation Stochastic Approximation (SPSA) Based Data-Driven Control Design (3 hours)

6. Data-Driven Control System Design Based on the Fundamental Lemma (6 hours)
7. Koopman Theory and Data-Driven Control System Design of Non-Linear Systems (4 hours)
8. Model-free adaptive control (MFAC) approach (6 hours)

PART B Philosophical-Historical Discussions and Roundup of Control System Design Methodologies

9. Philosophical Perspectives of the Paradigm Shift in Control System Design and the Re-emergence of Data-Driven Control (4 hours)
10. Open Discussion and Presentation Sessions (5 hours)

References

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2. **Safe Adaptive Control Data-Driven Stability Analysis and Robust Synthesis**, Margareta Stefanovic, Michael G. Safonov, Lecture Notes in Control and Information Sciences 405, 2011
3. **Data-Driven Controller Design The *H*2 Approach**, Alexandre Sanfelice Bazanella, Lucíola Campestrini, Diego Eckhard, Communications and Control Engineering, Springer, 2012
4. **Model-Free Adaptive Control Theory and Applications**, Zhongsheng Hou, Shangtai Jin, CRC Press, Taylor & Francis Group, 2014

References

5. **Data-Driven Model-Free Controllers**, Radu-Emil Precup, Raul-Cristian Roman, and Ali Safaei, CRC Press, 2022
6. **A Collection of Related Papers.**