Chapter 4
Introduction to Adaptive Control

4.1 What Is an Adaptive Controller?

Definition: a controller with an adjustable structure and/or parameter mechanism.
For example: a variable parameter PID controller.

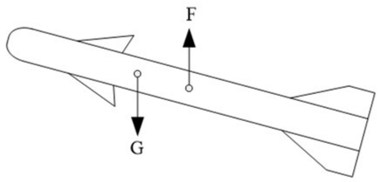
Form: the adaptive controller form is a nonlinear or linear time-varying control law.

Effect: according to the environment (including noise and interference) and the change of the controlled plant itself (parameter and structure change), adjust the controller structure and/or parameters to reduce or even eliminate these "changes" that affect control performance.

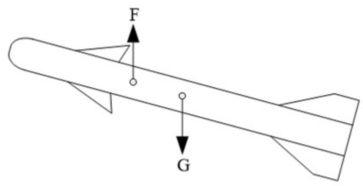
■ **Why do the “parameters or structure of the controller” change ?**

✓ "The controlled plant itself" or "environment" is changing with time greatly, and the previous control law "may" have failed to make the system "stable“,

e.g., the change of the position relationship between the "focus" and the "center of mass" of a missile: the static stable system may become the static unstable system.



✓ Due to the existence of parameter or structural uncertainty, the initially designed control parameters cannot achieve the desired control performance.



✓ To improve the "control performance", the controller structure or parameters need to be further modified, e.g., variable length inverted pendulum, adaptive driving system.

■ **Similarities and differences with robust control**

✓ Robust control: responding to changes with invariance

✓ Adaptive control: variable control

■ **Applicable controlled plants to adaptive control**

✓ Systems with uncertain parameters and structure: including linear and nonlinear controlled plants

✓ Model reference adaptive systems: The controlled plant whose parameters are unknown or change "slowly" with time.

✓ Stochastic adaptive systems

✓ Nonlinear systems

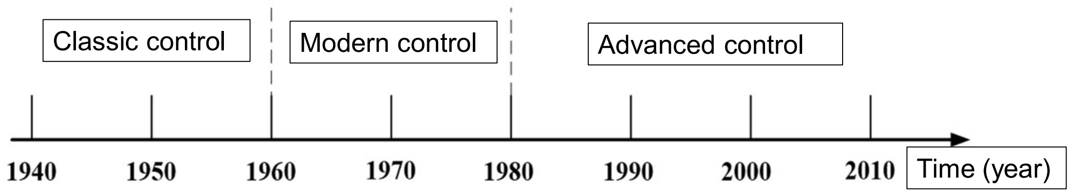
✓ Gain scheduling adaptive systems

4.2 History of Adaptive Control

■ **Development of Adaptive Control**

It is inseparable from the development of mainstream control theory (linear control theory).

Brief history of mainstream control theory



♦ **Classic control stage**

Research plants: mainly single input and single output systems;

Mathematical description: transfer functions;

Main mathematical tools: complex function, integral transformation;

Main achievements: various graphical design methods based on complex frequency domain, such as Nichles, Bode, Nyquist, root locus and other design methods.

♦ **Modern control stage**

Research plants: multiple-input multiple-output systems
Mathematical description: state space description
Main mathematical tools: matrix theory, differential equation theory
Tools: computers

Main achievements:

- ✓ L.S. Pontryagin proposed the Maximum Principle (SU, 1956);
- ✓ R Bellman's Dynamic Programming , establishing the basis of optimal control (1957);
- ✓ R E. Kalman published papers such as "On the General Theory of Control Systems", introduced the state-space method to analyze the system, put forward the concepts of controllability, observability, optimal regulator and Kalman filter, and laid the foundation of modern control theory (1960);
- ✓ E.I. Jury in US published "Sampled-Data Control System", which established the foundation of digital control and digital signal processing (1958);
- ✓ Karl J. Astrom put forward least squares identification, solved the problem of parameter estimation and order determination of linear time-invariant system (1967), and put forward self-tuning control later.

♦ **Advanced control stage**

Research plants: multiple-input multiple-output systems;

Mathematical description: linear fractional transformation;

Main mathematical tools: norm theory, matrix theory;

Main achievements:

- ✓ Robust control proposed by G Zames in Canada (1981) , and the developed comprehensive theory;
- ✓ Intelligent control
- ✓ Networked control

■ Brief history of adaptive control theory

♦ Adaptive control in the classical control stage

- ✓ In 1950, the idea of adaptive control was first proposed by W. Caldwell.
- ✓ In the early 1950s, gain scheduling control technology appeared: "autopilot of high-performance aircraft", "X-15 experimental aircraft of the United States Air Force", which was interrupted by the lack of necessary theoretical analysis tools.
- ✓ In 1958, Model reference adaptive control was proposed by H. P. Whitaker at MIT for the first time, known as "MIT" scheme (stability is difficult to guarantee), applied the MIT method based on parameter optimization design to design an adaptive autopilot for helicopters.
- ✓ In 1958, Kalman proposed the self-tuning control idea (including both control and identification).

♦ Adaptive control in the modern control stage

In 1960s:

The development of state space theory, optimal control technology, stability theory, stochastic control theory and system identification technology has promoted the understanding of "adaptive control theory".

Model reference adaptive control based on stability theory was greatly developed, e.g.,

- ✓ In the mid-1960s, Parks' model reference adaptive control design based on Lyapunov stability theory.

  P. C. Parks, Lyapunov Redesign of Model Reference adaptive control systems, IEEE Transaction on automatic control, vol. AC-11, pp. 362-367, 1966.
- ✓ In the late 1960s, Landau's model reference adaptive control design based on Popov hyperstability theory.

In 1970s:

The combination of different "estimation methods" and different "controller design methods" makes the "application" of adaptive control has been "revived".

- ✓ STR method (K.J. Astrom, and B. Wittenmark, on self-tuning Regulators, Automatica, Vol. 9, pp. 185-1991973)
- ✓ STC method (D.W. Clarke et al, self-tuning controller, IEEE Proceedings, Vol. 122, No. 9, pp 929-934, 1975)
- ✓ In the late 1970s, Ljung's convergence analysis based on ordinary differential equation (ODE) theory was conducted.
- ✓ For the needs of practical control system design and application, the rapid development of computing tools or devices such as microprocessors created conditions for the development of adaptive control applications, which in turn promoted the development of adaptive control theory

♦ **Adaptive control in the advanced control stage**

- ✓ In the early 1980s, Goodwin et al.'s stochastic process martingale
  Theoretical parameter convergence and stability and optimality analysis of control
- ✓ In the early 1980s, Rohs' Robustness analysis of adaptive control system
- ✓ In the early 1990s, Chen and Guo's self tuning regulator parameter convergence analysis
- ✓ The robustness of adaptive control system was widely studied.
  - The gain scheduling control theory was further developed by applying the convex optimization theory, and the LPV control theory.
    A.K. Packard, “Gain scheduling via linear fractional transformations,” System Control Letters, vol. 22, no. 2, pp. 79-92, 1994.
  - B. Widrow, a famous professor at Stanford University in the United States, proposed "Adaptive Inverse Control" in 1986, and published monographs in 1996:
    Adaptive Inverse Control/Bernard Widrow, Eugene Walach, Prentice-Hall, 1996.
    Chinese translation:

- ✓ Adaptive control technology combined with fuzzy theory and neural network theory produces

  Fuzzy adaptive control system: adaptive fuzzy system and control - design and stability analysis, written by Wang Lixin in 1994, Prentice-Hall Press, with Chinese translation, National Defense Industry Press.

  Intelligent adaptive control based on feature model, Wu Hongxin, Hu Jun, Xie Yongchun, China Science and Technology Press, 2009.

- ✓ Model-free adaptive control

  Iterative learning control and repetitive control

  Model-free adaptive control - theory and application, Hou Zhongsheng, Jin Shangtai, Science Press, June 2013.

- ✓ Adaptive control is closely related to "machine learning".

  AlphaGo: An AI Go program developed by Google's research team.

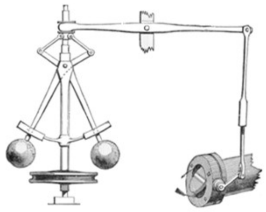
  On January 27, 2016, the cover article of Nature reported that Alpha Go defeated Fan Hui, the European Go champion and professional second-stage player, with a 5-0 victory without any yield;

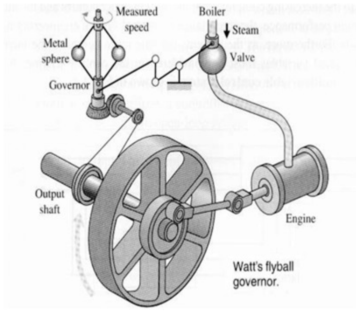
  From March 9 to 15, 2016, Alpha Go defeated the world Go champion Lee Se-Dol 4-1.

Man-machine Go Battle

■ **The "power" of the development of "adaptive" control theory**

♦ **Objective demand (practice) promotes the development of theory.**





UK James Watt used centrifugal governor to control the speed of steam engine (1788)

On Governors, J. Clerk Maxwell, Proceedings of the Royal Society of London, Vol. 16 (1867 - 1868), pp. 270-283.

♦ **Lyapunov method**

In 1892, Lyapunov defended his doctoral thesis:
The general problem of the stability of motion.
The thesis was defended in Moscow University on September 12, 1892.

♦ **Reasons for the maturity of classical and modern control theories**

In World War II, the research of control problems in artillery, radar, aircraft and communication systems directly promoted the development of classical control.

The arms race in the cold war era, such as missiles, satellites, spacecraft and star wars, as well as the emergence of computer technology, and promoted the development of modern control theory.

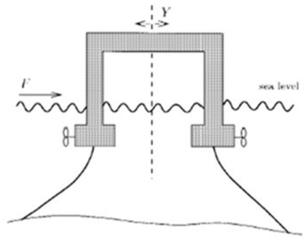
♦ **Reasons for the development of advanced control theory**

✓ uncertainty

✓ multivariable control system

① Control of distillation column (IEEE Transactions on Automatic Control, vol. 33, no. 12, December 1988).

② Moored floating platform (IEEE Transactions on Automatic Control, vol. 42, no. 7, July, 1997).



Schematic diagram of offshore platform

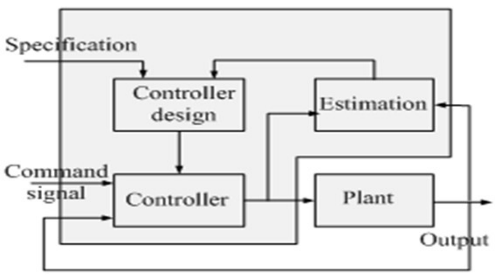
4.3 Types of Adaptive Control

■ **Classification of adaptive control systems**

♦ **Self-tuning regulators (STR)**

✓ Different design methods + different identification methods=multiple adaptive schemes;

✓ The design is not based on stability considerations and lacks the overall design scheme of "top to bottom".



Dual control

- ✓ In STR, the estimation part only gives the estimated values of the model parameters, and does not give the accuracy of the estimated values.
- ✓ In addition to the accuracy of the model parameter estimation, the dual control scheme will regenerate the signal excitation system "when the accuracy is considered to be very low", so as to obtain accurate model parameter estimation

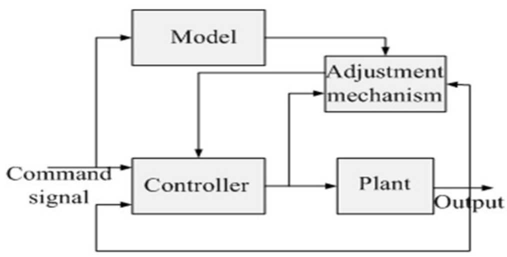
A.A. Fel‘dbaum, "Dual control theory, Parts I and II", Automation and Remote Control, Vol. 21, No. 9, April 1961, pp. 874-880 and Vol. 21, No. 11, May 1961, pp. 1033-1039. (Russian originals dated September 1960, 1240-1249 and November 1960, pp. 1453-1464)

♦ **Model-reference adaptive systems**

Origin: aircraft control.
The model describes the response of the aircraft to the joystick under ideal conditions.

Key: parameter adjustment mechanism.

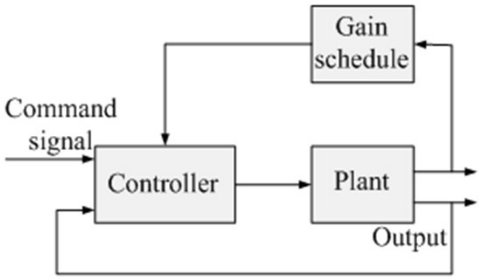
- ✓ Parameter optimization design method; (MIT scheme)
- ✓ Design method based on Lyapunov stability theory;
- ✓ Design method based on Popov's hyperstability theory.



♦ **Gain scheduling**

Idea: use auxiliary variables to measure the changes of the environment or the controlled plant itself, such as the "gain" changes, and then use the controller to compensate for the reduction of the control system performance caused by the "gain" changes.

Gain scheduling adaptive control system



Implementation: through "function setting" or "table lookup method", also known as gain scheduling compensation method.

Application: aircraft control (X-15 fighter), flight Mach number and flight altitude are used as scheduling variables.

♦ **Model-free adaptive control system**

Definition: the definition of "model-free control theory” given in [2]: “The controller design only uses the input and output data of the controlled system, and the controller does not contain any information about the mathematical model of the controlled process.”

[1]《非参数模型及其自适应控制理论》，科学出版社，侯忠生；1999。
[2] 无模型自适应控制的现状与展望，侯忠生，控制理论与应用，2006年，23卷第4期。
[3] 无模型自适应控制-理论与应用，侯忠生、金尚泰，科学出版社, 2013，6。

Hou Zhongsheng's method (1993-1994):
Basic idea: using a newly introduced concept of pseudogradient vector and pseudo-order, a series of dynamic linear time-varying models are used to replace the general discrete-time nonlinear system near the trajectory of the controlled system, and only the input and output data of the controlled system are used to estimate the pseudo gradient vector of the system online, thus realizing model-free adaptive control of the nonlinear system.

♦ **Iterative model-free control optimization method**

Swedish scholar H. Hjalmarsson et al presented the iterative model-free control optimization method (or iterative feedback self-tuning method)

Basic idea: Replace the identification of the whole nonlinear system model with the identification of a linear time-varying model near the operating point of the controlled system, and calculate the gradient information of the system output about the controller parameters according to the time-varying linear model. The gradient information is calculated by iterative method.

[1] H. Hjalmarsson, Svante Gunnarsson and Michel Gevers, A Convergent Iterative Restricted Complexity Control Design Scheme, *Proceedings of the 33rd IEEE Conference on Decision and Control*, pp. 1735 - 1740, Lake Buena Vista, FL, December 1994.

♦ **Unfalsified control**

Proposed by American scholar Michael G. Safonov in 1995.

Basic idea: This method first constructs a feasible controller parameter set that meets the performance specification, and then iteratively checks whether the performance specification is met, based on the measured new data.

When the newly measured data negates the currently used controller, the controller will automatically switch to the new controller.

[1] Michael G. Safonov and Tung-Ching Tsao, The Unfalsified Control Concept and Learning, *IEEE Transactions on Automatic Control*, pp. 843-847, Vol. 42, No. 6, June, 1997.

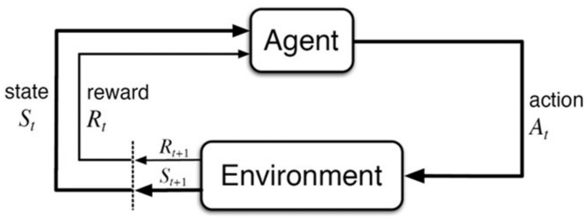
♦ **Iterative learning control and repetitive control.**

- ✓ Solve the track tracking control problem of "repeatable process", such as "manipulator" for repetitive operation.
- ✓ The system is required to repeat the same action accurately.
- ✓ Borrow the information from the previous action execution.
- ✓ "update" the controller parameters in the repeated process of the next task, and so on, and finally achieve perfect tracking through repeated correction.

[1] S. Arimoto, S. Kawamura, F. Miyazaki (1984). "Bettering operation of robots by learning". *Journal of Robotic Systems*. Vol. 1, No. 2, pp. 123-140.

♦ **Reinforcement learning adaptive control**

- ✓ The agent takes certain actions to interact with the environment, and the environment gives "rewards" to the intelligent "actions".
- ✓ The goal is to seek the "best strategy" to maximize the "cumulative reporting".
- ✓ No precise model information of the environment is required.
- ✓ Adaptive self-learning control that does not rely on mathematical model but only depends on input and output data.
- ✓ The optimal control can be achieved.



[1] Richard S. Sutton and Andrew G. Barto, Reinforcement Learning: An introduction, The MIT Press, Cambridge, 2018.

4.4 Applications of Adaptive Control

- **Applications of model reference adaptive control systems**
  - ✓ One of the most successful applications of the MRAC system in the past was in the field of electric propulsion.
    For example, the earliest application was the adaptive control of a thyristor powered DC propulsion system.
  - ✓ Due to the fact that using conventional PI regulators for speed feedback control cannot guarantee the required high performance, adopting adaptive control schemes can approximate the motor as a second-order system, and only adjusting two PI parameters can ensure that the performance remain unchanged when the motor parameters change, and can overcome the dead zone problem that PI regulators cannot solve when the motor speed exceeds zero.

- ✓ The application of MRAC technology in ship autopilot is also very successful.

  As reported in the literature, the application of MRAC technology in ship autopilot can simplify the nonlinear model to a second-order linear model.

  This way, when the external environment (wind, waves, water flow, etc.) changes and the dynamic characteristics of the ship change with draft, load, and water depth, the use of adaptive control autopilot can achieve the required performance, safe and reliable operation.
- ✓ In addition, MRAC technology has also been applied in other fields, such as internal combustion engines, steelmaking furnaces, hydraulic servo systems, etc.

- **Applications of self tuning control**
  - ✓ The application of self tuning control is much more extensive than MRAC.

    Examples: paper making, chemical engineering, titanium dioxide kilns, cement industry, ore crushing, single crystal furnace cylindrical boilers, etc.
  - ✓ It has also achieved good results in overcoming random disturbances such as wind, waves, tidal currents, speed, load, and water depth in super cruise ship autonomous driving.
  - ✓ At the same time, there are also successful examples of applications in the following sectors: such as the atomic energy industry, robotics, and artificial hearts.

4.5 Problems with Adaptive Control Systems

- **Stability**
  - ✓ Stability is the core issue of all control systems.
  - ✓ The design of adaptive control systems should be based on the principle of ensuring global stability of the systems.
  - ✓ It has been found that the existing stability theory is still unable to handle some of the proposed adaptive control problems, and a new stability theory needs to be established.

Convergence

- ✓ When an adaptive control algorithm is proven to be convergent, it can improve the credibility of the algorithm in practical applications.
- ✓ Due to the nonlinear characteristics of adaptive algorithms, it is difficult to establish convergence theory.
- ✓ Currently, only a limited number of simple adaptive control algorithms have achieved certain results.
- ✓ Moreover, the existing convergence results are very limited, and the assumption conditions are too strict, which is not conducive to practical application.
- ✓ The most basic requirements for ensuring the convergence of parameter estimation may not always be met for actual systems.
- ✓ Further research on convergence theory is needed.

Robustness

- ✓ The ability of a system to ensure its stability and certain dynamic performance in the presence of disturbances and unmodeled dynamic characteristics is called the robustness of an adaptive control system.
- ✓ Disturbances can cause serious drift of system parameters, leading to system instability, especially in the presence of unmodeled high-frequency dynamic characteristics.
- ✓ If the instruction signal is too large or contains high-frequency components, there is high-frequency noise, or the adaptive gain is too large, it may cause the adaptive control system to lose stability.
- ✓ At present, several different solutions have been proposed to overcome the instability caused by the above reasons, but it is still far from satisfactory.
- ✓ An important theoretical research topic in the future is to design a robust adaptive control system.

- **Performance and stability**
  - ✓ The good operation of an adaptive control system not only requires the designed system to be stable, but also to meet certain performance criteria.
  - ✓ Due to the fact that adaptive control systems are nonlinear and time-varying, changes in initial conditions or unmodeled dynamics are necessary to alter the motion trajectory of the system.

    Therefore, analyzing the dynamic quality of adaptive control systems is extremely difficult.
  - ✓ At present, there are very few achievements in this area.

Exercise 4.1

Using an industrial control system as an example，discuss:

1) why adaptive control is needed for this system;
2) what the control challenging problems in this system are.