

Control for Hobby Robotics Systems

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Abstract. This handout summarize general knowledge to implement control systems for Hobby Robotics Systems such as simple line following autonomous vehicles, open chain manipulator mechanisms using dc or stepper motors.

Keywords: Hobby Robotics Control, Feedforward control, Feedback control, on-off control, PID controller.

1 Introduction

Well known characteristics of the 19th century is industrial development for mass production. Production was transformed from hand-manufacturing to machine-manufacturing. Starting from 1940's, the fast development pace of electronics, and digital electronics resulted in a *revolution in data processing*. In thirty years amazing speeds of processing became possible on huge amount of data.

Human arm was considered as a model for *general purpose action device*. In 1955 Denavit and Hartenberg developed a convention for the systematic analysis of the manipulator kinematics.

In early 60's the first *articulated industrial robot* appeared for general purpose pick and place tasks. Later, similar robots took part in automation of mass welding, assembling, painting, gluing applications.

In 80's NASA started projects to develop *biped locomotion robots* for space research. The projects helped for the very fast development of the flexible-arm robotic, and provided the development of today's *space-arms reaching over 10-meter* work-span. The extension of these projects developed into the autonomous vehicles. Mars robot was one of the most successful samples of these *autonomous robot vehicles*.

In 90's, direct digital and adaptive control techniques has taken the place of conventional control techniques used in the industrial robots.

Mechatronics emerged in early 90's to use *mechanics, sensory electronics, and embedded data processing technology* in building highly flexible and functional intelligent equipments. Stand-alone individual robots with a platform on wheels or legs became typical *hobby of robotics* researchers.

Parallel to developments in the *control techniques*, development of *new sensors* started a new *revolution in intelligent robotics*. At the end of 90's optical sensors had changed to video cameras. Image and video processing methods developed to object recognition and registering level. In many applications, optical position calibration

became a standard method. Typical accuracy of the robots improved to 0.05 mm precision.

Today, the study of *robotic systems with autonomous agents* is recent research field of many researchers. Such systems can be used in *space colonization* to accomplish *constructions at moon or satellite-bases*. Military operations erect similar motivation for autonomous robotic agents as war machines. Medical operations are another motivation for *autonomous micro-robotic agents*.

Many robotics research centers are researching for world robotics coups to develop successful individual and social autonomous agent behaviour such as in playing soccer, off-road driving, etc.

2 Hierarchical Control Strategy in a typical Robotic System

Starting with this perspective, we can classify robotic control into four levels:

1. *Low level control*: In industrial robots, it corresponds to the position- orientation- and force-control at each joint. In the autonomous vehicle case, it corresponds to the individual motion and direction control of the platform.
2. *Mid level control* : In industrial robots, it corresponds to the coordination of the motion to track the desired trajectory. In the autonomous vehicle case, it corresponds to the coordination of the motion and direction control.
3. *High level control* consists of dynamic path and trajectory planning for both industrial and autonomous vehicular robots.
4. *Top level control* aims goal oriented task level planning starting from natural languages.

The contents and specifications of each level of control differs from the other levels. This handout will focus on Low level control of robotic systems.

2.1 Low Level Control

Low level control is applied by one or many controllers. Depending on the type of controllers, and their topology in the control we obtain different control strategies.

In control theory, the device to be controlled is called a *plant*. The aim of the control is mostly to apply best *plant inputs* track a *desired plant-output*. In other means, the *error* between the *plant output* and the *desired plant output* is wanted to be zero.

The aim of control is to reduce the output error while keeping the overall system *stable*. In the simplest meaning, *stability* is the reduction of the error and system states within desired acceptable bounds. An *asymptotic stability* is obtained when error ceases exponentially to zero. A Lyapunov stability is obtained when the error remains within a shrinking region around origin. For a beginner to robotic control, stability means simply error never burst above an acceptable tolerance.

2.2 Control Topologies

Several kind of strategies are possible to reduce the error.

2.3 Open-Loop Control

An *open loop*, or *feed forward control* is the simplest control strategy if the input-output relation of the plant is exactly known. For example, if our plant produces twice of the inputs, for any given desired output we can feed the plant with the calculated plant input, as shown in Figure 1.

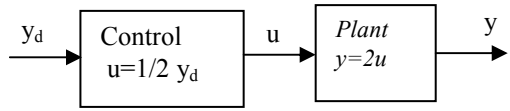


Figure 1. Example of open loop control.

Example: Assume that we designed a three-wheeled platform. The two back wheels are equipped with dc motors that provides constant speed, and one wheel at the front gives the desired direction of the platform. The direction wheel is driven with two solenoids, which rotates the wheel either 45 degrees left, or 45 degrees right.

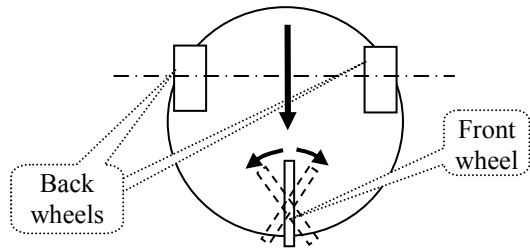


Figure 2. Top view of three wheeled platform for an Example of open loop control.

If you want to have straight direction, you will keep the front wheel straight. For a y -degrees right turn, you have to turn the front wheel 45 degrees right exactly u milliseconds, where $u = k \cdot v$; and k is a constant value which depends on the size of the platform, v is the speed of the front wheel.

The weakness of the open loop control is, accumulation of output error in time. For example, if there is a slight calibration error in zero-position of the front wheel, let's say δ degrees deviation from the zero direction, the platform will develop a rotation continuously at a rate of $(k v \delta / 45)$ degrees at every millisecond. This deviation can be corrected only if we can get a reading of absolute direction of the platform, for example using a compass, or a gyro meter sensor. The correction of the developed error requires a *closed-loop control strategy*.

2.4 Closed-Loop Control

The *closed loop control* is obtained by producing a corrective plant-input depending on the tracking error. Usually, the plant output is not directly readable. We need some *sensors* to get a measure of the plant output. Putting all together, the simplest closed loop system is seen in Figure 2.

The *stability of the closed loop* control system depends on Plant, Control and Sensor in an intricate relation. In the frequency domain analysis, the stability of a feedback system is guaranteed only if the phase shift of the signals never exceeds 180 degrees if the open loop gain of the system exceeds unity. In the Laplace domain, it corresponds to having all poles of the open loop function at the left side of the complex plane. For further study, a good reference book on time, frequency and Laplace domain analysis of the control loops is “Modern Control Engineering” by Katsuhiko Ogata (Prentice Hall).

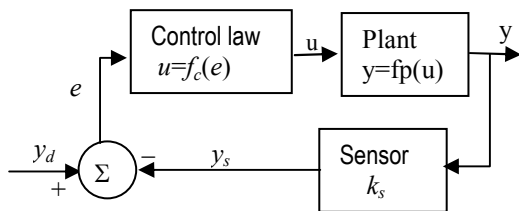


Figure 3. Example of open loop control.

Closed loop control is used in all servo-control systems to control the joint displacements of the industrial robot arms accurately with a stable action. It is also used in autonomous vehicles to control the position and the direction of the vehicle platform.

You can find detailed practical information on control of robotic in the robot hobbyists bible “The ROBOT builder’s BONANZA” by Gordon McComb and Myke Predko (McGraw Hill) . This book collects many working ideas for the vehicular hobby robots. It contains also detailed explanations of the techniques required in the design of several kind of robotic mechanisms.

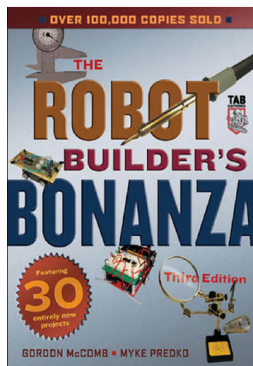


Figure 4. The Robot builder’s BONANZA by Gordon McComb and Myke Predko

2.5 Working with DC motors

DC-motors can be studied in many categories. A shunt motor provides moderate torque at zero motor speed, and constant speed even if it works without any load (wiper motors of the cars). The salient features of DC series motors are: (a) high torque at standstill and low speeds, (b) poor speed regulation, (c) runaway tendency at no-load, (d) reversal by transposing either armature or field connections, (e) basically operative from AC (starter motor of the cars). Reversing the rotation of a series motor cannot be brought about by simply reversing the polarity of the applied voltage. Doing so will reverse the current flow in both armature and field and the net result

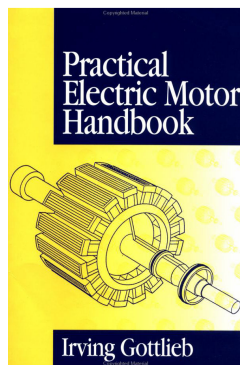


Figure 5. An easy to read source book on electric motors

will be that torque will continue to be exerted in the same direction. A compound wound motor balances drawbacks of series and shunt motors, and the windings can be optimized to provide the desired stationary torque and unloaded speed at the nominal terminal voltage. You can find the answers for many of your questions in the book "Practical Electric Motor Handbook" by Irving Gottlieb (e-book available).

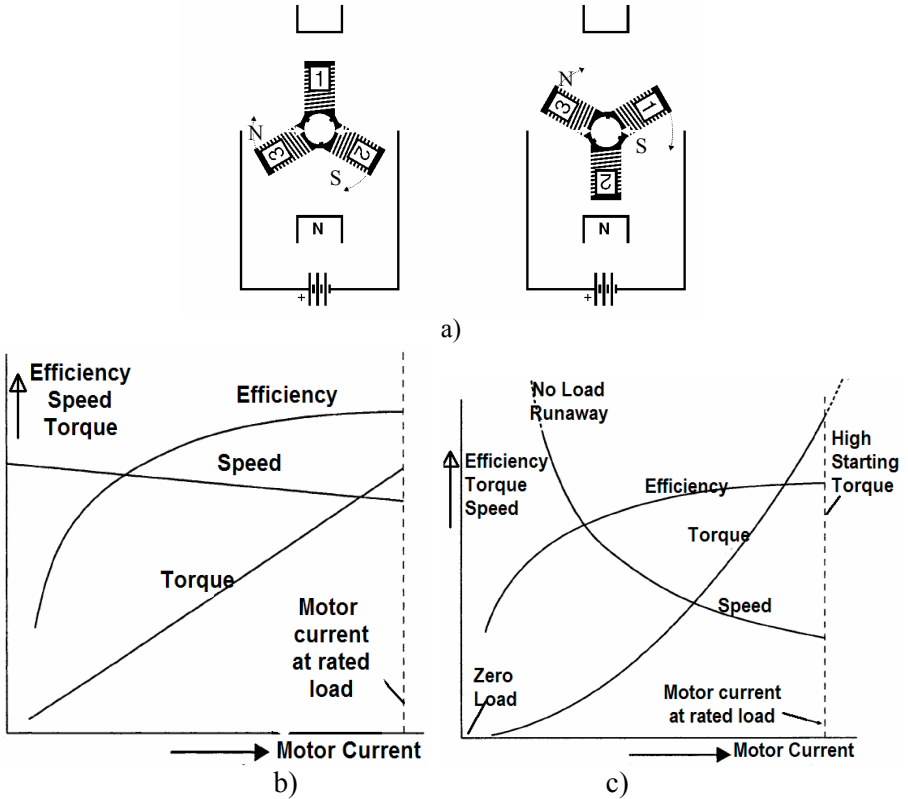


Figure 5. a) Two views of the three winding DC motor shaft at different positions. As the shaft turns, the polarity of the different windings change due to the changing position of the brushes relative to the commutators. b) DC-shunt motor characteristics c) DC-series motor characteristics.

A *constant magnet motor* is common component in most hobby robotic applications. The constant magnet motor theoretically corresponds to a constant field motor with individually excited rotor and stator windings. The basic characteristic of a permanent-magnet or shunt motor is a back-emf proportional to the motor speed, and a torque proportional to the winding current. These motors can work in reverse direction by applying reverse polarity voltage to their terminals.

2.6 On-Off Feedback Control

An *on-off feedback control* law is the simplest control function to correct the tracking error. On-off control can be applied to the DC motors to track a desired position. The mathematical model of on-off control is obtained simply by replacing

$$u = u_c \text{sign}(e)$$

into the control law $u = f_c(e)$, where u_c is the nominal terminal voltage of the motor, and $\text{sign}(e)$ is defined by $\text{sign}(e) = (-1$ if $e < 0$, 0 if $e = 0$, 1 otherwise). This kind of control is easily applied to a DC motor using an *electro-mechanical-relay*. However, electro-mechanical relays need large currents to pull the contacts, and not suitable for battery powered applications. A modern bipolar or field-effect *transistor* can do the same *switching* action, and is preferred over the relays since they need much lower operating power. Indeed, motor driver is a common requirement in the electronics world.

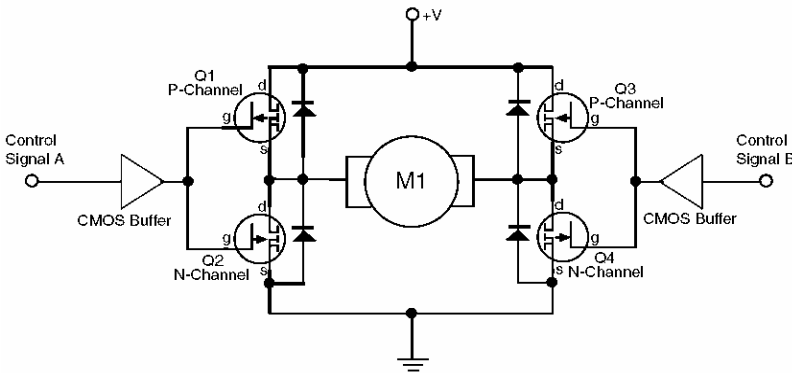


Figure 6. Four N-channel power MOSFET transistors in an “H” pattern can be used to control the direction of a motor. In a circuit application such as this, MOSFET devices do not strictly require current limiting resistors, as do standard transistors.

Many companies are manufacturing solid-state (transistor based) H-bridge drivers to drive the DC motors in forward and reverse direction through on-off control. The slow response of the DC motor with respect to the very fast switching offers an energy saving possibility for proportional control. Pulse Width Modulation (PWM) is based on the effective terminal voltage of a square wave signal. This voltage is almost proportional to the duty cycle of the PWM signal. A microcontroller can generate PWM signals under the control of its program code.

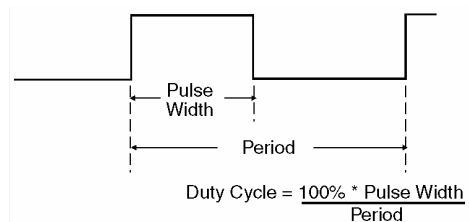
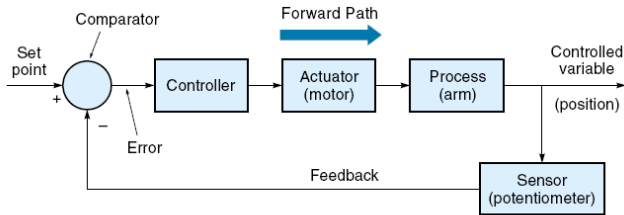


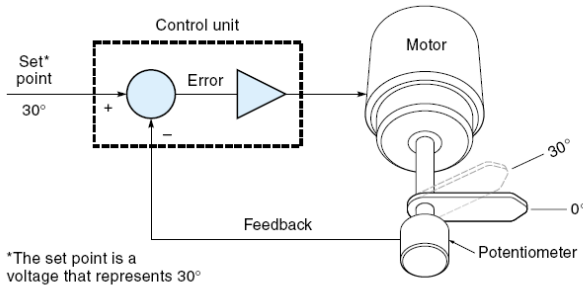
Figure 7. This PWM unit keeps the pulse width constant while varying the PWM period proportional to the input voltage of the unit.

2.7 Position Servo Control

The closed loop position control applied on a dc motor is called positional dc-servomotor. Positional servoing of the dc-motors requires a convenient position sensor in control system. A potentiometer can work as a simple position sensor. Indeed, for example, original PUMA robot design used an analog servo control



(a) Block diagram



(b) A simple closed-loop position system (Example 1.2)

Figure 8. A servo-control-loop with proportional gain.

system with wire-wound potentiometers installed for position feedback. The overall servo-control loop for this kind of mechanisms is shown in Figure 8.

2.8 PID Controller

PID stands for *Proportional, Integral and Derivative*. As the name implies, it generates a correction signal that is proportional to the sum of three terms: the error, integral of the error, and derivative of the error. The joint dynamics contain gravitational terms that exerts steady-state torque on a joint. A proportional control alone can reduce this offset to a tolerable range with excessive controller gain. The Integral term compensates the offset by accumulating the effect of error in the time integral. But, the integration of error introduces an additional phase delay, and together with the higher modes of the joint dynamics the phase delay easily exceeds 180 degrees, which starts growing oscillations. The derivative term of the controller suppresses the phase shift and provides a stable operation.

Pure PID control has three main parameters, and there may be extra parameters for the simplified PID implementations. The adjustment of these parameters requires dynamics of the joints. Modeling of a joint as a process block requires kinematics, and dynamics analysis of the robotic system, which can be found in most robotics textbooks i.e., by R. Kelly, V. Santibáñez and A. Loria, “Control of Robot Manipulators in Joint Space” shown in Fig.9.

2.9 Other Control Topologies and Control Laws

Cascaded Feedback Control is a topology that allows control of the set point of the inner control loop. It provides better stability and performance than a single feedback loop.

Adaptive Control, Sliding Mode Control, and several kinds of Fuzzy Control methods and laws are available in the technical literature on robotics. From these methods, Craig’s model reference adaptive scheme (an adaptive output and state estimator used in both feedback and feedforward modes), Koivo’s adaptive pole placement with a linear quadratic state estimator (feedback structure), and Asada’s fuzzy feedback control structures were successfully implemented in many robot servo control systems.

2.9 Stepper Motor Control

Unlike the torque generating character of the stepper motors provide directly a known quantity of accurate displacement depending on the pattern of terminal voltages. The modern clam-shell design of these motors reduced their manufacturing costs to less than a dollar. They are light-weighted for miniature mechanical actions, such as in printers, scanners, and many toys. However, it is a reality that their power/weight ratio, and efficiencies are much lower than DC motors. Anyway, these motors have an important place in robotics for miniature manipulations such as hand and finger movements, and especially in hobby robotics because their positional control is much easier than the servo-controlled dc motors. The control of stepper motors are explained in details in the “Robot Builder’s Bonanza” and in the book “Modern Control Technology, Components and Systems”, by Christopher T. Kilian Delmar

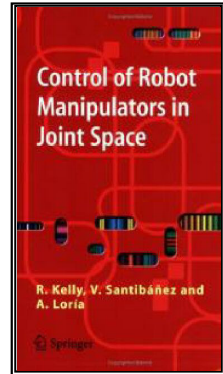


Figure 9. Detailed analysis and design on control of joints are available in this Book

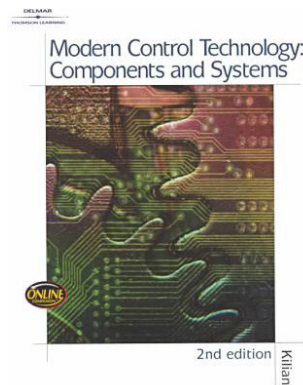


Figure 10. Modern Control Theory

2.10 Stepper Motor Open Loop Control

The **feedforward control of the stepper motors** is obtained by sending a sequence of excitation patterns to its terminals. For a 5-wire configuration, the voltage applied to A directs the N-pole of the rotor to the AB coil. Next, applying voltage to C rotates the rotor to align N-pole next to the CD coil. Exciting coils A, C, E, and G after each other completes one turn of rotation. This kind of excitation produces the half torque of the motor, since only one of the aligned coils has excitation. A bipolar motor can be fully excited by giving negative voltages to the complementary coil, i.e., $A=V_m$, $E=-V_m$, $C=G=0$; thereafter, $A=E=0$, $C=V_m$, $G=-V_m$; thereafter $A=-V_m$, $E=V_m$, $C=G=0$; etc. It is possible to have half steps exciting two adjacent coils, i.e., $A=C=V_m$, $E=G=0$; thereafter $A=0$, $C=E=V_m$, $G=0$; thereafter $A=C=0$, $E=G=V_m$, etc. Mostly the driving circuit delivers only unipolar voltage, and the full steps are combined with half steps in the excitation pattern to complete one period: A ; A and C, C, C and E, E, E and G, G, G and A; giving total 8-steps for a complete revolution.

However, the clam-shell design allows multiple poles to be used in the stator, yielding full step angles down to 1/180 revolutions instead of 1/4 revolution. The excitation sequence is easily generated by an 8-bit microcontroller system.

2.10 Stepper Motor Position Servo Control

The main drawback of feed forward control is valid for these control systems too, since there can be missing steps due to excessive load torque or excessive speed. The remedy is constructing a feedback loop for the correction.

Commonly, an absolute or incremental encoder is used for a digital position correction feedback instead of using analog potentiometric sensors. Incremental encoder that produce two signals with 90 degrees phase shift are common since the direction of rotation, and accurate position counting is very simple by a microcontroller.

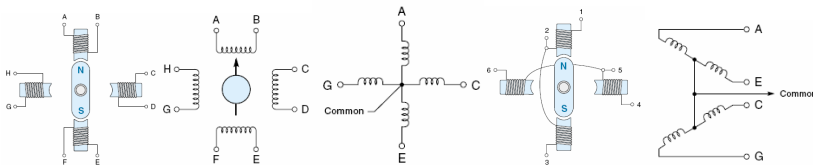


Figure 11. 8-wire, and 5-wire configuration for four-phase unipolar permanent magnet stepper motors

2.11 Other Common Positional Control Systems

Hydraulic servosystems are used for very high loads such as excavation machines. Because of their stiffness they can be used for accurate open loop positioning of the joints. But they are mostly used in a servo-loop built with a potentiometer to switch the hydraulic pumps on and off.

The open loop *Pneumatic system* is not suitable for fine control of the position, and it used either for bang-bang control or to get very low joint stiffness (to drive grippers for fragile objects).

Some heavy payload industrial robots use AC motors, and AC positional servo systems. AC motor have advantages over DC motor since it needs less maintenance because it has no commutator, which needs regular replacement of carbon brushes. AC positional servo is still an expensive system for small size motors, because it needs fast current and voltage sensors, and fast solid-state switching elements for phase control.

3 Conclusion

An introduction to the control system strategies, topologies, and laws are presented by introducing the relevant literature on the robotic control systems. A hobby robotic control system can be composed of common motors and controllers we use in our daily life such as DC and stepper motor from old printers, scanners, shaving machines and toys. There is sufficient detailed information to build such control systems even with little electronics and mechanics experience. However, the professional design and implementation of robotic control systems require extensive design and material know how. This know how increases when the goal is special purpose robots such as under water, avionics and medical surgery robots.

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