Control motion: Notions*

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Abstract

Motion Control is a sub-field of automation encompassing the systems or sub-systems involved in the moving parts of machines in a controlled manner. Using a computer to control an *actuator* offers benefits, but today getting data and feedback is increasingly important. Motion control may be *open loop* or *closed loop*. In open loop systems, the controller sends a command through the amplifier to the prime mover or actuator, and does not know if the desired motion was actually achieved. Typical systems include *stepper motor*. For tighter control with more precision, a measuring device may be added to the system (usually near the end motion). When the measurement is converted to a signal that is sent back to the controller, and the controller compensates for any error, it becomes a Closed loop System.

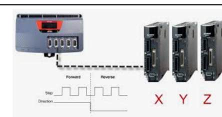
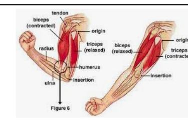
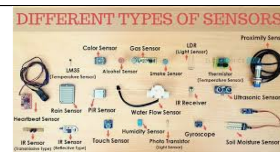
Keywords: Accuracy; Ball screws; Microstepping; Repeatability; Resolution.

INTRODUCTION

Motion Control is a sub-field of automation encompassing the systems or sub-systems involved in the moving parts of machines in a controlled manner. Using a computer to control an actuator offers benefits, but today getting data and feedback is increasingly important.

Some companies are already seeing the advantage of adding sensors and feedback to a production line. In addition, this extra information can let machines communicate to each and connect to the internet to take advantage of the Industrial Internet of Things (IIoT).

Today motion control often includes a blend of electronics and mechanical components divided into three parts, which have been seen as analagous to how the human body operates.

Motion control	**Humans**
	
Processor or Motion controller	Brain
	
Actuator	Muscle and joints
	
Sensors	Senses

To elaborate on this further, we added more detail.

Processor or Motion controller

There are three types of motion controllers: standalone, PC-based, and individual microcontrollers. This is becoming more and more of an important consideration when setting up production lines. To prevent incumbent inertia and future-proof a production line, the manufacturing brain is evolving.

The motion controller acts as the brain of system by taking the desired target position and motion profiles, and creatring the trajectories for the motors to follow. It outputs a ± 10V signal for servo motors and step and direction pulses for stepper motors.

*This is a brief resume about control motion. Essential knowledge for the movement of machines in the design stage.

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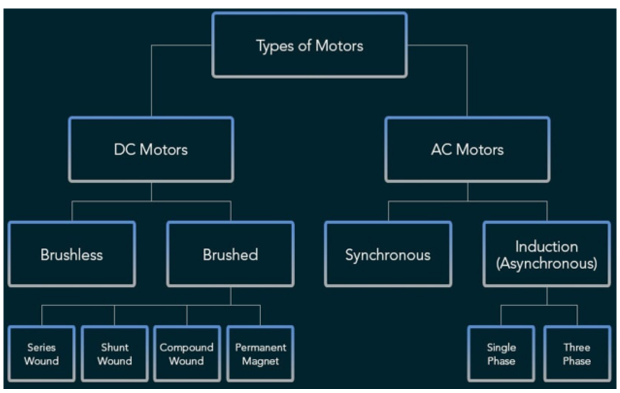
Specifications to consider when searching for motion cotrollers include

- Number of axes
- Update time
- D/A resolution
- Type of motion supported

DRIVES

There are many types of amplifiers and drives. But when looking at advanced automation, servos look like they are able to add more value and feature to a line when compared to stepper motors. However, this can add more cost and complexity. Servo drives and servo amplifiers transform a low power current/voltage applied to the servo motor windings to produce torque. Different amplifiers include analog servo drives, sinusoidal, trapezoidal, digital servo drives, single phase (brushed) servo drives, three phase (brushless) servo drives, and electric vehicle motor control.



Key features of AC and DC motors

AC
Low power demand on start
Controlled acceleration
Adjustable operational speed
Controlled starting current
Adjustable torque limit
AC synchronous motors
DC
Easy installation
Speed control over a wide range
Quick starting, stopping, reversing, and acceleration
High starting torque
Linear speed-torque curve

Feedback Sensors and Mechanical Components

Feedback sensors provide motor location. There are several types, including:

- Quadrature encoder: Gives position relative to the starting point.
- Potentiometers: Gives analog position feedback.
- Tachometers: provides velocity feedback.
- Absolute encoders: for absolute position measurements.
- Resolvers: convert mechanical motion into an electric analog signal to find an absolute position.

MECHANICAL COMPONENTS

Mechanical components transform the motion of the actuator into the desired motion.

Bearings

A ball bearing is a type of rolling-elements bearing that uses balls to maintain the separation between the bearing races. The purpose of a ball bearing is to reduce rotational friction and support radial and axial loads. It achieves this by using at least two races to contain the ball and transmit the loads through the balls. Ball bearing tends to have lower load capacity for their size than other kinds of rolling-element bearing due to the smaller contact area between the balls and races.

Gearboxes and speed reducers

- Use of speed reducers
  - Multiply the amount of torque generated by an input power source to increase the amount of usable work.
  - Reduce the input power source speed to achieve desired output speeds.
- Use of gearbox
  - Gearboxes are used to increase torque while reducing the speed of a prime mover output shaft.

Ball screws

A ball screws is a mechanical lineal actuator that converts rotational to lineal motion. Ball screws can endure high thrust loads and deliver high precision with minimal internal friction.

Linkages

A mechanical linkage is an assembly of bodies connected to manage forces and movement. Linkages may be constructed from open chain, closed chains or a combination of open and closed chains.

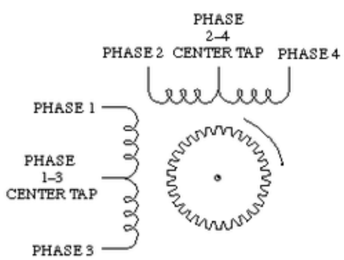
Actuators

A linear actuator is an actuator that creates motion in a straight line.

- Basic types of linear actuators
  - Belt-driven and screw-driven actuators
  - Pneumatically driven actuators
  - Rack-and-pinion driven actuators
  - Linear motor driven actuators
- Choosing the right actuator involves
  - Considering amount of force required
  - Considering the distance actuator needs to move
  - Speed required
  - Need of the project

Stepper motor

Standard 1.8 degree stepping motors consist of a laminated, toothed stator wound with two center tapped coils, surrounding a 50 pole hybrid rotor. The rotor consists of an axially magnetized permanent magnet, with two laminated iron cups. Unlike DC motors, applying current to the motor windings generates a torque which resists rotation (the holding torque).



1.8° Stepper motor

However, by switching coils on and off in a specific four step sequence (full step), the rotor will "step" 1.8 degrees per current change. An optional eight step sequence (half step), doubles the resolution to 0.9 degrees (400 steps per revolution). Rotation is therefore achieved by simply applying an appropriate sequence of winding currents.

FULL STEP CURRENT SWITCHING SEQUENCE

	Phase 1	Phase 2	Phase 3	Phase 4
step 1	on	on	off	off
step 2	on	off	off	on
step 3	off	off	on	on
step 4	off	on	on	off

HALF STEP CURRENT SWITCHING SEQUENCE

	Phase 1	Phase 2	Phase 3	Phase 4
step 1	on	on	off	off
step 2	on	off	off	off
step 3	on	off	off	on
step 4	off	off	off	on
step 5	off	off	on	on
step 6	off	off	on	off
step 7	off	on	on	off
step 8	off	on	off	off

Several factors complicate this otherwise simple scheme. An energized stepper motor exhibits a rotary stiffness which resists deflection from its current position. Coupled with the rotary inertia of the rotor, this spring-mass system produces a fundamental resonance in the 50 to 150 Hz range. Operation at step rates near this natural frequency increases noise and vibration, and may cause the motor to drop out of synchronization (lose position). The use of microstepping, which is implemented on stepper motor drives, dramatically reduces or eliminates this effect.

Microstepping

An important variation on conventional stepping motor drives is that of microstepping.

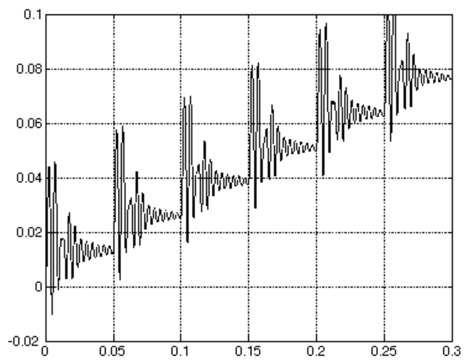
Conventional bipolar drives alternate the current direction in one coil at every step, resulting in a rotor displacement of 1.8 degrees. In microstepping, the coil current is changed in much smaller increments, increasing in one coil as it decreases in the other. The rotor responds by swinging to its new magnetic equilibrium, which can be a small fraction of a full step.

Microstepping has two principal benefits: it provides increased resolution without a sacrifice in top speed, and it provides smoother low speed motion. For example, to achieve a resolution of 5 microns with a full step system requires the use of a screw with a 1.0 mm lead. This places substantial constraints on top speed. A shaft speed of 40 revolutions per second results in a linear velocity of only 40 mm per second. Use of a divide-by-10 microstepper provides the same 5 micron resolution with a 10 mm leadscrew, but the linear velocity in this case is now 400 mm per second. Alternately, the resolution can be increased, to 0.5 micron with a 1 mm lead, or 1.0 micron with a 2 mm lead.

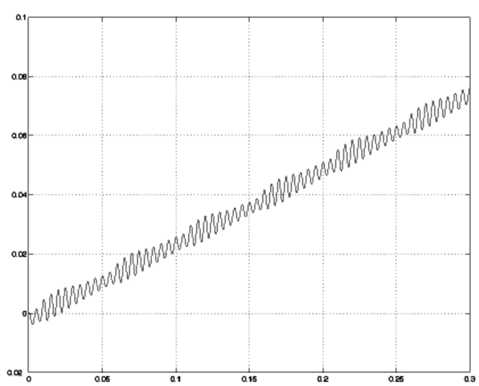
	Resolution	Lead	Top velocity (shaft speed 40 $\frac{rev}{\min}$)
Full step	5 μm	1 mm	40 mm/s
Microstepper ($\frac{1}{10}$ per step)	5 μm	10 mm	400 mm/s

Operation at low step rates (especially near the fundamental resonance) generates noise and vibration, since stepping motors, by definition, move in discrete angular increments.

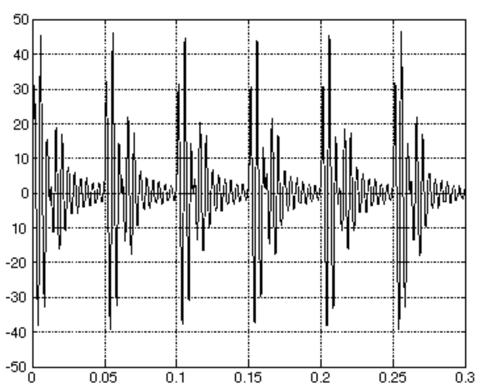
Microstepping decreases the size of these increments, and increases their frequency for a given rotation rate. This results in significantly smoother low speed operation. As an example, a laser interferometer was used to produce the graphs in figures below, which show the reduction in positional oscillations and velocity ripple for a positioner at a low (0.05 revolution/second) step rate.



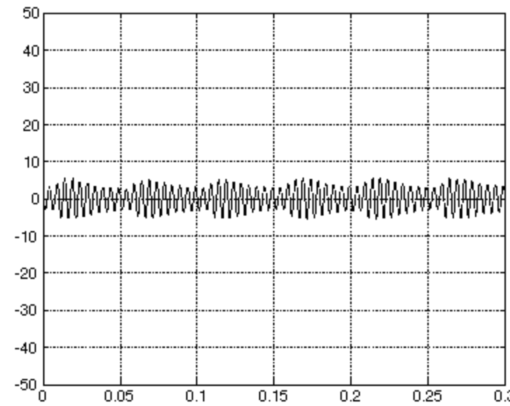
Full Step Position vs. Time



Microstepping Position vs. Time



Full Step Velocity Deviation



Microstepping Velocity Deviation

ACCURACY, REPEATABILITY, AND RESOLUTION: APLICATIONS IN MOTION CONTROL

The terms accuracy, repeatability, and resolution can be found on the spec sheets of many engineered products. They are often misunderstood, used interchangeably, or just plain confused. This can cause products to be incorrectly specified and, in many cases, over-designed for an application. I would like to take a few minutes to talk about these specifications and how they apply in the field of automation and motion control.

Here are some very simple definitions for each term:

- Accuracy: How close a measurement is to the actual value.
- Repeatability: How close a group of measurements are to each other.
- Resolution: The smallest difference that can be measured.

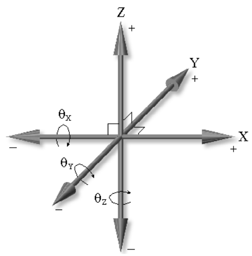
Accuracy

Positioning system accuracy can be conveniently divided into two categories: the accuracy of the way itself, and the linear positioning accuracy along the way.

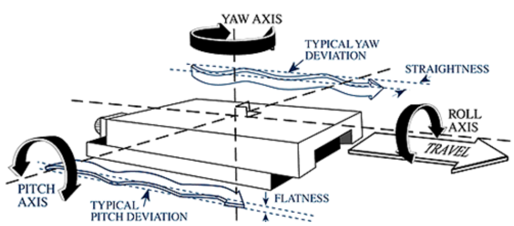
The former describes the degree to which the ways (ball and rod, crossed roller, air bearing, etc.) provide an ideal single-axis translation, while the latter is concerned with the precision of incremental motion along the axis (typically related to the leadscrew, linear encoder, or other feedback device).

Way accuracy

Any moving object has six available degrees of freedom (see figure below). These consist of translation, or linear movement, along any of three perpendicular axes (X, Y, and Z), as well as rotation around any of those axes (θx, θy, and θz). The function of a linear positioning way is to precisely constrain the movement of an object to a single translational axis only (typically described as the X axis). Any deviations from ideal straight line motion along the X axis are the result of inaccuracy in the way assembly.



There are five possible types of way inaccuracy, corresponding to the five remaining degrees of freedom (see figure below): translation in the Y axis; translation in the Z axis; rotation around the X axis (roll); rotation around the Y axis (pitch); and rotation around the Z axis (yaw). Since there are interrelations between these errors (angular rotation, for example, produces a translational error at any point other than the center of rotation), it is worthwhile to carefully examine the effects of each type of error and its method of measurement.



Linear positioning accuracy

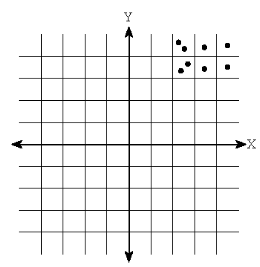
A variety of techniques are available to incrementally position a user payload along a linear axis. Leadscrews and ball screws are by far the most common, although linear motors are also used. Linear positioning accuracy is simply the degree to which commanded moves match internationally defined units of length.

Low to moderate accuracy systems typically depend on a leadscrew or ball screw to provide accurate incremental motion. Such systems are often operated open loop via stepping motors; if closed loop operation is employed, it is frequently with a rotary encoder. In either case, the screw is a principal accuracy determining element. screws exhibit a cumulative lead error, which is usually monotonic in nature, together with a periodic component, which is cyclic and varies over each revolution of the screw. In addition, there can be backlash in a leadscrew nut, which will reveal itself upon direction reversal. Precision positioning stages generally employ either a preloaded ball screw, or a leadscrew with an anti-backlash friction nut. Ball screws are preferred for high speed applications, and offer a high natural frequency due to their inherent stiffness. Leadscrews with anti-backlash nuts provide very high repeatability at modest cost, and are appropriate for most applications.

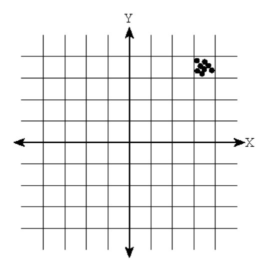
Repeatability

The repeatability of a positioning system is the extent to which successive attempts to move to a specific location vary in position.

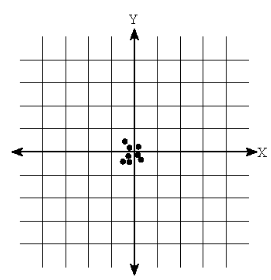
A highly repeatable system (which may or may not also be accurate) exhibits very low scatter in repeated moves to a given position, regardless of the direction from which the point was approached. Figures below illustrates the difference between repeatability and accuracy.



Low accuracy - Low repeatability



Low accuracy - High repeatability



High accuracy - High repeatability

A distinction can be drawn between the variance in moves to a point made from the same direction (uni-directional repeatability) and moves to a point from opposing directions (bi-directional repeatability). In general, the positional variance for bi-directional moves is higher than that for uni-directional moves.

Resolution

Resolution is defined as the smallest positional increment which can be commanded of a motion control system.

Aspects that play a role in determining the overall system resolution include:

- Mechanical positioning components.
- Motor.
- Feedback device.
- Electronic controller.

Using Microstepping to Increase Resolution

A stepper motor system's resolution is set by the stepper motor lead screw pitch, motor step angle, and drive electronics. For any given pitch, two full-step resolutions can be achieved through the use of either 1.8-degree or 0.9-degree stepping motors which provide 200 and 400 full steps/revolutions, respectively. Full-step resolution can be further increased by microstepping. Most microsteppers electronically subdivide each full step into 10 or 50 microsteps to produce 2,000 or 10,000 microsteps per revolution with 1.8-degree steppers, or 4,000 or 20,000 microsteps per revolution with 0.9-degree motors. While microstepping can be implemented with higher division ratios than 50, the increased resolution is often of limited use. This chart provides resolutions for full line of stepper motor lead screws and ball screws, together with motor options and microstepping drives.

RESOLUTIONS OF ROTARY MOTOR SYSTEMS

	Drive Screw	Stepper Motor												Servo Motor			
		1.8 Degree (200 Full Steps/Rev.)						0.9 Degree (400 Full Steps/Rev.)						With RE-2000'		With RE-4000	
	Lead	Full Step		+10 Microstep		+50 Microstep		Full Step		+10 Microstep		+50 Microstep					
ENGLISH	(inch)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)
	0.5 (2TPI)	0.002500	63.5	0.000250	6.35	0.000050	1.27	0.001250	31.75	0.000125	3.175	0.000025	0.635	0.000250	6.35	0.000125	3.175
	0.4 (2.5TPI)	0.002000	50.8	0.000200	5.08	0.000040	1.016	0.001000	25.4	0.000100	2.54	0.000020	0.508	0.000200	5.08	0.000100	2.54
	0.2 (5TPI)	0.001000	25.4	0.000100	2.54	0.000020	0.508	0.000500	12.7	0.000050	1.27	0.000010	0.254	0.000100	2.54	0.000050	1.27
	0.1 (10TPI)	0.000500	12.7	0.000050	1.27	0.000010	0.254	0.000250	6.35	0.000025	0.635	0.000005	0.127	0.000050	1.27	0.000025	0.635
	0.05 (20TPI)	0.000250	6.35	0.000025	0.635	0.000005	0.127	0.000125	3.175	0.000013	0.3175	0.000003	0.0635	0.000025	0.635	0.000013	0.3175
	0.025 (40TPI)	0.000125	3.175	0.000013	0.3175	0.000003	0.0635	0.000063	1.5875	0.000006	0.15875	0.000001	0.03175	0.000013	0.3175	0.000006	0.15875
	0.02 (50TPI)	0.000100	2.54	0.000010	0.254	0.000002	0.0508	0.000050	1.27	0.000005	0.127	0.000001	0.0254	0.000010	0.254	0.000005	0.127
METRIC	(mm)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(um)	(inch)	(μm)	(inch)
	10	50	0.001969	5	0.000197	1	0.000039	25	0.000984	2.5	0.000098	0.5	0.000020	5	0.000197	2.5	0.000098
	5	25	0.000984	2.5	0.000098	0.5	0.000020	12.5	0.000492	1.25	0.000049	0.25	0.000010	2.5	0.000098	1.25	0.000049
	3	15	0.000591	1.5	0.000059	0.3	0.000012	7.5	0.000295	0.75	0.000030	0.15	0.000006	1.5	0.000059	0.75	0.000030
	2	10	0.000394	1	0.000039	0.2	0.000008	5	0.000197	0.5	0.000020	0.1	0.000004	1	0.000039	0.5	0.000020
	1.4	7	0.000276	0.7	0.000028	0.14	0.000006	3.5	0.000138	0.35	0.000014	0.07	0.000003	0.7	0.000028	0.35	0.000014

Defining our resolution

The key question to ask in determining the required system resolution is "What are the minimum incremental moves which must be performed in a given application?" Resolution is easily over-specified or confused with accuracy or repeatability. In general, it is appropriate to specify a resolution that is about 5 times smaller than the position error that is required by the application. Popular resolutions for stepper motor stages are 0.0001 inches and 1 micron. To achieve a resolution of .0001 inch, a 0.20-inch lead screw is used with a 200 step/revolution motor operated in /10 microstep mode. To achieve a resolution of 1 micron, a 2-millimeter lead screw is used with the same motor.

Some images were taken from:

https://www.machinedesign.com
https://dovermotion.com