Multi-Axis Synchronization

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Abstract

In many machine control and automation problems, there are two or more axes of motion which must be coordinated. The term "multi-axis synchronization" refers to the motion which requires coordination, and the techniques used to achieve control of the motion. With today's increasing automation and machine sophistication, the control applications have become more demanding, and the control techniques have improved. This paper reviews some of the basic elements of motion coordination, illustrated with the requirements of familiar applications. A review of control choices is presented, with special emphasis on a technique called following. The key concepts and capabilities of following are explained with the help of a detailed web processing example.

Introduction to Multi-Axis Synchronization

The term "axis of motion" refers to one degree of freedom, or forward and backward motion along one direction. It may be linear or rotary motion, and may take the form of a conveyer belt, a rotary knife, or many other types. When two or more axes of motion are involved on a single machine, that machine is employing multi-axis motion. The axes may be working independently, or moving together. The need for multi-axis synchronization arises whenever the axes must move together, and the relationship between their respective motion is important.

The most familiar example of a multi-axis application requiring synchronization is that of an X-Y plotter. Here there are two axes, the X direction and the Y direction. Each may move independently of each other, but if a two dimensional figure is to be drawn accurately, their motion must be coordinated. The figure below illustrates what happens to a 45 degree line if the X axis starts and ends later than the Y axis.

X-Y Plotter

synchronized   X starts late

Figure 1
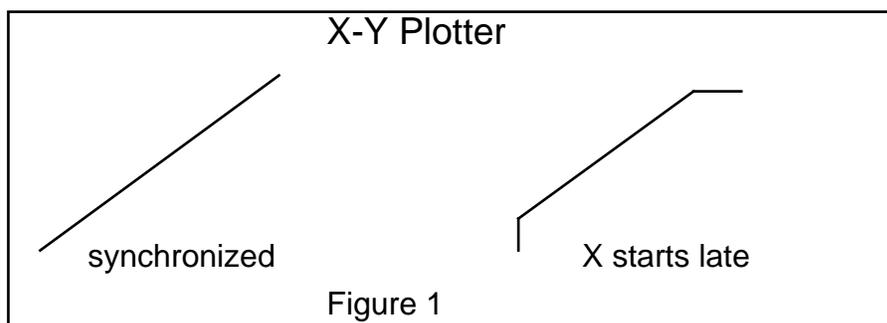
In many machines, the synchronization requires more than the coordination of starting and stopping. The position and velocity relationship between the axes will often be important to the proper operation of the machine. For example, if there are interlocking moving parts on a machine, position coordination during motion may be

required to avoid collision. If multiple axes control the orientation of a moving part, the position and velocity synchronization of the axes will determine how accurately the part is oriented as it moves. In some cases, a certain velocity or position achieved on one axis will be the signal to start motion on another axis. In such cases, the accuracy of the eventual position relationship of the axes will depend on how accurately the position of first axis is monitored by the second.

The Mechanical Approach to Synchronization

By definition, synchronization of two or more axes requires a definite relationship between one axis and the others. Before electronic motion control was available, the traditional approach to this had been largely mechanical, using a central motion source. Individual axes were driven from this source with gears and drive trains. The gears determine the speed relationship, and the drive trains deliver the motion to the appropriate place. Such an approach works well if the desired gear ratio is constant and the drive train is short and direct. More complex arrangements require more costly mechanics, and the problems of backlash and mechanical wear become more pronounced.

If the relationship desired between axes was not constant, but needed to follow a pattern, mechanical cams were used. The shape of the cam determines the motion pattern of the cam follower with respect to the motion of the cam driver. If the required shape is very complex, the cam can be quite difficult to design, and expensive to machine and produce. Cams are also subject to wear, which directly affects the accuracy and repeatability of the cam follower motion.

Individual axes were started and stopped using clutches and brakes. These are required to accelerate and decelerate the load, but as with all mechanics, they suffer the problem of wear. They also do not allow for precise control of the position relationship between axes, because the amount of slip during starting and stopping can not be precisely controlled. Clutches and brakes tend to be rough on the rest of the machinery, because of the sudden jerk when they are engaged.
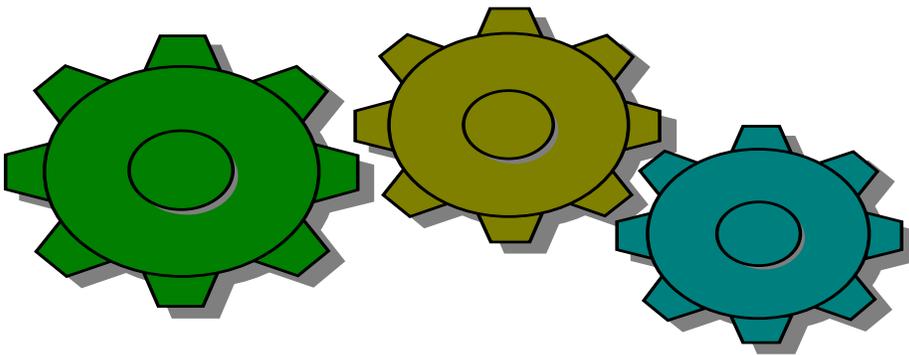
Stepper and Servo Motion Control Systems

The availability of electronic motion control has brought solutions to the problems inherent with the mechanical approach to synchronization. To understand how these solutions are achieved, it is helpful to review basic electronic motion control systems. One

axis of electronic motion control consists of the motor, the motor drive, and the controller. The controller accepts motion commands from a host computer or an internally stored program. These commands are interpreted by the controller to generate continuously updated position commands (motion profiles) to the drive. The motor drive controls the current to the motor which will result in the commanded position. In a multi-axis system, one controller can control several motor and drive combinations.

The motion control system may be a stepper or servo system. Stepper systems tend to be less expensive than servo systems, but have less speed and power for a given size of motor. In stepper systems, the drive receives position commands in the form of low voltage pulses (steps), and adjusts the *phase* of the current in two sets of motor coils to align the motor shaft. Each new step received corresponds to an additional increment of rotation on the shaft. Current is maintained in the motor coils, even when the motor shaft is in the correct position. Common step motor resolutions range from 200 steps per revolution (full stepping) to 50,000 steps per revolution (micro-stepping).

Servo systems employ motor shaft position feedback , either from an incremental encoder or from a resolver. The actual position and velocity derived from the feedback is compared to that commanded in the motion profile to result in a torque command to the drive. In servo motors, the phase of the current is adjusted according to the actual position of the shaft. It is continuously adjusted to produce maximum torque for a given current amplitude. This process is called commutation, and is done mechanically in brushed motors, and electronically in brushless motors. The drive controls the *amplitude* of the current to the motor in proportion to the torque command. In analog servo systems, the feedback goes to the controller, and the controller's output is an analog torque command. In digital servo systems, the drive accepts steps as the position commands, and the shaft feedback goes only to the drive. Servo systems must be tuned to match the load they are moving for the best performance. A properly tuned system results in powerful and precise positioning of the load.

The choice of motion control system will depend on the particular application. A dedicated motion control company such as Compumotor can provide any of these systems, as well as expert technical assistance in the design, implementation, and tuning of the system.

The Electronic Approach to Synchronization

Programmable stepper and servo motor systems provide a direct replacement to mechanical components, and solve many problems. Individual axes are driven from individual motors instead of gears and drive trains. The speed and position relationship between axes is controlled with the controller, and this may be infinitely and continuously adjusted, rather than fixed as with gears. Motors deliver the motion directly to the appropriate place, eliminating the need for drive trains. The problems of backlash and mechanical wear are gone, resulting in precise, repeatable control and reduced maintenance.

Complex position relationships between axes may be programmed and stored in the controller as direct replacements for mechanical cams, eliminating the cost and maintenance associated with cams and improving the reliability and accuracy of the

resulting motion. Controllers can also accept electronic inputs from sensors, read run-time status from other parts of a machine, and impose delays or dwells. These features give much greater design flexibility and run-time decision-making power to a machine than could be achieved with mechanical components.

Programmable acceleration and deceleration allow very smooth and controlled starts and stops to individual axes of motion. The smoothness reduces machine wear and makes a machine run more quietly. The control gives better precision in the axis synchronization, which results in better quality in overall machine function. The increased control also allows higher speed moves on the individual axes. This translates directly into increased throughput and higher productivity for a machine.

The Benefits of Flexibility

While increased quality, reliability, and throughput of a machine are certainly desirable design considerations, perhaps the most important benefit of programmable motion control is that of flexibility. A machine built with mechanical synchronization components is limited in function by the particular gears and cams installed. To process a different product on the same machine could require significant machine downtime and changeover labor as cams and gears are replaced. By contrast, a machine built with programmable synchronization components is limited only by the programs. The machine may be modified for a different product simply by selecting a new program. This allows a given machine to produce a wide variety of products, and remain fully utilized, regardless of changes in production requirements. As production practices become increasingly capital-intensive, the significance of full machine utilization becomes increasingly important.
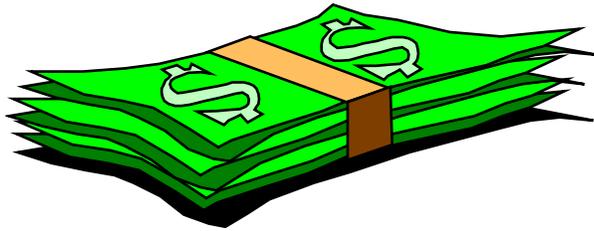
The economics of production today also demand flexibility. The competitive advantage goes not just to those who produce great quantity of product on a machine, but also to those who can produce a great variety on a single machine. The flexibility and rapid changeover made possible by programmable electronic motion control is becoming increasingly important with today's manufacturing trends. The emphasis on Just-In-Time (JIT) manufacturing and higher standards of customer service make rapid response to changing product mix imperative to remaining competitive.   The vendor who can respond to a custom product order, or a small quantity request for product, will be the preferred vendor. Similarly, those who design, build, and sell machines for others will benefit if their customers can build several products with one machine, or if one machine can serve the needs of many different types of customers.

Introduction to Following

In the motion control applications described above, we could assume that all axes are under central control, and that this central controller is synchronizing the motion of each axis. In many applications, however, there may be motion which is generated or controlled externally. Even so, it may be important to synchronize other axes to this motion. The general term for this type of synchronization is "following", and it applies to any controlled motion which responds to some other measured motion. The measured motion axis is called the "master", and the controlled axis is called the "follower".

The discussion of gears and cams above gives a good example of the need for following. Suppose other axes must be synchronized to an externally controlled rotating shaft. By measuring its motion, the shaft becomes the master, and the motion of secondary axes may be controlled as a function of the motion of that shaft. Electronic gearing is achieved by moving a follower axis at a defined ratio to the motion of the master shaft. Electronic cams may be created by designing a repeating pattern of changing ratio to the motion of the master shaft.

Key Concepts of Following

The concept that distinguishes following from other methods of synchronization is the assignment of a master to a controlled axis. The master motion is measured and responded to by the follower. The actual master motion will usually be external motion measured with an encoder. It may also simply be another axis of a multi-axis controller.

The concept of ratio is the most basic in following. The ratio is the change in an axis position (follower travel) with respect to the change in master travel. A direct analogy is velocity, which is the change in an axis position with respect to time. The important difference is that the control of the follower is programmed as a function of master motion, not of time. This is what locks the relationship between the motion of two or more axes, and allows for precise synchronization. The ratio may change within a profile, as shown in the winding example below. In order to completely define the position relationship between master and follower axes, the master travel over which the ratio changes must be specified. A change in ratio over a known master travel is analogous to acceleration, which is a change in velocity over time.

Coil winding and filter winding are good examples of applications which may benefit from following. These winding applications often use a repetitive pattern of changing ratio. Typically, a rapidly rotating spindle holds a bobbin onto which a coil is wound. A traverse axis moves back and forth along the length of the coil at a ratio to the spindle rotation, guiding the wire as it is wound onto the bobbin. A low ratio of traverse motion to spindle rotation will result in a tight coil, i.e., a large number of turns per inch. A higher ratio of traverse motion to spindle rotation will result in a looser coil.

Coil Winding

Traverse axis ratio

0   5   Spindle Rotation   20   25

Resulting Coil

Figure 2
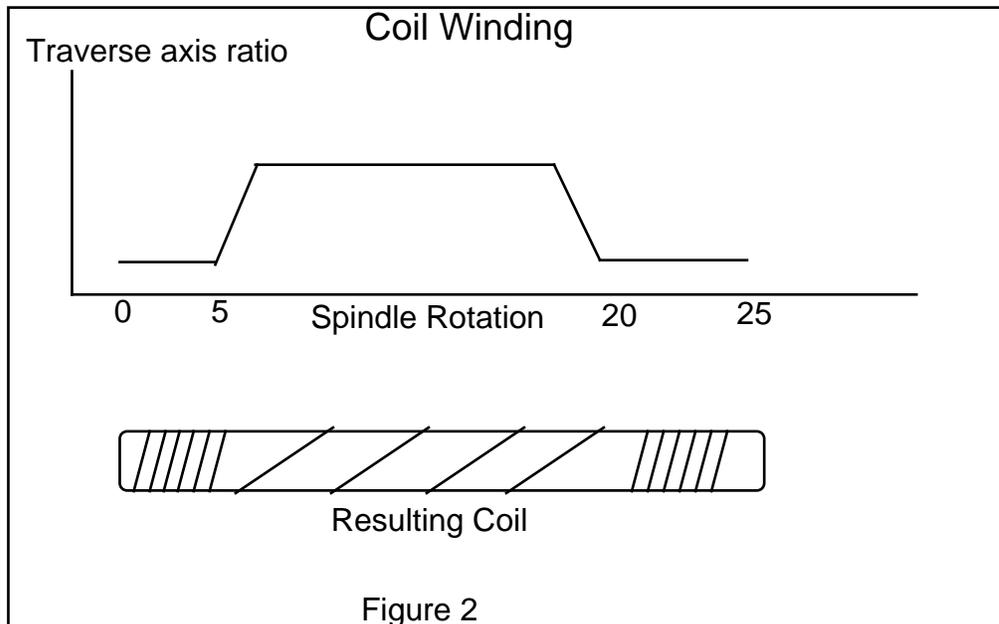
The Master Cycle Concept

The master cycle concept provides a useful way of dividing continuous master motion into meaningful portions. The controller accepts a master cycle length definition from the programmer, and subsequently measures master travel in terms of cycles and positions within a cycle. The master cycle concept is analogous to minutes and hours on a clock. Even though time marches on continuously, it is useful for us to divide time into hours and minutes within an hour. We define a cycle length of 60 minutes, and discuss time in terms of how many minutes past which hour. In most applications, one master cycle will correspond to one machine cycle, or one product. In the winding example above, the master cycle length would probably be defined as the amount of spindle rotation required for one complete forward and backward traverse cycle of the wire guide axis. A coil with 20 layers would go through 10 master cycles.

Because a master cycle usually corresponds to a product cycle, it is important to begin the measurement of master travel at the spot that corresponds to the beginning of a product cycle. This is usually initiated by detecting the arrival of a product or moving machine part with an electronic sensor. In some cases, it may not be possible to physically place the sensor at the location that corresponds to the beginning of a product cycle. In this case, the controller would be programmed to assign an initial non-zero value of master travel that corresponded to the physical offset of the sensor.

Phase Shifts During Following

If a controlled follower axis is following a master axis at certain ratio, that ratio determines the *change* in follower position with respect to a *change* in master position, but not the alignment of master and follower. In most applications, a moving machine part must exactly match the speed of another moving part or product, i.e., they move at a 1:1 ratio. They must also be properly aligned, and this alignment is known as phase. A

familiar example of phase adjustment is the use of a timing strobe in the adjustment of automobile engine timing.

In following, a phase shift may be commanded to correct the alignment of master and follower without affecting the ratio of the motion. In terms of visual alignment, the phase shift appears as an advance or retard of the follower. During a shift, motion has two components. One component is the result of following, the other is the result of shifting. The shift is a normal move, and is specified with an acceleration and velocity. This motion is superimposed onto the motion which results from following at a specified ratio. If the amount of alignment correction is known, a preset shift may be commanded as shown in the graph below. In some cases, a visual alignment must be done by an operator of the machine. In these cases, a continuous shift would be commanded until the alignment was corrected. The shift component would then be stopped, without stopping the component of motion resulting from following.

Superimposed Preset Shift

Ratio

Preset shift (advance)

constant ratio

ratio ramp

Master travel

Figure 2
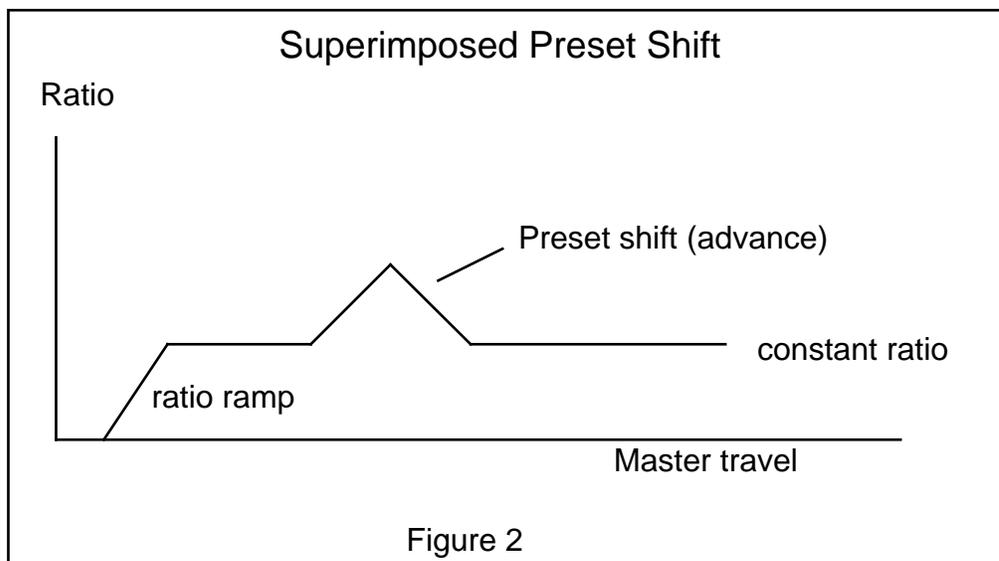
Web Processing

Printing onto a continuous web of paper is a common example of web processing. The application problems in this task are solved using the capabilities of following described above. In the drawing below, the inked print portion of the print drum must apply the print pattern onto the paper exactly between the registration marks on the paper. While the print is being applied, the surface speed of the print drum must match the speed of the paper exactly, to avoid smearing the print. In this particular paper product, the distance between registration marks is shorter than the circumference of the drum. This means that the drum must speed up during the non-print portion of its rotation, then slow back down to match surface speed at the proper location. Although the distance between registration marks is nominally even, minor variations require that alignment correction be done each time a registration mark is detected.
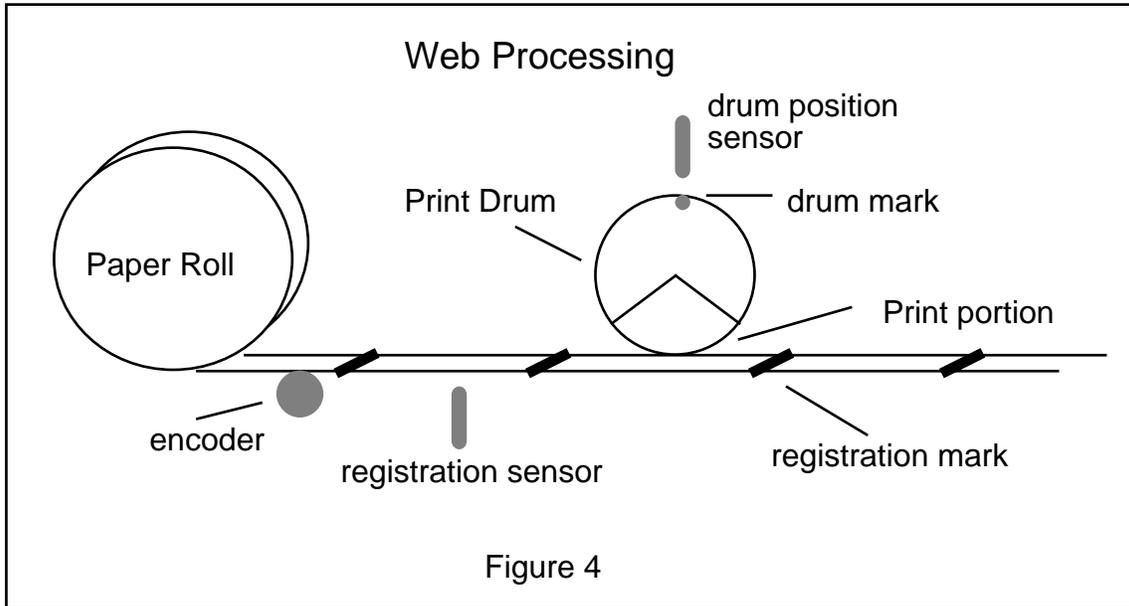
Figure 4

A solution for this application which would use following is shown in figure 5. The paper travel is measured with an encoder, and is the master axis for this application. The print drum is the follower axis, and must follow the motion of the paper. The ratio is described in terms of surface travel, and must be 1:1 during the printing portion of the cycle. During the remainder of the cycle, the ratio must be higher, such that the drum travels one revolution for each registration mark. When the registration mark passes the registration sensor, the drum *should be* exactly halfway through the non-print portion of the cycle. The *actual* drum position is captured when the registration mark is sensed, and it alignment is corrected with a superimposed phase shift.

Figure 5
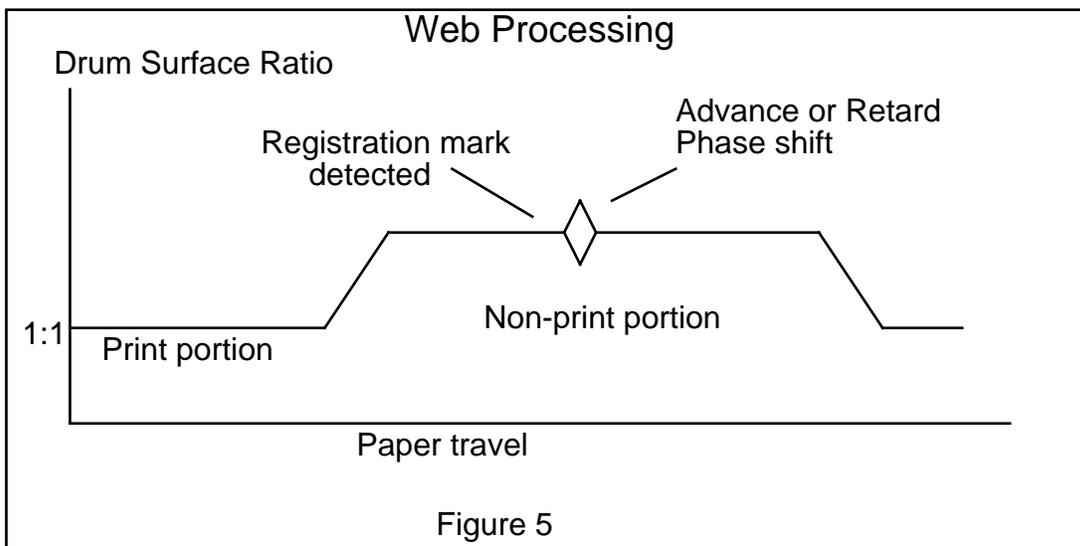
Summary

Motion coordination is required in many industrial processes, and can take many forms. The accuracy of motion synchronization in a machine directly affects the quality of the products made by that machine. In the past, the speed and accuracy of synchronization has been limited by the use of mechanical components. The development of programmable electronic motion control, however, has made great improvements in multi-axis synchronization possible, replacing mechanical components such as gears, clutches, and brakes. The flexibility of programmable electronic motion control has significant economic benefits as well, because it allows short production runs and custom product requests. The downtime associated with these short runs is minimized when the setup is programmable.

One specific technique called "following" allows programming the motion of one axis as a function of the measured motion of another. Key following concepts are the ratio of follower to master motion, superimposed shifts, and measurement of master motion in meaningful cycles. Any application which is described with terms such as "gearing", "catch up with", "advance and retard", or "cam motion pattern" may be best solved using the capabilities of programmable electronic motion control with following.

The motion controller chosen for the application must have the sophisticated following and multi-axis control features described above. One such controller is the 6K from Compumotor, which can control up to eight axes of stepper or servo systems. Multiple axes may follow a single master, or multiple masters and control programs may be used simultaneously.