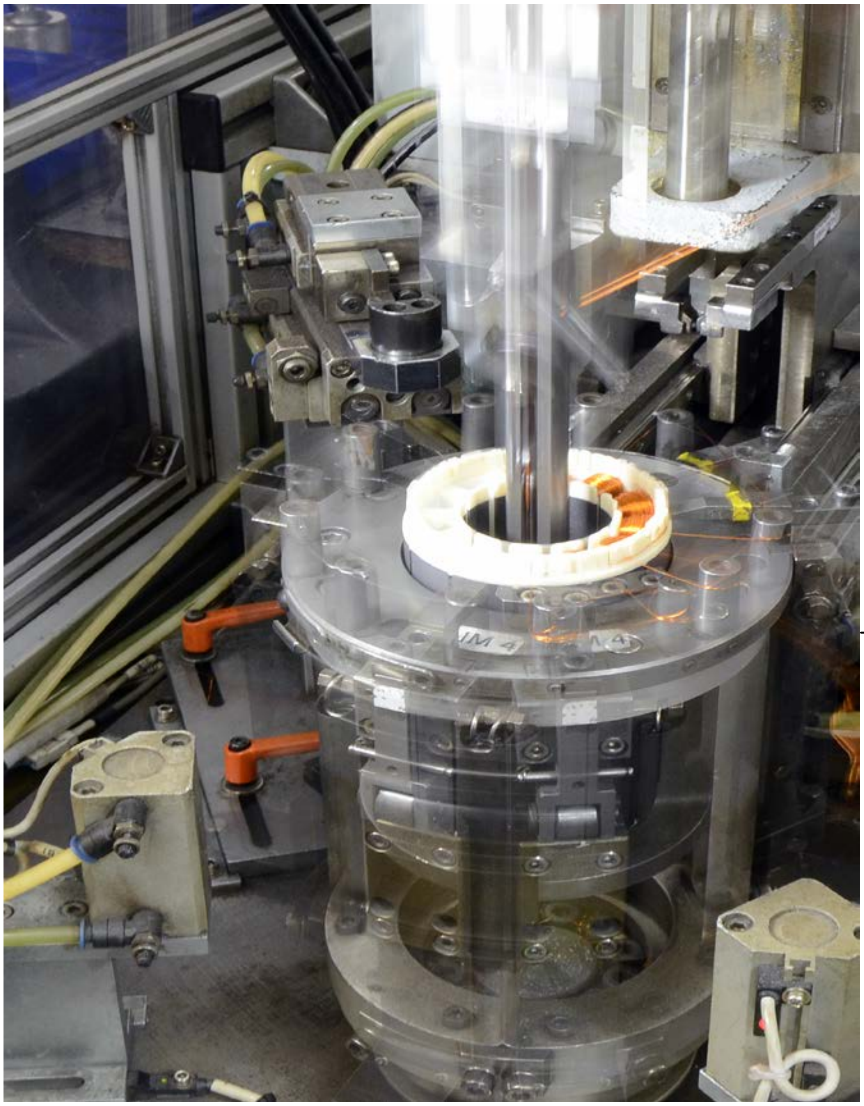

A Simplified Machine Design Approach for Optimal Servomotor Control

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White Paper

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An often asked question from industrial machine builders or integrators is how can they effectively design or implement the conversion of a machine with servo technology to meet performance expectations. This is a specialized task filled with layers of complexity that can prove difficult to execute, even when the scope of work is fully understood.

Available and different technologies present various possible engineering variations and unique operating processes. Then if there is a misunderstanding or knowledge gap, for any given process on the work to be performed, the possibilities expand exponentially and create further complexity with added risk. The intent of this article is to present a simplified design approach for servomotor utilization to overcome many of the initial challenges. The approach is based on several different but typical mechanical axis configurations and requirements that highlight risk management, optimal performance and reduced development time.

When considering a machine design there are clearly many factors to address in the planning phase. Reviewing all the possible situations to reduce risk of failure as well as working through the different combination scenarios, all the *ands*, *ifs* and *buts*, are a demanding set of tasks. For this reason, it's essential to build baseline knowledge of machine functions and each of its axes, relative to the overall chosen operating process and work to be performed. Start by developing a thorough understanding of the chosen process to complete the machine's function, the full picture encompassing the *ins* and *outs*, as well as identifying any variables and trade-offs, and recognize there likely will be some unknowns. This extends to the advantages and disadvantages of available motion technologies considered and applied to each axis of the machine.

Acquiring as much in-depth comprehension upfront will undoubtedly alleviate potential issues downstream and greatly enhance the opportunity for successful execution. Also, at the center of the design is risk management of specific technologies available and their interface with each other, related to the trade-offs and decision priorities to be given to the machine's function for the desired process.

Closer Review of Technologies and Varying Degrees of Performance

What is considered high technology performance for one manufacturing process is not necessarily high performance for another. It is natural for the machine builder to deploy technologies they have experience with. However, new challenges often entail the utilization of newer technologies. When a retrofit or a new machine design requires the utilization of closed-loop (servo) motion control technologies, there are often misconceptions involved. For example, misconceptions often occur between what was required for a machine's optimization utilizing **previous technologies** and what is now required for a machine's optimized performance. Proper deployment of closed-loop motion control technologies requires balancing its capabilities, trade-offs and other factors that will enhance the new machine's performance.

Previous technologies may include, but are not limited to, hydraulics actuators, variable speed motors, pneumatics or any number of the typical open-loop, ON-OFF control and in some cases, semi or pseudo closed-loop technologies. Even newer closed-loop control concepts must be considered or balanced with older concepts to reduce risk. For example, it may be a great enhancement to run a machine and control all its axes by a virtual master axis. However, if one axis is essentially driven by two or more motors *(hard coupled or pseudo coupled mechanically by the mechanism / load),* the additional latency of one motor's drive talking to another through the virtual master's control, rather than directly to each other, will increase risk as a function of speed the machine is to operate.

In general, any process that is to be sped-up or to run at a faster rate requires a machine with the capability of faster response times than its previous design to maintain quality. In other words, the machine must have the capability to move and act on the product at a faster rate and to respond to all commands and disturbances within the limit of the product and process itself.

Often an actual process time is fixed and cannot be increased under an existing technology, leaving only product transfer times as the available time to be sped-up. In turn, this increases specific axis' peak horsepower (hp) requirements during acceleration/deceleration times from its baseline by the product of the increased ratio: speed and torque (*a 15% increase of each, speed and torque, during peak requirements is a 32.25% hp increase*). Many of the issues involved, when converting a process machine from some form of open-loop, ON-OFF *(bang-bang)* control or pseudo closed-loop control method to a closed-loop servomotor controlled machine, may not be particularly intuitive to a first-time servo machine designer.

Identifiable Issues Below:

Inertia. Inertia was not a concern or even a consideration in the past for some specific axes of a machine design. For some other axes, an optimal machine required a high system inertia *(load and actuator)* to dampen any disturbance from being seen by the product. We want to utilize a high performance servo to increase speed and thus productivity, with the same or improved quality. This requires axes with higher BW *(bandwidth)* capability than most previous designs in order to sense commands, product changes and disturbances, such that we can respond to errors *(delta (Δ) between: command and actual)* and make the appropriate corrections, both quickly and easily. In order to accomplish these tasks a lower system inertia is generally desirable and most frequently required. This is especially true of processes requiring point-to-point moves or on-the-fly corrections for continuous or pseudo continuous processes. Production energy costs are often reduced by the higher levels of production efficiency.

Mechanical Advantage by Gears. Another issue that occurs especially with previously designed machines is backlash within an axis's mechanism. Often this type of axis movement was only mildly considered a potential process issue. The reason is because the unidirectional driven advantaged mechanism driving against the load, pretty-much stays on one side of the mechanism's backlash. However, with the constant velocity correction of a servomotor, the full +/- displacement is repeatedly seen.

Illustration of gears and backlash

Mechanical Advantage by Timing Belt. For many previously designed machines *(especially uni-directionally driven),* the amount of compliance produced by a belt is typically not a major concern in regards to the process, as long as it is sized large enough so that it does not break. However, with the constant velocity correction of a servomotor, the full +/- displacement of the belt's compliance can be repeatedly seen. The typical doubling of the belt's width (*as calculated for a unidirectional mechanism*) to reduce compliance may make the belt too wide. In this case, the designer may need to utilize as much width as the available space will allow and if possible, further reduce belt compliance *(increase rigidity)* by selecting a stronger or thicker style belt. {Note: Be careful. A thicker belt reduces compliance *(desirable),* but lowers natural resonance frequency *(undesirable)* – depending on where the frequency is within the control system's spectrum. Then there is another issue, a larger belt will have a greater side load that must be considered in the design *(bearings, tensioners, pulleys, and/or motors could be affected*).}

Mechanically advantaged mechanism by a belt and planetary gearhead

For many designers, these new issues can present hard concepts to get through at first. Because what worked for a host of different open-loop, ON-OFF control and pseudo closed-loop control technologies, is now in part or as a whole, a potential hindrance against the new machine design, impacting the desired goal for increased production and quality. Thus this new design may need additional effort from the mechatronic designers with typical disciplines in mechanical, electrical, electronic, control, process and programming fields in order to simplify and achieve the goals of risk management, optimal performance and reduced development time.

Minimize the Potential Process Issues Involved with the New Design

Typically, when utilizing a servo system technology to meet this overall goal, the designer will need to enhance the BW *(bandwidth)* response capability for each axis of the new machine. To accomplish the task, we must consider a number of variables. They include frictional loads and any external loading *(gravity or otherwise),* the inertia between the load reflected back to the motor for a practical controllable solution within the process required tolerances and also the backlash and compliance of each axis. For a typical servo mechanism, it is desirable to have a rigid style *(compression, etc.)* coupling to minimize compliance.

For many direct-drive axes, the steel's compliance between the motor and load can be a limiting factor. The steel's compliance can affect the ultimate BW of the servo control loops. Even a machine's frame compliance can become a major player against axis BW capability, motion stability and controllability, where with previous technologies it may not have been of any concern. For example, to achieve the best possible axis BW capability, controllability and minimal risk of any issues for direct-drive cartridge motors, it is very important to design the driven shaft *(if applicable)* with an outside dimension (OD) as large as possible for as long as possible, with an overall shaft length as short as possible. *(Use as large an ID bearing here as possible to help system BW.)*

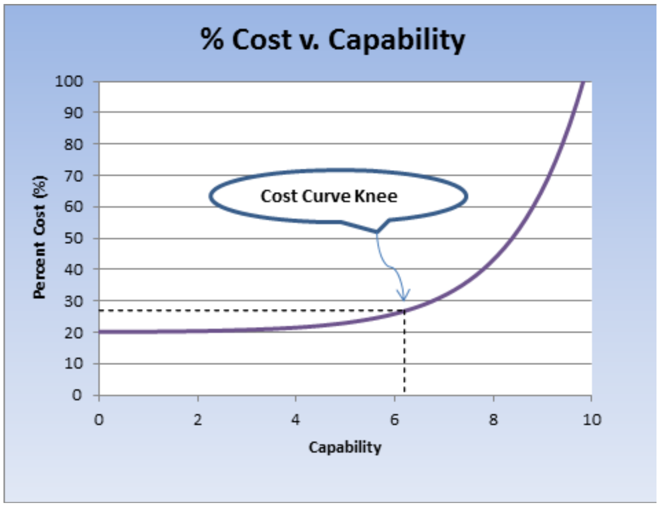
Direct drive cartridge motor technology utilizes a machine's bearings to support the rotor of a full-frame motor for the ease of installation, and can often eliminate the need for a mechanical advantaged mechanism (gearheads, pulleys and belts, etc) like other direct-drive motor designs. Kollmorgen is a pioneer in developing direct drive motor technology.

Direct-drive mechanism

Prioritizing for Risk Management and Trade-offs

It cannot be stressed enough that controlling factors for risk management are the machine's functions with the chosen process to accomplish the work of each axis, as it applies to the new product production requirements and not, the new or original machine's design. Remember, for all new designs and especially for proof-of-concept designs, cost reductions cannot be reasonably applied to a machine whose manufacturing process doesn't yet work. Changing the machine's motion technology and control by specifically keeping the machine functions and chosen process in the forefront for making decisions and trade-offs for each axis, with available servo system technologies, will greatly reduce risk and enhance the success of any machine design.

After chosen process and machines functions are understood *(ins and outs, and basic safety requirements),* we can now begin asking questions to determine direction and possible solutions for the work to be performed by each axis. The following set of questions are not meant to be all inclusive, but rather a strong start to simplifying the design approach of each axis for servomotor system utilization.

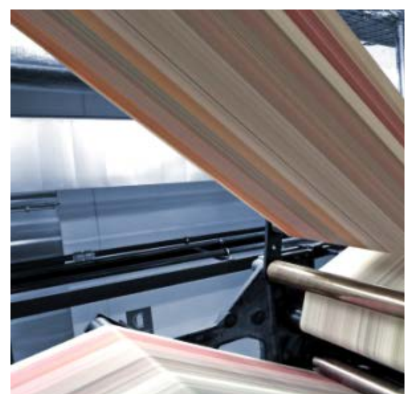


Graphical illustration showing knee of cost curve vs capability

AXIS QUESTIONS:

1. **Does the axis in question require point-to-point moves (typical Position Mode operation)?**
   a. Reduce load inertia and mechanism inertia as much as possible. For example, utilize aluminum over steel if possible, and/or remove unnecessary metal from components, especially at the larger diameters where not otherwise needed. Remember, the moment of inertia of a rotating component about its center axis goes up by its diameter to the 4^{th} power.
   b. Reduce friction as much as possible: bearings versus bushings, ball screw versus acme style screw, etc.
   c. Reduce mechanism compliance as much as possible *(use the knee of the cost curve versus capability, when applicable).*
   d. Reduce, minimize or eliminate mechanism backlash as much as possible: belt versus gearhead, versus direct-drive, etc.
   e. Minimize the number of moving bodies between the load and motor and make the mechanism's drive train rigid as possible. For example, a rack and pinion mechanism must be locked together such that the rack/pinion does not rise up on its teeth during a high speed acceleration or deceleration.
   f. Use a rigid (compression style, etc.) or equivalent coupling when applicable for the mechanism, reducing potential for mechanical winded-up and otherwise, relatively large coupling inertia.
   g. For indexing applications (especially high speed), increase feedback resolution to maximum *(knee of the cost v capability curve)*, if one has not done so already.
   h. Ensure proposed control method(s) can achieve safety protocols and any other specific requirements.
   i. Consider basic maintenance procedure requirements in harmony with the process and safety protocols, up front.

2. **Does the axis in question require a continuous operating velocity (typical Velocity Mode operation)?**
   a. One must consider velocity tolerances long term versus short term, if applicable**:**
      I. If very short term tolerance is more critical/dominate (smaller short term Δ tolerance required per some time unit), then a higher than normally desirable load inertia may still be more suitable. (Process needs to be understood and for a specific process it could go either way: minimized load inertia (with maximum feedback resolution) versus a purposely designed larger load inertia (to dampen short term response) – it is very hard to make a judgment call without specific process information.)
      II. If long term tolerance is dominate (tight long term Δ tolerance required per some time unit), then typically it is best to maximize feedback resolution, reduce load and mechanism inertia, allowing servo to maintain best control with highest BW.
      III. If the process requires best of both worlds: reduce load inertia and mechanism inertia, and increase feedback resolution to maximum available (utilize knee of the cost curve vs. capability).



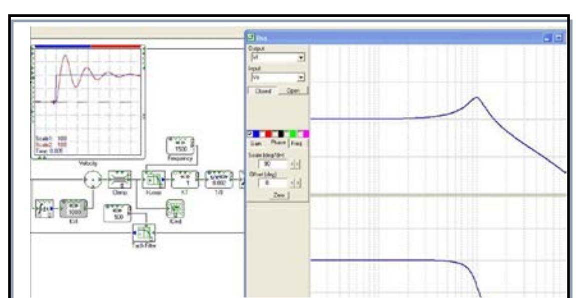
   b. When applicable**:**
      I. Reduce load inertia and mechanism inertia as much as possible to increase BW capability.
      II. Reduce friction as much as possible.
      III. Reduce stiction as much as possible, especially for low speed process applications.
         i. Eliminate mechanism backlash.
         ii. Reduce mechanism compliance as much as possible, use a rigid (compression style, etc.) or equivalent coupling when applicable for the mechanism, and minimize the number of moving bodies between the load and motor.
   c. Increase feedback resolution to maximum *(knee of the cost curve v capability*).
   d. Controls: if possible run drive in a position mode for the appropriate time and displacement range *(typically a better constant velocity tolerance can be achieved at the servomotor when run in-side a position-loop*).
   e. Ensure proposed control method(s) can achieve safety protocols and any other specific requirements.
   f. Consider basic maintenance procedure requirements in harmony with the process and safety protocols up front.

3. **Does the axis in question require a continuous force be applied against some load (typically Torque Mode)?**
   a. Reduce friction as much as possible because stiction can easily become an issue.
   b. If an external force is applied for some time in a locked-rotor state, motor must be sized accordingly. This is not a typical servo application *(Many, if not most servomotors are rated at a low RPM (stalled rotor state), with just enough speed to insure even heat distribution.) Contact motor manufacturer when applicable.*
   c. Ensure proposed control method(s) can achieve safety protocols and any other specific requirements.
   d. Consider basic maintenance procedure requirements in harmony with the process and safety protocols up front.

4. **Does the axis in question require extremely low speed (<=1_rpm**)?
   a. Reduce friction and stiction, as much as possible; stiction can easily become an issue.
   b. Eliminate mechanism backlash.
   c. Reduce mechanism compliance as much as possible, use a rigid (compression style, etc.) or equivalent coupling when applicable for the mechanism and minimize the number of moving bodies between the load and motor.
   d. Increase feedback resolution to maximum or at minimum, use knee of the cost curve for higher resolution.
   e. Control: if it is a velocity application versus positioning than, if possible, run drive in a position mode for the appropriate time and displacement range (*typically a better constant velocity tolerance can be achieved at the servomotor when run inside a position-loop).*
   f. Ensure proposed control method(s) can achieve safety protocols and any other specific requirements.
   g. Consider basic maintenance procedure requirements in harmony with the process and safety protocols up front.

5. **Is the specific axis in question: vertical?**
   a. Utilize a failsafe-brake *(internal to the motor or external axis brake)* and/or counterbalance load.
   b. If a failsafe-brake is utilized, ensure its physical engagement and dis-engagement is timed with the drive commands with proper delays for the subject brake's engagement and dis-engagement.
   c. If counterbalancing load, take into consideration the additional load inertia and its effect on acceleration and deceleration torque requirements.
   d. If counterbalancing load, there are typically trade-offs due to actual process cycle times, resulting in only a percentage of the load being counterbalanced.
   e. For partially unbalanced loads, use a current offset when applicable to offset the imbalanced load and to minimize control-loop integration requirements (typically reduces phase shift and lowers risk).
   f. Ensure proposed control method(s) can achieve safety protocols and any other specific requirements.
   g. Consider basic maintenance procedure requirements in harmony with the process and safety protocols up front.
   h. Refer to suggestions above for typical mode of axis operation: position, velocity, etc.

Summary of the Design Approach for Each Axis



In order to enhance the bandwidth response capability and controllability of any servomotor controlled axis a combination of factors must be considered in relation to the machine function, chosen process and work to be performed by each subject axis. They are friction and stiction; external loading; backlash and compliance; load and mechanism inertia at the motor; feedback resolution and finally, when applicable, the motor's drive, PWM/SVM and update rates *(separate controller update rates, if applicable).* Furthermore, the total *(but desirably minimized)* number of moving bodies between the load and motor along with the natural frequencies of the design may also need to be considered as the mechatronic design comes to a completion.

One cannot reasonably apply cost reductions to a machine whose manufacturing process doesn't yet work. This is why the needs of the chosen operating process should take decision priority over the machines' initial performance trade-offs and cost reductions. It is often best, for the initial machine build, to design for the highest capability at the lowest cost. If the new machine meets the production requirements utilizing the knee of the cost curve for its components, there may still be room for some cost reductions. On the other hand, if any specific component of the machine requires additional capability, the additional cost can be more easily justified.

ADDITIONAL QUESTIONS AND CONSIDERATIONS:

> NOTE:
>
> *The next set of questions and its considerations may further apply to the specific axis defined in the prior listing above with the goal to further narrow down the new design, axis by axis.*

1. **Is the machine to be capable of running more than one product?**
   a. Physical envelope must be defined as a function of the range of products.
   b. Highest rates *(smallest products*) typically set worse case motion profiles for maximum production rates.
   c. What is the desired production rate/goal: feet/minute, parts per minute, etc.?
      i. Sets maximum operation velocities/speeds: continuous or for a specific motion profile.
   d. What are the required process tolerances for the specific axis and job at hand?
      i. Sets minimum feedback resolution and accuracy requirements through the mechanism to the product or the physical need for a second feedback device *(start with the knee of the cost v capability curve*).

2. **Are there any process advantages if backlash and/or compliance are minimized beyond the knee of the cost versus capability curve?**
   Sets cost/price justification for additional capability and/or reliability, if necessary.

3. **Are there specific conditions for starting or stopping, maintenance, and/or safety that must be met?**
   a. Critical/dominate requirements/specifications can determine final motor and/or drive sizing, and/or control architecture. For example, does the axis need to hold its present location in the event a communication cable gets cut between the machine controller and servo drive?
      If so, the servo drive likely needs to control the subject servo axis position-loop versus the servo drive being sent a torque/velocity command from a separate/external controller.

Conclusion

Machine builders are continually faced with challenges in areas of technology complexity and knowledge barriers related to the scope of work to be performed, whether it involves a new design, re-design or conversion implementation. By utilizing the latest servo system technology with a simplified axis design approach and identifying the action items for a number of typical mechanical configurations, they can effectively manage design risk and achieve optimal machine performance while reducing development time.

ABOUT KOLLMORGEN

Kollmorgen is a leading provider of motion systems and components for machine builders around the globe, with over 70 years of motion control design and application expertise.

Through world-class knowledge in motion, industry-leading quality and deep expertise in linking and integrating standard and custom products, Kollmorgen delivers breakthrough solutions unmatched in performance, reliability and ease-of-use, giving machine builders an irrefutable marketplace advantage.

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