Special Motion Control Requirements for Medical Instruments

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Medical equipment motion control runs the gauntlet from electric wheel chair motion to heart assist pumps. This article will focus on the segment consisting of medical laboratory instruments. Even in this segment motion control ranges from precision liquid handling and dispensing to sample handling robotics and automated sample storage and retrieval systems. This article will delve into the precision liquid handling and dispensing and related functions and the interaction between the mechanical system and the motion control system. High pole count permanent magnet AC servo motors can simplify system design and improve system performance and reliability when mated with control systems capable of bringing out their full potentials.

Common to many liquid transfer systems is the need for repeatable operation, minimal down time, and robust fault detection. Many of the motions also require “gentle” motion profiles. Harsh, jerky motion profiles can generate air bubbles in both samples and reagents, or worse, generate unwanted aerosols from patient samples. The SilverDust™ and SilverSterling™ motion control systems from QuickSilver Controls incorporate advanced control techniques to improve motion performance through added damping techniques including synthetic inertial dampers and motor driver impedance control. These damping methods allow for smoother motions over a wide ranges of loads, as well as operation in the presence of stiction.

MEDICAL LIQUID DELIVERY SYSTEMS – FORWARD SAMPLING

Precise liquid delivery of discrete aliquots (portions) is commonly done using either the forward sampling or the reverse sampling methods. In the case of forward sampling, the pump first aspirates air, allowing any backlash in the piston mechanics as well as the associated seals to taken up before the critical sampling motions occur. The tip is immersed in the liquid and the net sample volume is aspirated. The tip is removed from the source liquid. An optional extension to the forward sampling method aspirates a small volume of air following the sample to isolate the liquid at the probe tip to allow the sampling probe/tip to be washed without diluting the contained liquid. The tip is then moved to the dispense container - either against a wall or under the liquid to avoid remaining drops on the tip after dispensing. The pump then dispenses a slightly larger volume than was aspirated to make sure that all of the sampled volume is delivered. This method is most useful for liquids that do not adhere to the sample tip/probe as any adhered liquid that remains in the tip reduces the delivered volume.

SMOOTH MOTION CONTROL

The volume captured in the forward method is related to the piston motion between immersion into the source container and the removal of the tip. The motion of the sampling piston must be smooth to avoid pressure surges or overshoot that will change the aspirated volume. A consistent meniscus is needed to make the aspirated volume consistent, which will not occur if the liquid flow motion is not well controlled; ringing or overshoot are to be avoided. Moving the piston in a unidirectional manner allows the backlash in the system to be taken up while aspirating air. If the direction does not reverse, the backlash of the system does not enter into additional motions in the same direction. The critical volume determining motions should thus be in the same direction as the previous motion. The presence of overshoot or ringing disrupts this unidirectional motion sequence, reducing the accuracy of the system. Of note, the backlash in the volumetric system is not just the position of the piston, but includes any changes in the shape or position of the seals as well.

REVERSE LIQUID SAMPLING

Reverse sampling is more useful for liquids that wet the sample tip and leave a residue upon dispensing. To overcome the effects of the retained liquid, an excess of sample is aspirated. According to preference and or contamination considerations, the piston can be reversed to take up backlash and some surface tension effects while still in the source container (if the tip is not subject to introducing contamination) or after it has been removed and placed into wash station. The tip is then moved to the dispense location, either under the liquid surface or against a wall to prevent a drop of the dispensed liquid from adhering to the tip. The volume to be delivered is then pumped to the delivery container, with some excess liquid left remaining within the tip. The dispense phase must be carefully controlled. The dispense motion again must be unidirectional. The rate of sample delivery must be shaped to avoid sudden pressure change. The liquid flow must be smooth and allowed to stop gently. It is easy to stop a pump cylinder rapidly, but a column of liquid will not respond as quickly, with an excess of liquid being delivered with some of the delivery container liquid picked up into the tip on the rebound if the pump stops too quickly.

HIGH ACCURACY MOTION CONTROL

Careful control of the probe motion is also needed to achieve high accuracy, especially for smaller samples. An example of probe motion that can affect delivery is moving the probe down into a delivery receptacle. If the deceleration of the probe is too abrupt, the liquid column can continue to move while the probe is coming to a stop, causing some of the aliquot to exit the probe before any motion of the pump. This can change the amount of liquid delivered in a reverse pipetting delivery. In the case of a forward pipetting system, lifting the probe following aspiration is also a critical motion, as this could reduce the captured volume if some of the metered liquid stays behind as the probe lifts too suddenly.

The sample handling motion capabilities are defined in the selection of the mechanical design including its coupling to the motion components, the motion components including drivers and controllers, trajectory shaping and the tuning of closed loop control systems. Backlash should generally be minimized in the mechanical design. The use of direct drive, single stage pulleys or single stage gearing helps to minimize backlash and compliance. Simple mechanisms also contribute to reliability in a 24x7 environment. Direct drive brushless motors with good bearing systems stand up to the life expectancy and low failure requirements typical of these applications. High ratio gears should be avoided to prevent damage in the case of back-driving; when needed, they should be rated to not fail when back driven. Direct drive systems not only need to provide the required torque, but also need to be able to handle higher inertial mismatches in order to provide smooth, reliable motion.

STABILIZING MOTION CONTROL

S-curve and raised sine trajectories are a starting point for configuring these motions, but improved results can be found in the tuning of the control loop. The addition of viscous inertial damping, either physical or emulated within the control system (or sometimes both), can be used to improve the phase margin of the system. The resulting additional phase margin available to the designer can be used to reduce overshoot and ringing. The reshaped phase response can allow the system gains to be increased for tighter control. The added effective inertia of the viscous inertial damper can also help damp out limit cycle oscillations that arise from backlash in the system. As the forces reverse across a gear having backlash, the teeth momentarily disengage and then reengage on the opposite side of the drive tooth. The uncoupling of the load during this period reduces the inertia reflected to the motor, allowing for higher acceleration for the same motor torque. This reduced load temporarily raises the gain of the control system as compared to when the teeth are engaged. According to the gear material, there can be significant rebound at tooth engagement, causing the teeth to bounce several times before remaining in contact. Without care in the design of the control system, an oscillation can occur in the control loop in this transition time causing noise and wear at the least and damage and wrong volumes and answers at the worse. Viscous inertial damping effectively raises the (effective) inertia coupled to the motor, reducing the change in acceleration when decoupled. The viscous coupling operates differently from a pure inertia, as can be seen when the teeth again come into contact. The addition of a tightly coupled inertia would cause high forces as the teeth came into contact and the now larger inertia coupled to the driving gear is suddenly slowed to match the speed of the load gear (or visa versa). This is like ball peen hammer to an anvil. The viscous inertial system has the mass less directly coupled – more like a rubber mallet to the anvil. The impact impulse is spread over a larger time period, lowering the forces. To a significant degree, the actions of a physical viscous inertial damper can be simulated within the control system. This includes the phase boost improvements to the system and the reduced acceleration upon load decoupling. The simulated viscous inertial damper has advantages in cost and size over using a physical inertial damper. Further, motor torque is not wasted accelerating and decelerating a physical inertia.

TUNING MOTION CONTROL LOOPS

The accuracy of delivery can also be improved by tuning of the control loop away from “optimal” from the control engineer’s view. The closed loop control system can be tuned to emulate a low pass filter to help reduce the high frequency content in the jerk (third derivative of position) in the motion. Several changes are involved. Feed-forward is an open loop method often used to pre-compensate the effective motion command to the servo system to help overcome (hide) some of the filtering properties of the servo system. For this very reason, feed-forward should be significantly reduced in liquid delivery systems, allowing the filtering aspects of the control system to be effective. The viscous inertial damping may be increased as well as the estimated velocity feedback terms to help over-damp the control system so as to match the motions to the following capabilities of the liquids.

NEW MOTION CONTROL SYSTEMS FOR PRECISION APPLICATIONS

High torque motors allow either direct drive or single stage reduction to be used in many applications. This in turn, generally allows these motors to be back-driven with no damage to either the motor or the mechanical drive components. Brushless motor designs using high-grade ball bearing construction should be used in systems requiring long life capabilities. The capabilities of the control system combined with proper commissioning of the control loops and motion sequences can significantly reduce variance in a liquid delivery system.