

Rack Drive Panel (RDP): Controlling Backlash with the SERVOSTAR[®] 600

This document describes the use of a SERVOSTAR[®] 600 to provide velocity control for a two-motor rack-drive system.

Overview

Rack-drive loads place special requirements on the servo control system. On one hand, rack-and-pinion mechanisms have a relatively large amount of lost mechanical motion or backlash. Many applications require that the rack be driven by two motors that place the rack in tension or compression to remove this backlash, at least while the mechanism is under light loads. This demands that the velocity loops within the drives operate, to a large extent, independently. On the other hand, the two drive systems are strongly linked through the rack. When the backlash is taken up, the average speed is the same for the two motors. This linkage prevents using fully-independent, integrating velocity loops for the two drives. The special needs of rack-driven loads force system designers to use control schemes developed specially for the mechanism. This document outlines one scheme, referred to as Rack-Drive Panel (or RDP).

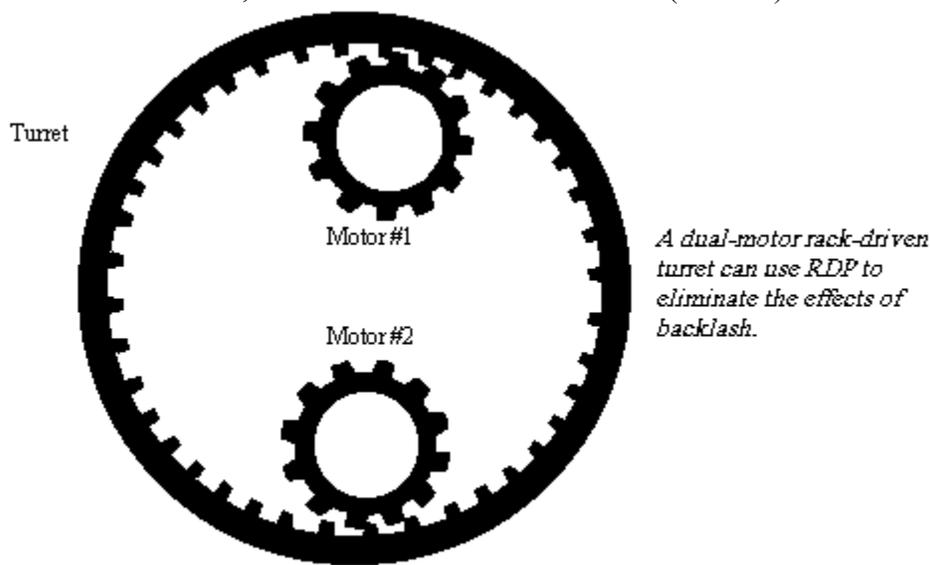


Figure 1: Rack-Drive Dual-Motor Turret

RDP is a velocity control method that allows a positioner to control the two pinion motors as if they were a single, ordinary servo motor. RDP simplifies the control of the rack by automatically taking up backlash during periods of light loads. Here, the motors provide torque in opposite directions to hold the rack in tension or compression. During heavy loads, RDP automatically pulls one motor across the backlash so both motors share the burden. This is especially important during large accelerations where RDP allows both motors to share the acceleration load. This halves the size of the motors required to attain a certain acceleration level or resistance to disturbance torque, as compared to when the motors cannot share the load. At the end of the acceleration, the load naturally decreases and RDP automatically returns the motor through the backlash, holding the rack once again, in tension or compression.

Since RDP provides two integrating velocity loops, when the rack is in tension, loads from either direction are resisted up to the full torque of the motors. RDP ensures that the two loops do not fight each other when the velocity commands to the two drives are slightly different, such as when an offset in an A/D converter injects a slight error. Without this feature, the two velocity loops normally ramp off in opposite directions because the two integrating loops have slightly different commands but are forced (by mechanical linkage) to have identical speeds. Such a loop structure cannot be satisfied until the loops saturate.

The advantages of RDP are:

- Allow virtually any motion controller to control the two pinion motors as a single motor.
- Eliminate backlash during light loads.
- Allow two drives to share heavy loads, such as during large acceleration.
- Support two integrating velocity loops that do not fight each other.
- Maintain smooth control when a motor crosses over the backlash, avoid banging of gears.

Mechanical System

Rack drive systems are commonly used where the travel distances are long. For example, large telescopes and large machining tables are often rack driven. While a ball screw is typically limited to about 2 meters, rack drives are commonly used for more than 10 times that distance. The primary difficulty in controlling rack-driven mechanisms is backlash. The construction of the rack-and-pinion mechanism makes it more difficult to maintain the tight tolerances required to mechanically reduce backlash to acceptable levels. Additionally, because of the relatively low gear ratio of rack-and-pinion mechanisms, they commonly use gearboxes, which add to the backlash. As a result, a drive mechanism is often required to reduce backlash. The most common mechanism is to use two motors that hold the rack in tension or compression.

A simplified schematic of the mechanical structure is shown in Figure 2. At steady-state, the left motor applies a bias force to the right and the right motor applies a bias force to the left. This compression takes backlash out of the system at steady state. When there is a large acceleration force, both drives share the load. In this case, one of the two motors must cross over the backlash to provide acceleration force (torque). At the end of the move, the motor that came across the backlash must return to other side of the rack to take the backlash back out. This requires a specialized control structure.

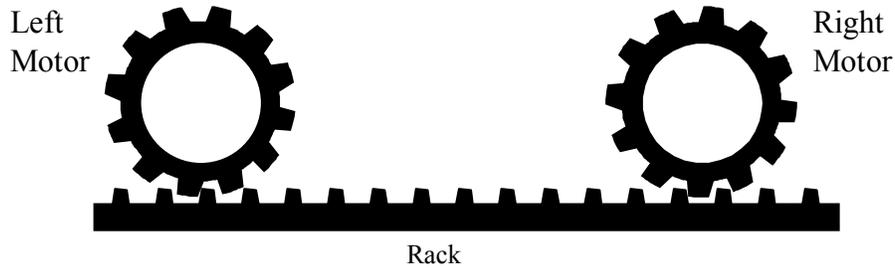


Figure 2: Simplified Rack-Drive System

A similar structure is sometimes used to drive a large ball screw. Here, one motor is placed at either end of the ball screw. Depending on the couplings used between the motors and the screw, there may or may not be backlash. If there is backlash, an anti-backlash system such as RDP is often required.

Why Standard Velocity Loops Cannot Be Used

When controlling a rack-driven load with two motors, a traditional velocity loop structure cannot be used. If the two loops are configured as integrating loops, they fight each other. Over time, small differences accumulate in the two integrators. These differences come from several sources. One example of a source of error in the velocity command is analog-to-digital conversion errors. A source of error that affects feedback velocity is the slight differences in the cycle time of the digital control loops in the two drives that arises from small differences the frequency of the microprocessor crystals. Bear in mind that over a long period, the mechanical linkage forces the actual average speeds of the two systems to be identical. Perceived differences in command or feedback velocities are accumulated. In this case, it is not possible to satisfy both integrating loops. One loop ramps off in one direction, trying to pull its motor speed up while the other ramps off in the other direction, trying to hold its motor back. Given enough time, both loops ramp up to the maximum current of the drives, producing no net torque.

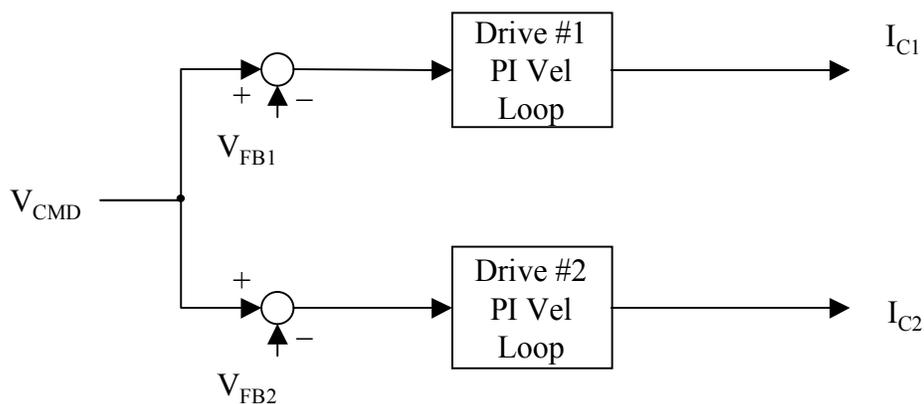


Figure 3: Traditional Velocity Control

An alternative to using two integrating velocity loops is to configure only one of the loops as fully-integrating. This is achieved with the structure of Figure 3 where one loop is a proportional velocity loop. As an alternative, it could be achieved using a master-slave configuration where the master drive produces a torque command used by both itself and the slave drive. This eliminates the problem of two integrating loops fighting each other. However, it does not remove the backlash.

The problem of disturbance response can be seen in the master-slave system in Figure 4. This system shows the addition of bias current. Bias current produces torque that holds the system in tension or compression during light loads. There is always a torque differential of $2 \times I_{BIAS}$ between the two drives. From Figure 2, notice that at rest, one drive responds to disturbances from one direction and the other responds to disturbances from the other direction. This is evident because the motors are only engaged in one direction, either clockwise (CW) or counter-clockwise (CCW). In Figure 4, should the disturbance go against the fully-integrating drive, it is resisted (as desired). However, should the disturbance come from the other direction, the torque drive does not respond, other than continuing to produce I_{BIAS} . If the disturbance is larger than I_{BIAS} , (as it often is) the rack disengages from the slave motor. Until the rack travels a distance equal to the backlash so that the position of the integrating drive system is disturbed, the output current of both drives remains unchanged. The system does not respond. A similar behavior occurs in Figure 3 where one loop is proportional.

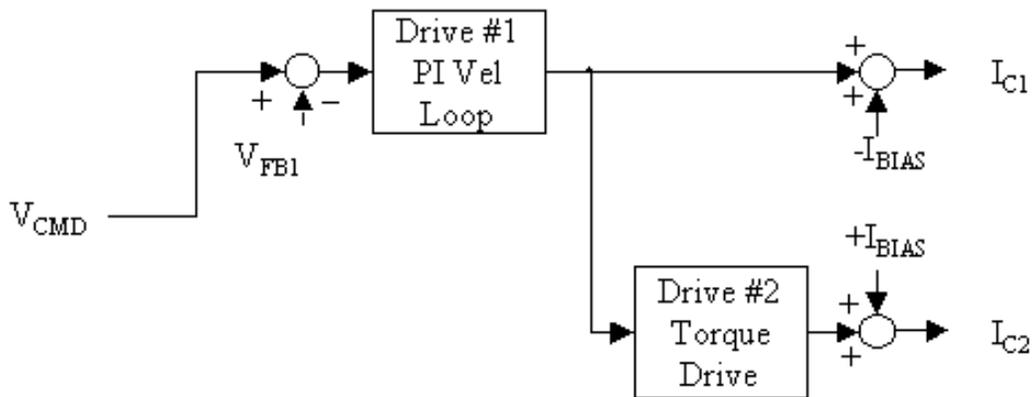


Figure 4: Master-Slave Configuration

Rack Drive Servo Loops

A better alternative for rack-drive systems is to use a process of equalization between two fully-integrating velocity loops (Figure 5). Notice that both velocity loops are fully-integrating as they were in Figure 3. Also, the bias current from Figure 4 is present. Finally, equalization has been added.

Equalization comes in two parts. First, the torque output is the sum of the outputs of the two loops. This assures that the output to both velocity loops is the same (not including the bias current). Second, a PI equalization controller (shown as $K_P + K_I/s$) ensures that the two outputs are equal (except for the difference induced by I_{BIAS}). The equalization controller drives the difference of the outputs of the two PI velocity loops to zero, ensuring that the loops do not fight each other.

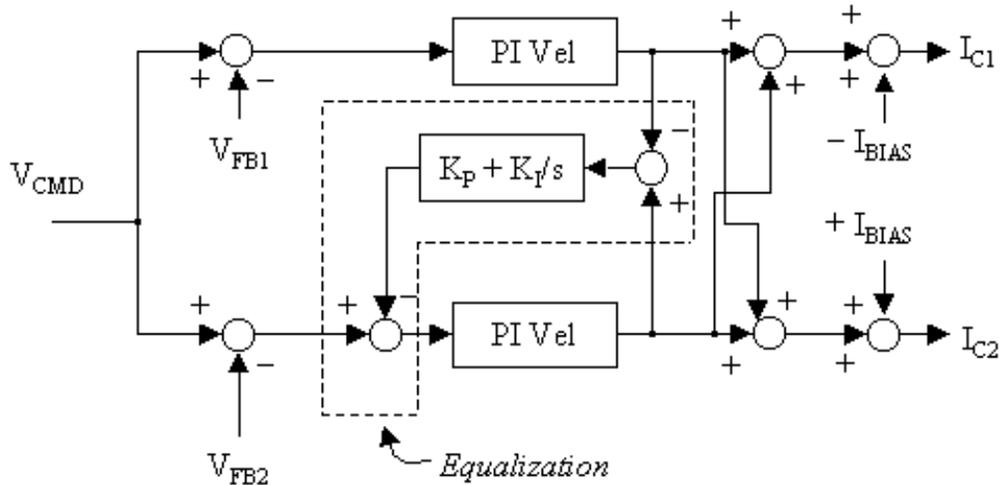


Figure 5: Rack-Drive Equalization and Bias

The RDP structure ensures that one drive comes across the backlash to help the other during periods of heavy loading. This occurs wherever the sum of the two velocity loops is greater than I_{BIAS} . This is shown in Figure 5. If the sum of the outputs of the two PI velocity controller is greater than I_{BIAS} , I_{C1} changes from negative to positive. When this occurs, Drive 1 reverses direction and begins aiding Drive 2. Similarly, when the sum of the two velocity loops is less than $-I_{BIAS}$, I_{C2} changes sign and Drive 2 aids Drive 1. In both cases, when the load is reduced, the sum of the PI velocity outputs fall below I_{BIAS} , and the system is in tension or compression. I_{BIAS} is a user-configurable variable. It can be set at any level from zero current to the continuous current of the drive. Larger I_{BIAS} has the advantage of increasing the load level up where backlash is eliminated. Unfortunately, larger I_{BIAS} increases power usage and reduces the total peak torque available to the rack.

Once the RDP system is installed and configured, the two axes together behave like a single axis. The motion controller produces a single velocity command. The RDP configuration provides the removal of backlash, the elimination of fighting, and one drive comes across the backlash to aid the other during heavy loads. The positioner needs only take a position feedback signal and produce a velocity command, just as it would for a single motor and drive. That feedback is usually taken from one drive or the other (the feedback sensors are approximately equivalent in a properly-configured system). This is shown in Figure 6. In some cases, the positioner relies on a separate feedback device connected to the rack.

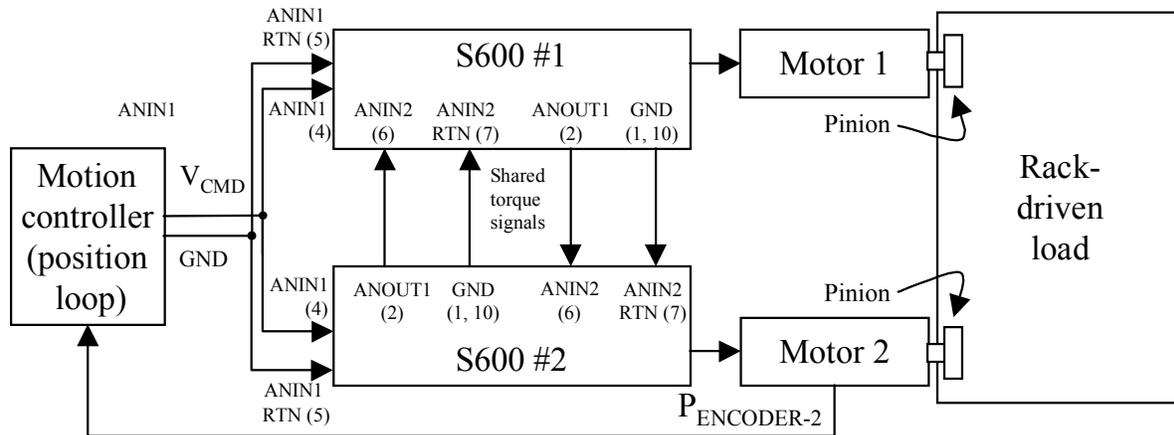


Figure 6: Servo Control Architecture with RDP

The analog input from the motion controller is connected in “differential” mode as shown in Figure 6. The motion controller connection to the drives includes lines to both the “+” and “-” inputs of Analog Setpoint 1 (pins 4 and 5), which drives the software variable ANIN1. Using differential mode connection reduces noise in the velocity command signal. This is as true for a rack-drive system as it is for almost any velocity-commanded servo system.

Expanding the Number of Drives

In some cases, more than two drives are used in RDP systems. The most common reason to do this is when two motors cannot provide sufficient torque for the application. In these cases, torque-mode drives can be added in pairs, with one the pair using the torque command from one of the RDP-mode drives, and the other of the pair using the torque command from the other RDP-mode drive. This is shown in *Figure 7* for four drives. ***RDP-mode drives must be manually configured to produce current command on AOUT2***; see SERVOSTAR[®] 600 product literature for details.

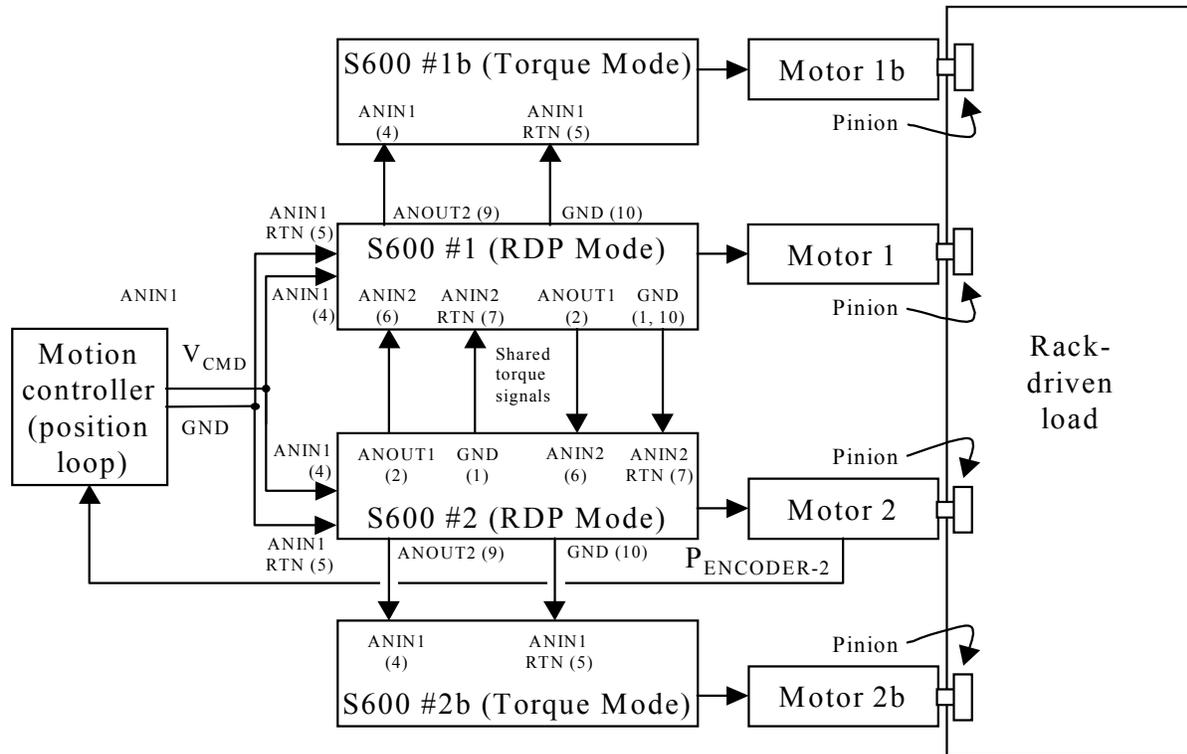


Figure 7: RDP with four drives.

Selecting Enable Mode

RDP requires that two drives operate interdependently. If one drive faults, the other drive should be taken out of RDP mode. Otherwise, the remaining drive may run away or produce unexpected motion. Because faults can occur unexpectedly, a mechanism must be in place to automatically prevent one drive from operating in RDP mode when the other drive is faulted. There are two common methods for doing this.

One mode of operation is called “fault disables other drive.” In this mode, when one drive faults, it disables the other drive, causing the rack to coast. This mode causes any fault in either drive to disable both drives. This prevents motion in the rack until the drives are reset.

Another mode of operation is called “fault forces other drive from RDP.” In the event of a fault, this mode of operation forces the remaining enabled drive out of RDP and into standard velocity mode. This condition does not support the benefits of RDP—backlash is not taken up and torque from only one motor is available. However, it does allow the table to operate, for example, in a “limp home” mode. One disadvantage of this mode is that it takes one input from the drive.

When selecting the enable mode, you must configure both drives to be the same. Also, you must wire the drives appropriately as discussed in the “Wiring the Drives” section.

RDP and the SERVOSTAR 600

Danaher Motion has used the RDP method for many years, using its analog motor drives such as the SBD3, BDS3, and BDS4. However, the implementation of RDP for a digital drive at Danaher Motion is new. This solution is available for the SERVOSTAR 600. RDP works for all SERVOSTAR 600 hardware with serial numbers greater than 220,000. RDP is standard for SERVOSTAR 600 firmware versions 5.04 and above. There is a version of RDP for older hardware. For additional information, contact Customer Support.

Wiring The Drives

Wire the SERVOSTAR 600 according to the *SERVOSTAR® 600 Installation Manual* with the following exceptions:

Select Enable Mode

Select mode of operation if one drive faults. Choose either “fault disables other drive” or “fault forces other drive from RDP.” Both drives must be configured the same way. Software configuration, using the variable RDP, is discussed later in this application note.



Both drives must be configured for either “Fault disables other drive” or Fault forces other drive from RDP.” Failing to observe this may result in non-faulted drive running away at full speed with the other drive faulted.

Wiring The Enable—Fault Disables Other Drive

When configuring the drives as “Fault Disables Other Drive” (*Figure 8*), the enable of the two drives must be wired through the BTB/RTO (Ready To Operate) contacts of both drives. This prevents one drive from being enabled before the other is ready to be enabled.



When configuring the drives as “Fault Disables Other Drive,” wire the enable signals of both RDP drives through the series combination of the BTB/RTO lines of both drives. This prevents one drive from enabling while the other is faulted. Failing to observe this may result in the non-faulted drive running away at full speed with the other drive faulted.

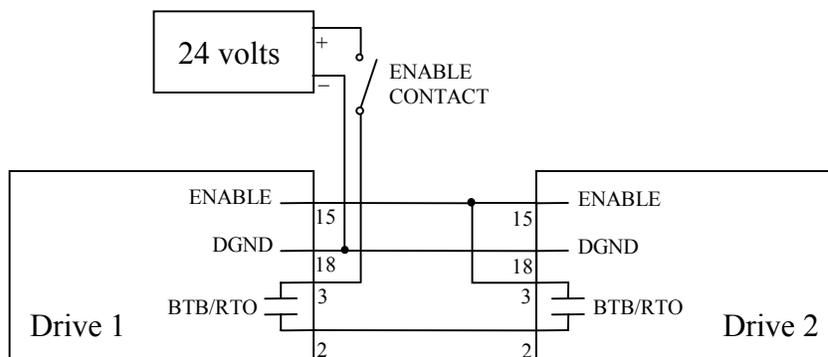


Figure 8: Enable Configuration for RDP for “Fault Disables Other Drive” Mode

Wiring The Enable—Fault Forces Other Drive From RDP

When configuring the drives as “Fault Forces Other Drive From RDP,” the BTB/RTO of each drive must be wired to Input 1 of the opposite drive. A fault in a drive opens its BTB/RTO contact. This contact is wired to Digital Input 1 as shown in Figure 9. When the RDP system is configured as “Fault Forces Other Drive From RDP,” the drive will exit RDP mode when Digital Input 1 opens. The end effect is that, when a fault occurs, it forces the opposite drive out of RDP mode.



When configuring the drives as “Fault Forces Other Drive Out From RDP,” wire BTB/RTO lines of both drives to Digital Input 1 of the opposite drive. This prevents one drive from being enabled in RDP mode while the other is faulted. Failing to observe this may result in the non-faulted drive running away at full speed with the other drive faulted.

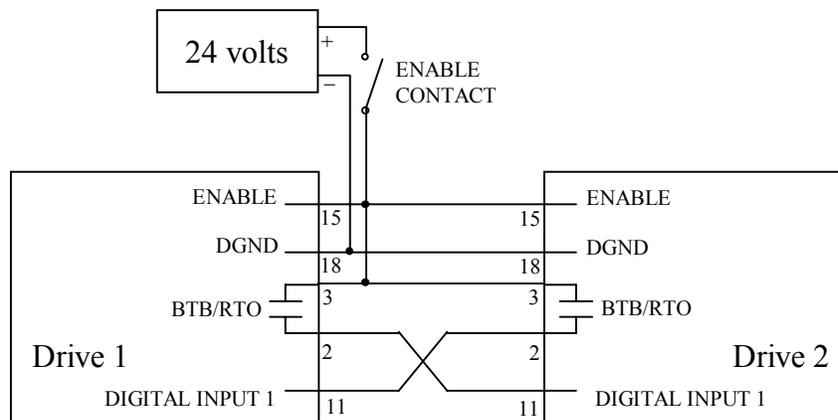


Figure 9: Enable Configuration for RDP for “Fault Forces Other Drive From RDP” Mode

Connecting to Velocity Command from the Controller

Connect velocity command from the motion controller to the Analog Setpoint 1 (pins 4 and 5) of both drives. Analog Setpoint1 drives the variable ANIN1. Provide proper shielding, filtering, and grounding to reduce noise. Connect the command signal in differential mode as shown in Figure 6.

Sharing Current Command Signals between the Drives

The current command signals must be shared between drives as shown in Figure 6.

- Connect ANIN2 (or “SW//SETP.2+”) [pin 6] of Drive 1 to ANOUT1 (or “MONITOR1”) [pin 8] of Drive 2.
- Connect ANIN2 RTN (or “SW//SETP.2-”) [pin 7] of Drive 1 to AGND [pin 1 or 10] of Drive 2.
- Connect ANIN2 (or “SW//SETP.2+”) [pin 6] of Drive 2 to ANOUT1 (or “MONITOR1”) [pin 8] of Drive 1.
- Connect ANIN2 RTN (or “SW//SETP.2-”) [pin 7] of Drive 2 to AGND [pin 1 or 10] of Drive 1.

Configuring The Rack System

Configure the SERVOSTAR 600 as normal with the following exceptions:

Configuring Variables

- Check the firmware
RDP requires version 5.04 firmware or greater. Contact Customer Support if your version of firmware needs to be updated. Version 5.04 requires SERVOSTAR[®] 600 drives with serial numbers greater than 220,000.
- Zero offsets in the analog-to-digital converter by adjusting ANZERO1 and ANZERO2. For more information, refer to the SERVOSTAR[®] 600 ASCII HTML Help file (VarCom) located on the website (www.DanaherMotion.com).
- Set the analog configuration for rack-drive
ANCNFG = 0 (8 is also acceptable. For more information, refer to the SERVOSTAR[®] 600 ASCII HTML Help file located on the website (www.DanaherMotion.com)).
ANOUT1 = 0
AN1TRIG=100 (sets 10V = full speed)
- Set VSCALE1 for top speed of the application. VSCALE1 must be identical in both drives.
- Ensure that IN1MODE through IN4MODE are *not* set to 8.
- Disable the RDP variables:
RDP = 0
RDPKI = 0
RDPKP = 0
RDPCLAMP = 0
RDPBIAS = 0
- Place both drives in analog velocity mode (OPMODE=1).
- Zero the velocity loop integral gain (GVTN). Set the velocity loop proportional gain (GV) to a low initial value (~ 0.1).
- Leave one drive disabled and enable the other.
- Apply low-speed square-wave velocity command to the drive.
- Raise the proportional gain (GV) in small steps. Keep raising the gain until the settling time in response to the step command is about 35 ms. Do not tune the system for higher gains. The fully-enabled RDP system may be difficult to stabilize. The goal of this step is to get the system operational with reasonable response. The gains can be increased after the RDP system fully enabled. (If your system does not need the velocity loop tuned this aggressively, a smaller GV would be acceptable.)

- Set the velocity loop integral gain (GVTN) to 100. Lower this gain slowly until the system overshoots by no more than 20%. You should a response similar to that shown in Figure 10. (If your system does not need the velocity loop tuned this aggressively, a larger GVTN would be acceptable.)

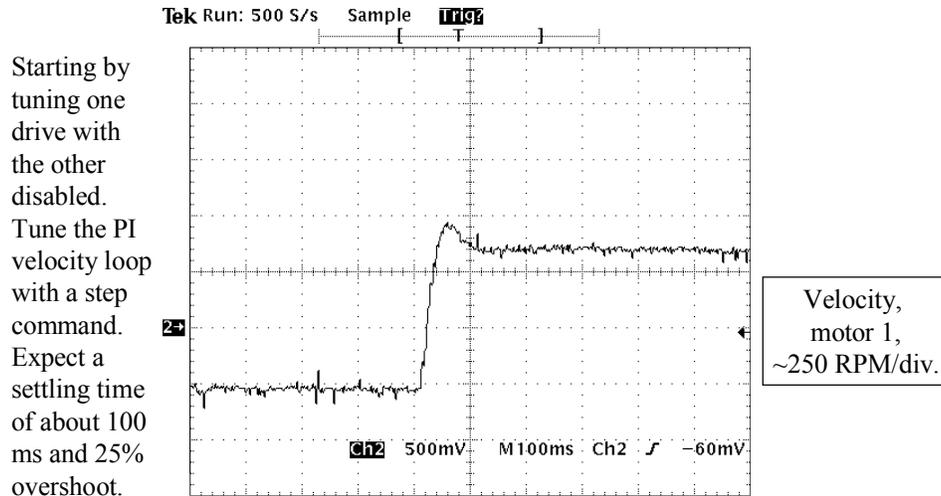


Figure 10: Tuning One Drive With The Other Disabled

- Half the proportional gain (GV). The gain of the servo loop naturally doubles when you enable the other drive. This is because once the drive is enabled it takes half the load, making the system appear only about half as difficult to move. This effectively doubles the servo gain. When the proportional gain is cut in half, the system slows down and overshoots more, as shown in Figure 11.

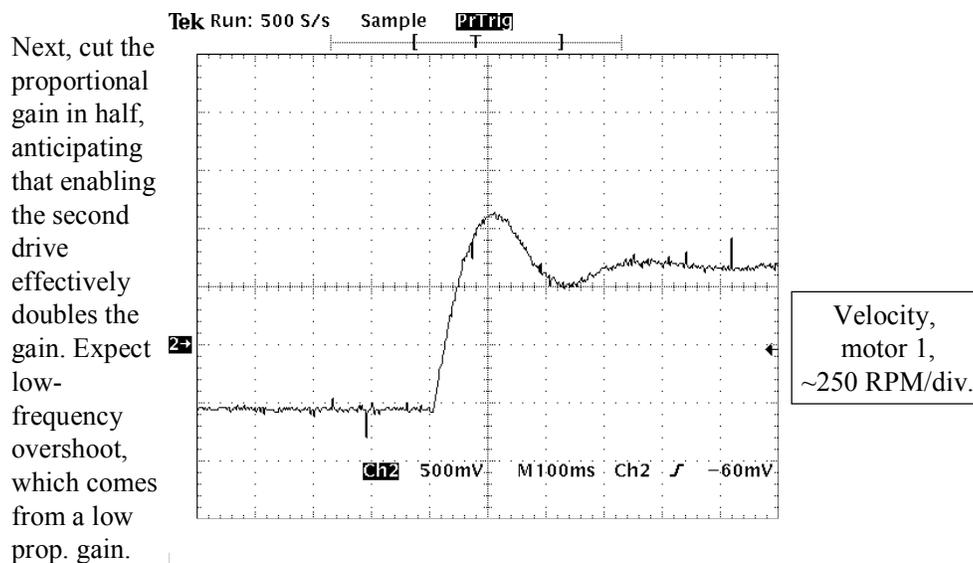


Figure 11: Before Enabling The Second Drive, Cut The Proportional Gain In Half

- Disable the first drive.
- Enable the second drive and repeat the tuning process. The resultant gains should be same for both drives.
- Disable the second drive. Leave the first drive disabled.
- Configure both drives for RDP. Recall the Enable Mode you selected above (refer to “Selecting Enable Mode” section above). If you selected “Fault Disables Other Drive,” type “RDP = 1” in both drives. If you selected “Fault Forces Other Drive From RDP,” type “RDP = 2” in both drives. Configure both drives for the same Enable Mode. You must wire the enable inputs appropriately for the selected mode as discussed in “Wiring the Enable.”
- Configure the equalization loop in one drive or the other (but not both) setting the variables RDPCLAMP, RDPKI, and RDPKP. Normal values are RDPCLAMP = 50, RDPKI = 13, and RDPKP = 300. These values rarely change. However, if you need to increase the rate at which the loops equalize, raise RDPKI and RDPKP in increments of 20% until desired performance is attained. RDPCLAMP limits the maximum output of the equalization circuit to 50 rpm. This is normally adequate to deal with errors that occur in velocity command and feedback.



Stand clear of the machine. Be prepared to remove power quickly in case the system becomes unstable. Provide mechanical guards to protect people and equipment if the system becomes unstable.

When drives are switched to RDP mode, the system may become unstable, even if it was completely stable when one drive was operated at a time.

- Enable both drives. Ensure that the system is stable by subjecting the rack to step changes in velocity. Be prepared for the system to become unstable when the second drive is enabled.
- Observe the step response of one motor or the other (Figure 12). The step response should change from the top waveform when one drive is enabled to the bottom waveform when both are enabled.

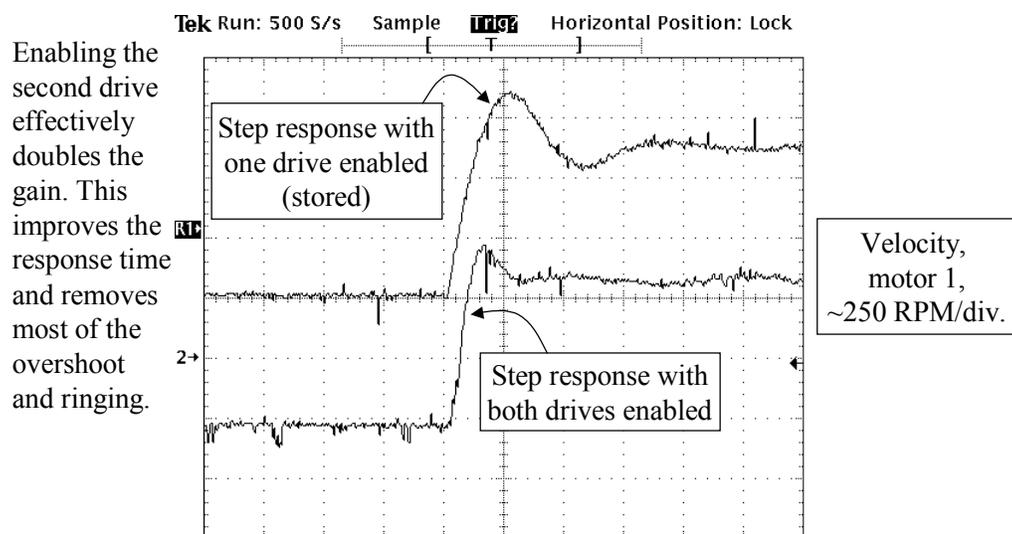


Figure 12: Step Motor Response

- Set the bias current according to the application with the variable \pm RDPBIAS. This is typically set to between 10% and 25% of drive continuous current. Larger levels of bias current keep the rack in tension or compression with larger loads, but also use more power and generate more heat. They also reduce the peak torque output of the servo system. Set RDPBIAS positive in one drive and negative in the other.
- If faster servo performance is required, raise the proportional gain (GV) and the integral gain (GVTN) on both drives in 10% increments. Raising the servo loops gains can cause instability in the RDP equalization circuit that is manifested by high-frequency, sustained oscillations.

Tuning with Expanded Number of Drives

The tuning process must be modified when using more than two drives. First tune the system with just the two RDP-mode drives as discussed above. After that, each time a pair of torque mode drives is added, it increases the torque applied to the system, effectively increasing the loop gain. Thus, GV must be reduced in proportion to the total number of drives that are enabled. For example, if the tuning process above produced a value of $GV=1$ when just the RDP drives were connected, expect to reduce this value to $GV=0.5$ if two torque-mode drives were added. Similarly, expect to reduce the value to $GV = 0.33$ if four torque-mode drives were added. In general, expect the product of GV and the number of enabled drives to remain approximately constant.



Stand clear of the machine when enabling drives. Be prepared to remove power quickly in case the system becomes unstable. Provide mechanical guards to protect people and equipment if the system becomes unstable.

When addition drives are enabled, the system may become unstable.

Limitations

As of the printing of this document, RDP works only with motors aligned to add torque. This occurs when the motors are mounted on the same side of the rack. You must ensure that the torque from the two motors is additive. If the motors are mounted so one motor is on one side of the rack and the other is on the other side, the torques are subtractive. Such an application cannot use the current embodiment of RDP on the SERVOSTAR 600.

As of the printing of this document, RDP works only for analog velocity commands. The use of RDP using field buses such as SERCOS interface™ require that some modifications be made to the firmware.

Results From Laboratory Test Unit

The SERVOSTAR 600-based RDP control structure was applied to a laboratory test unit. This unit (Figure 13) uses two motors to drive a single load. The motors are connected to the load through pinions. The load, which is in the center of the two motors, has a steel wheel added to make its inertia approximately equal to that of either motor. The backlash of the motor/load interface is adjustable. The backlash between both the left motor and the load, and the right motor and the load, was adjusted to be approximately 0.010" (0.4mm).

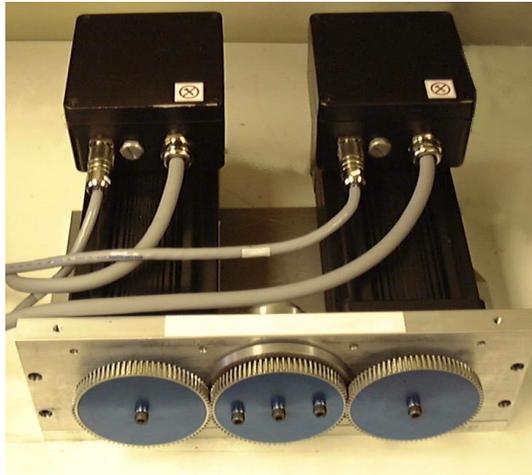


Figure 13: Laboratory Test Unit

The motor/load interface is shown in Figure 14. The steel inertia wheel mounted on the load is just visible behind the load (center) gear.

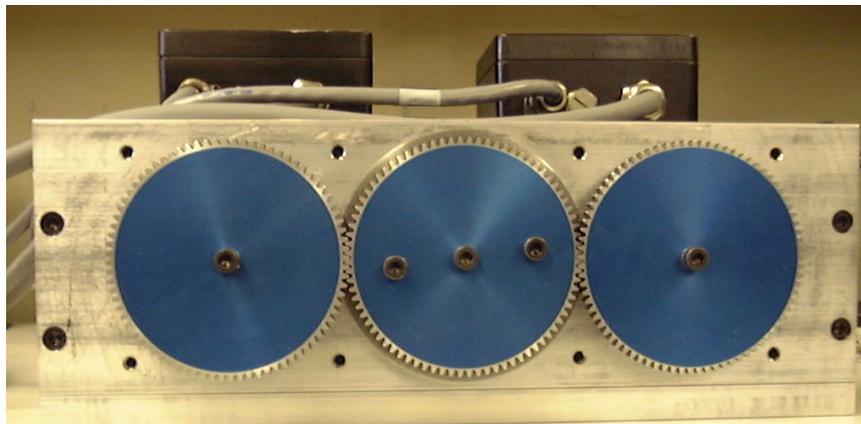


Figure 14: Laboratory Test Unit, Detail Of Gears

Figure 15 shows that RDP eliminates fighting between the velocity loop. At the beginning (left) of this scope frame, RPD is disabled and both loops are fully-independent, integrating loops. Over 30 seconds or so, the integrators built up to 5 amps in opposite directions. RDP was enabled, and current immediately dropped to IBias.

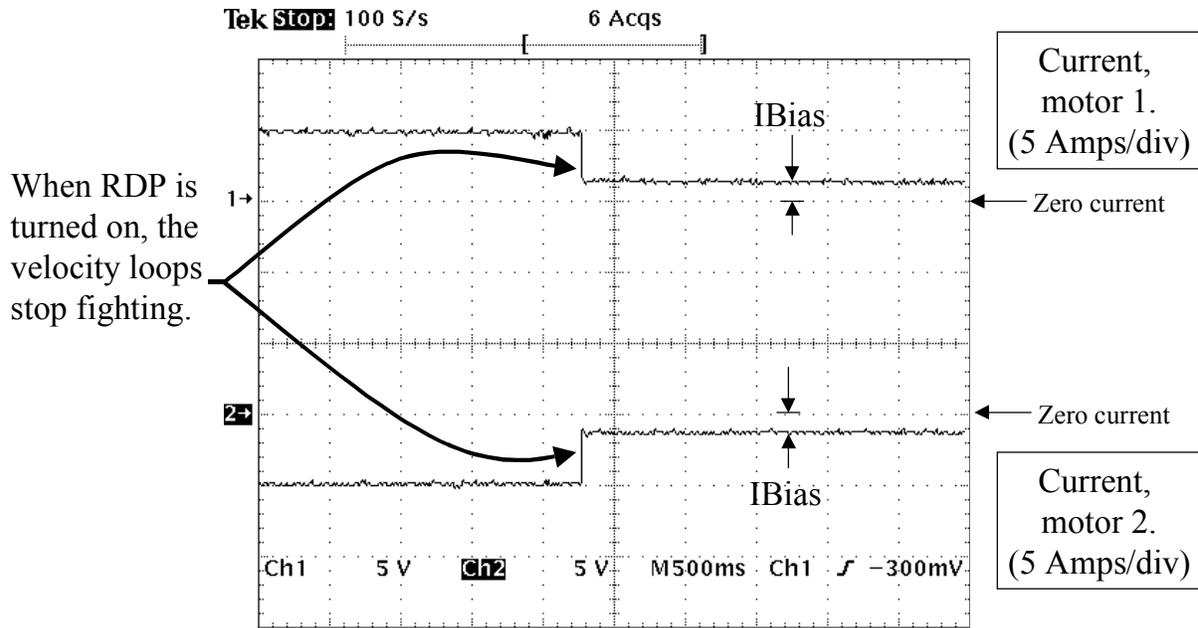


Figure 15: RDP Stops Fighting Between Velocity Loops

Figure 16 shows how one motor comes across the backlash to help the other. The motor was rotating in one direction at a few hundred rpm. A reversal was commanded. This reversal occurs approximately in the middle of Figure 16. (Velocity is not shown in this figure. It shows only the torque producing current of the two drives.) In the middle of the acceleration, the bottom trace reverses sign briefly. During this period (approximately 25 ms), the bottom motor was aiding the top motor. At all other times, the rack was in tension.

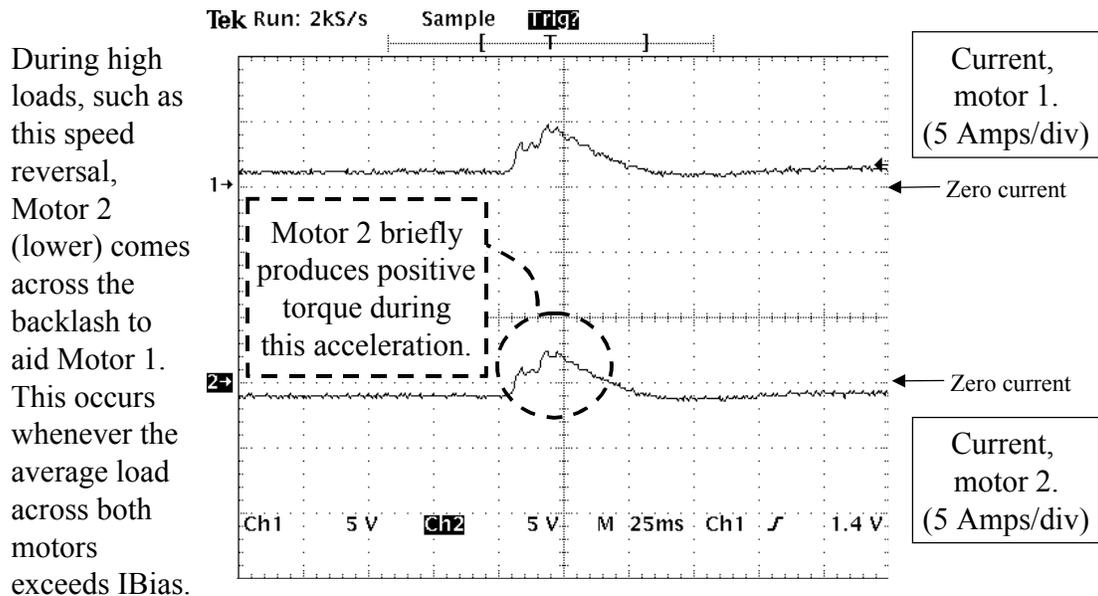


Figure 16: Motor Comes Across The Backlash To Aid The Other

Variables and Commands

The following variables are used solely for RDP and are only accessed from the terminal screen:

RDP	Select RDP and RDP Enable mode 0 RDP disabled; normal ServoStar 600 operation. 1 RDP mode enabled; Enable mode = "Fault Disables Other Drive." 2 RDP mode enabled; Enable mode = "Fault Forces Other Drive From RDP." SAVE and COLDSTART are required after setting RDP.
RDPBIAS	Bias current in amps. Normally set at 10%-25% of continuous current.
RDPCLAMP	Maximum output of equalization circuit in rpm. Normally set at 50 rpm.
RDPKI	Integral gain of equalization circuit. Normally set at 13.
RDPKP	Proportional gain of equalization circuit. Normally set at 300.
RDPON	Test variable. Will be set to 1 only when RDP is active, otherwise 0.
RDPINT	Test variable. Equals the integral value of the RDP equalization circuit. Scaled for 9000000 = 1 rpm (this is 9 million = 1 rpm). Limited by RDPCLAMP.

Refer to the **SERVOSTAR**[®] 600 ASCII HTML Help file located on the website (www.DanaherMotion.com) for current syntax and related information on the variables and commands discussed in this document. This document is also included on the Product Support Package CD-ROM shipped with every product.

References

For additional information, the following **SERVOSTAR**[®] 600 material is available from the Kollmorgen website:

- SERVOSTAR*[®] 601-620 Installation Manual
- SERVOSTAR*[®] 640-670 Installation Manual
- SERVOSTAR*[®] 600 SERCOS Interface IDN Manual
- SERVOSTAR*[®] 600 Setup Software Manual
- Listing of ASCII Objects SERVOSTAR*[®] 600 (Printable VarCom)
- SERVOSTAR*[®] 600 ASCII HTML Help File (VarCom)