

Introduction

Gain scheduling is an approach to control nonlinear systems using a family of linear controls, each providing satisfactory control for a different operating point of the system. Gain-scheduled control is typically implemented using a controller whose gains are automatically adjusted as a function of *scheduling variables* that describe the current operating point. These variables can include time, external operating conditions, or system states such as orientation or velocity.

Gain-scheduled control systems are often designed by choosing a small set of operating points (*design points*) and designing a suitable linear controller for each point. In operation, the system switches or interpolates between these controllers according to the current values of the scheduling variables.

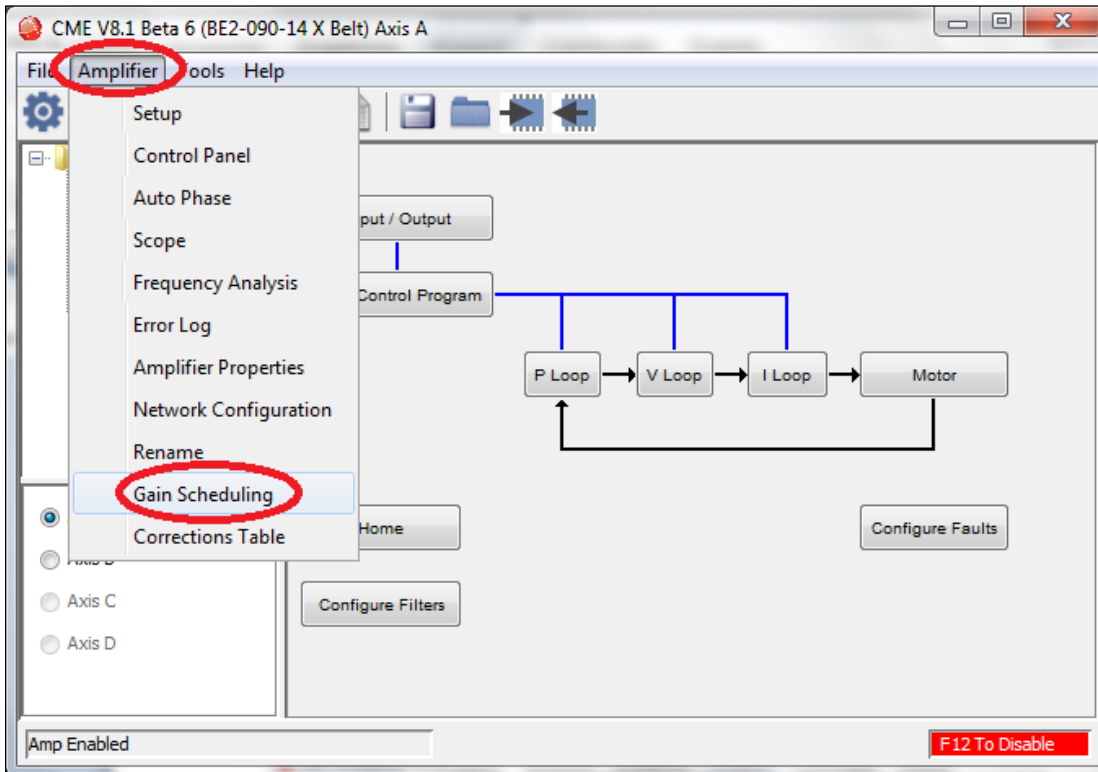
Gain scheduling is most suitable when the scheduling variables are external parameters that vary slowly compared to the control bandwidth. For example, using a robot to load a furnace with a large mass may require different parameters when loading to retracting.

Gain scheduling is most challenging when the scheduling variables depend on fast-varying states of the system. Because local linear performance near operating points is no guarantee of global performance in nonlinear systems, extensive simulation-based validation is required. The more points collected, the better the interpolation.

Controllers on a network, such as CAN or EtherCAT, could continually write the control loop parameters each time position, velocity, or a specific point in the process is reached. However, this could add an unacceptable overhead on the network.

Gains Scheduling Tables

A method used within Copley Drives is to build a Gain Scheduling Table. This table is accessed via CME2 as shown below and allows users to schedule gain adjustments based on changes to a key parameter. For instance, Pp, Vp, Vi, and Current Offset (A) could be adjusted based on changes to commanded velocity. Gain adjustments are specified in the Gain Scheduling Table. Each table row contains a key parameter value and the corresponding gain settings. The amplifier uses linear interpolation to make smooth gain adjustments between the programmed settings.

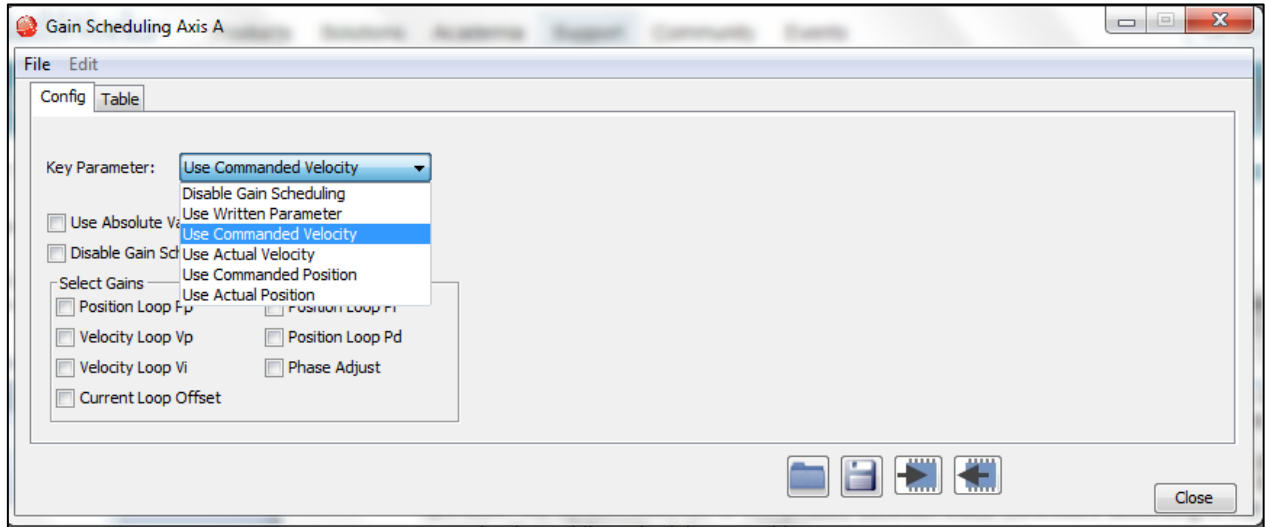


Assume that the system has been tuned and is stable at speeds below 1,000 rpm. If after testing it is discovered to be unstable above 1,000 rpm, then building a gains table might be the optimal solution.

Setting up a Gains Scheduling Table

1. Manually tune the system at various speeds, such as 500 rpm and 1,500 rpm. Note each set of tuning parameters and load them into the gains table. Gain schedules may need to be tuned to achieve a control system that meets performance objectives across the entire operating range.

The table below displays the available options.



The key parameter is the value used to compare, and it determines which line of the gains table we use.

2. Choose the key parameter.

Key parameter	Description
Disable Gain Scheduling	Disable Gain Scheduling
Use Written Parameter	An external controller can write to this parameter using any of several protocols and corresponding parameter IDs: Copley ASCII Interface or the Copley Indexer 2 Program (ID 0x128), CANopen and EtherCAT (Index 0x2371), and MACRO I-variable (0x528). See the Copley ASCII Interface Programmer's Guide, the Copley Indexer 2 Program User Guide, or the Copley CANopen Programmer's Guide.
Use Commanded Velocity.	Schedule gain adjustments based on changes to commanded velocity
Use Actual Velocity	Schedule gain adjustments based on changes to actual velocity.

Use Commanded Position	Schedule gain adjustments based on changes to commanded position.
Use Actual position	Schedule gain adjustments based on changes to actual position.

Optionally set controls:

Control	Description
Use Absolute Value of Key Parameter	If a velocity or position value is chosen for the Key Parameter and this option is set, the Key Parameter is interpreted as an absolute value
Disable Gain Scheduling Until Axis is Referenced	When this option is set, the scheduled gain adjustments do not take place until the axis is referenced (homed).

3. Select the gains to adjust by schedule. The choices are Pp, Vp, Vi and Current Offset (A). For each gain selected, a column will be enabled in the Gain Scheduling Table.

Select Gains

<input type="checkbox"/> Position Loop Pp	<input type="checkbox"/> Position Loop Pi
<input type="checkbox"/> Velocity Loop Vp	<input type="checkbox"/> Position Loop Pd
<input type="checkbox"/> Velocity Loop Vi	<input type="checkbox"/> Phase Adjust
<input type="checkbox"/> Current Loop Offset	

In this example, Velocity Loop Vp and Velocity Loop Vi are selected.

Config **Table**

Key Parameter: Use Actual Velocity

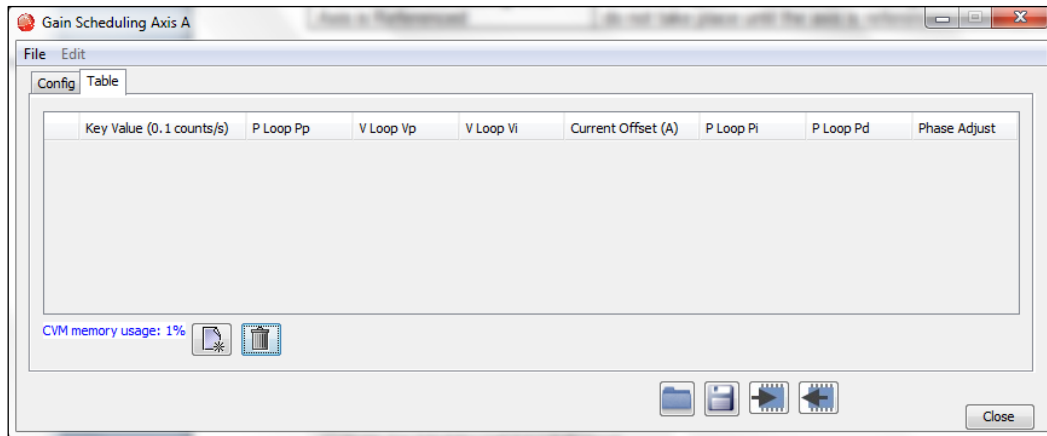
Use Absolute Value of Key Parameter

Disable Gain Scheduling Until Axis is Referenced

Select Gains

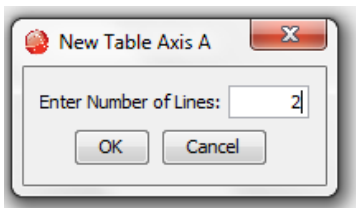
<input type="checkbox"/> Position Loop Pp	<input type="checkbox"/> Position Loop Pi
<input checked="" type="checkbox"/> Velocity Loop Vp	<input type="checkbox"/> Position Loop Pd
<input checked="" type="checkbox"/> Velocity Loop Vi	<input type="checkbox"/> Phase Adjust
<input type="checkbox"/> Current Loop Offset	

4. Select the table tab.



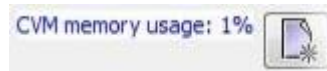
5. Select  icon







6. Enter the number of lines required.



The maximum number of lines that can be stored in the Gain Scheduling Table is 1,000. A typical Gain Schedule Table contains far fewer lines. The number of Gain Scheduling Table lines is also limited by the amount of CVM memory space available in the amplifier. A Gain Scheduling Table shares that space with CVM programs and Camming Tables. Therefore, the maximum number of Gain Schedule Table lines decreases if CVM programs or Camming Tables are stored in the amplifier.

The Table tab of the Gain Scheduling screen displays the percentage of amplifier memory used:



Action	Description
	Creates a new table
	Deletes the table from amplifier flash and PC RAM
	Saves configuration and table to disk
	Restores configuration and table to PC only
	Saves configuration and table to amplifier flash
	Restores configuration and table from amplifier flash to PC. This operation overwrites all data on the Gains Scheduling screen.

7. Enter the Key Parameter and gain adjustment values.

NOTE:

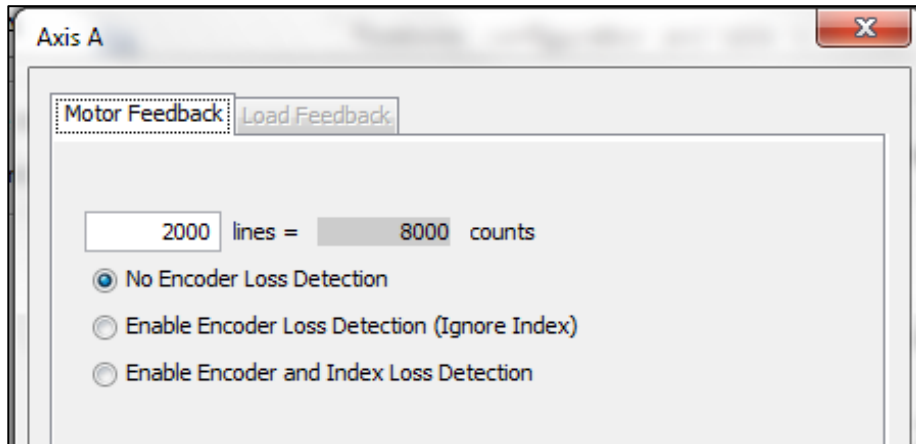
- All values must be whole numbers (no fractional values).
- All Key Values must be increasing.

8. After all values have been entered, click the Save Table button to save configuration and table data.

Note the units of the key parameter.

For Velocity is 0.1 counts per second. Check the encoder resolution.

In this example, there is a 2,000 line encoder, providing 8,000 counts per rev.

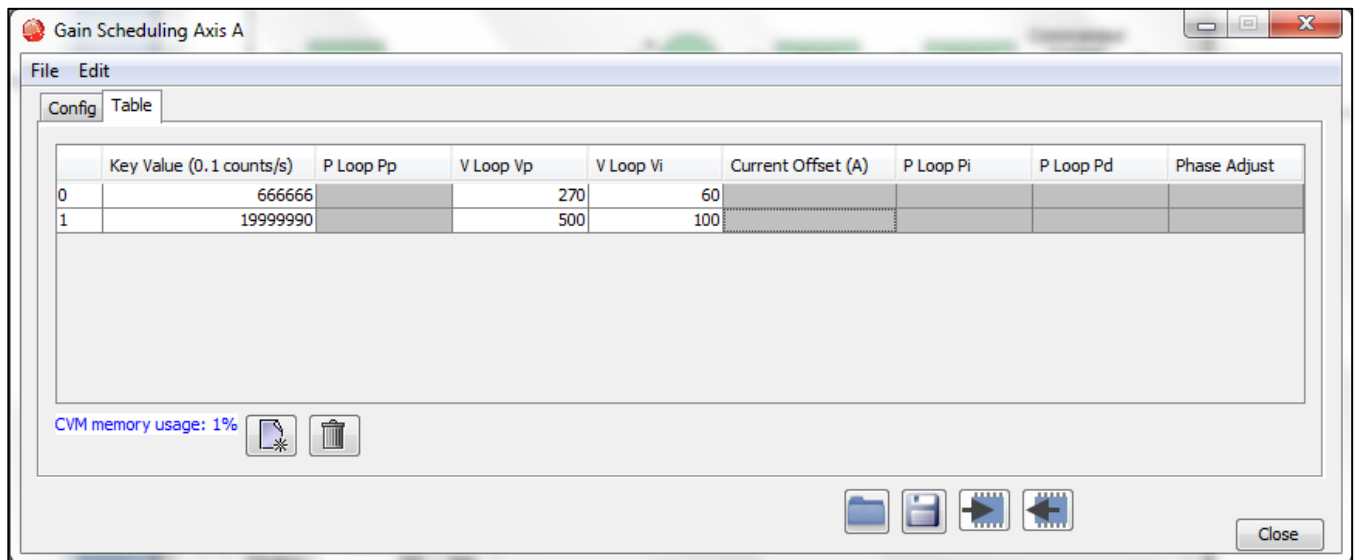


Therefore, if one of our points is 500 rpm, then in 0.1 counts / second this would be:

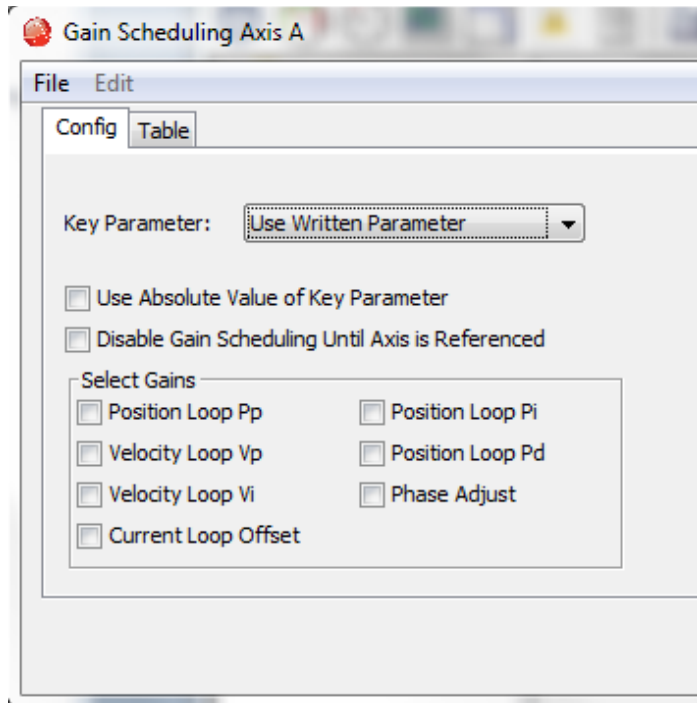
1 rpm = 8,000 counts / minute

Therefore 500 rpm x (8,000 / 60) x 10 = 666,666 0.1 counts / sec

And 1,500 rpm would be 1,999,999



If you need to change the gains based on the expected load change, then we could use the User Written Parameter.

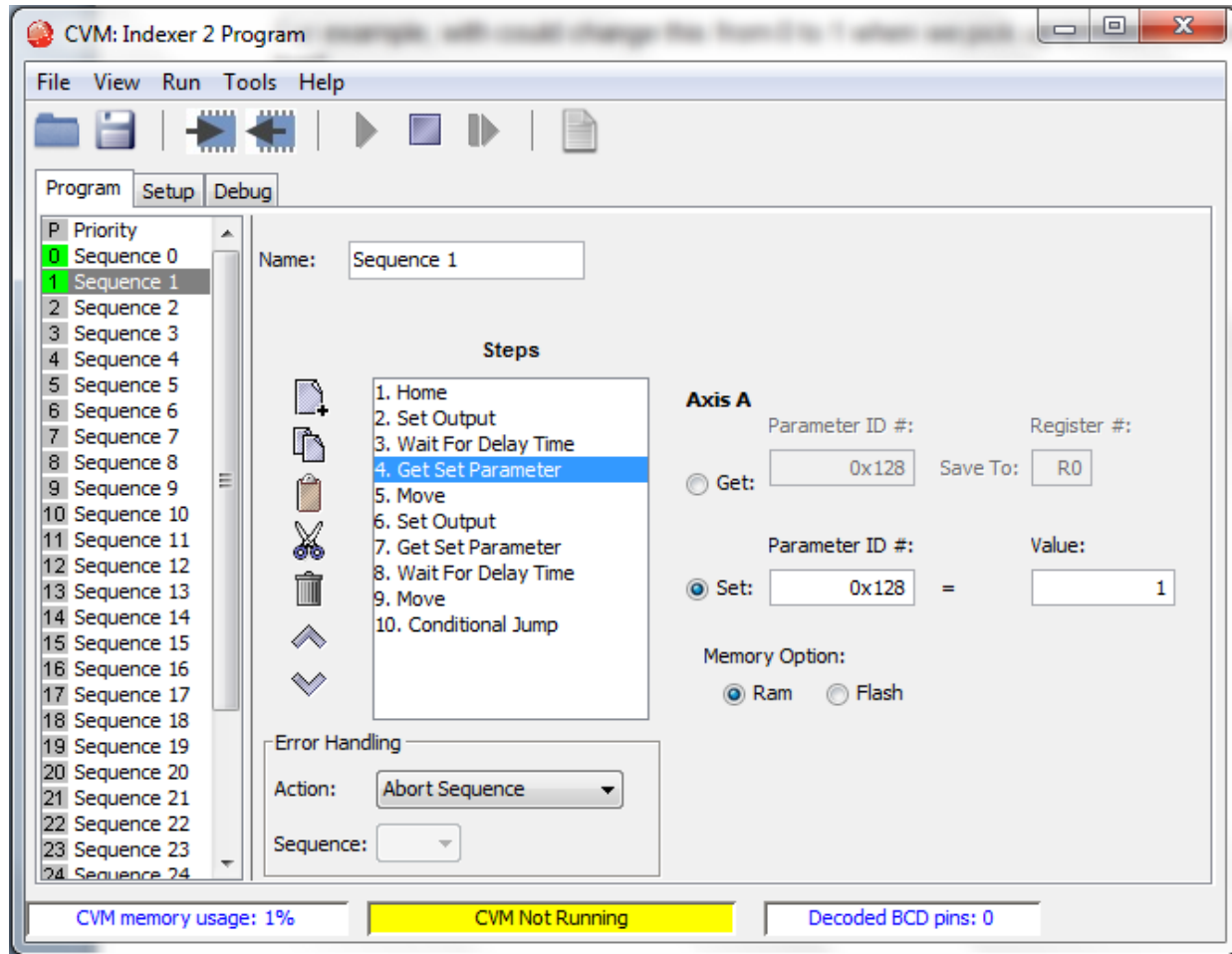


The User Written parameter is a number saved in register 0x128.

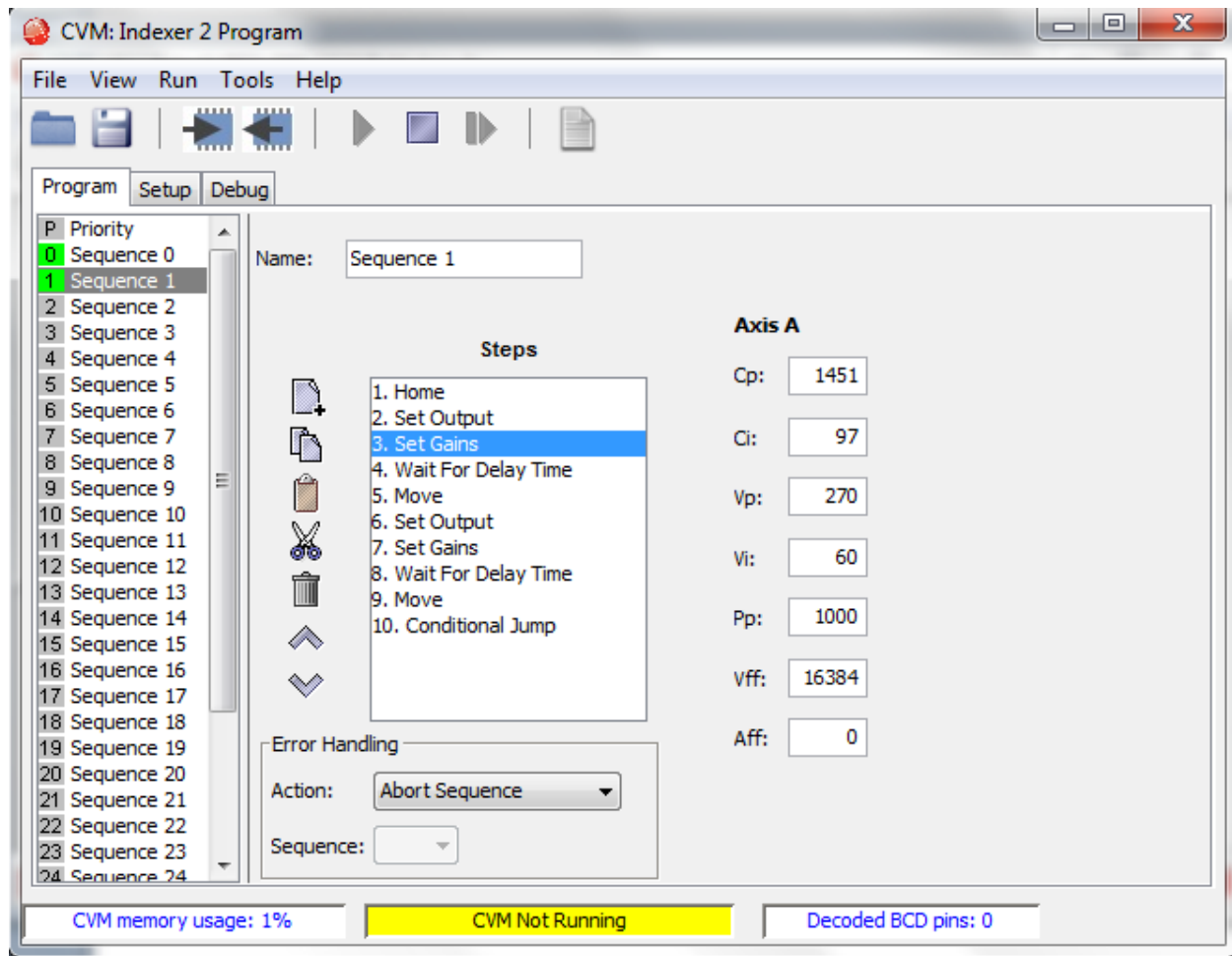
					20	Table includes position loop PI if set
					21	Table includes position loop PD if set
					22-31	Reserved.
0x128	0x528	0x2371	R	INT32	Gain Scheduling Key Parameter Value. When gain scheduling is enabled, current value of key parameter is stored here. When this parameter is selected as key parameter for gain scheduling, then it may be written to manually move through entries in gain scheduling table.	
0x129	0x529	0x2384:29	R	U32	Drive Hardware Options. Reserved for Copley Controls use.	
0x12A	0x52A	0x2222	F	U32	Motor Encoder Options. Used to specify various configuration options for	

As mentioned above, an external controller can write to this parameter using any of the several protocols and corresponding parameter IDs: Copley ASCII Interface or the Copley Indexer 2 Program (ID 0x128), CANopen and EtherCAT (Index 0x2371), and MACRO I-variable (0x528).

For example, this value could change from 1 to 2 when a mass is picked up thus increasing the load.



Alternatively, one could change all the gains as shown below at various stages of the program or process.



The main difference being that the later will not interpolate between changes.

Conclusion

Gain scheduling is attractive because the designer can guarantee that at each operating point, the feedback system has the desired stability and performance properties. In addition, the controller gains are adjusted to reflect the plant operating conditions, the gain-scheduled control system has the potential of responding rapidly to changing operating conditions. The gain-scheduling method has been proven sound by successful applications throughout the motion industry.

Although the gain-scheduling approach is a simple extension of linear design methods, the technique can guarantee closed-loop stability and performance only in a local sense. Stability and performance properties of the gain-scheduled designs must be inferred from extensive simulation studies.

Revision History

Date	Version	Revision
12/10/2020	Rev 00	Initial release