LABORATORY EXERCISE 24
FAMILIARIZATION WITH MODEL PREDICTIVE CONTROL

OBJECTIVE: To provide a basic understanding of the behavior of model predictive control as enhanced through visual demonstration and interactive calculation.

PREREQUISITES:

Familiarity with the operation of **PC-ControLAB 3.**

Familiarity with model predictive control technology, at least to the level presented in Chapter 15 of:

> Wade, H.L., *Basic and Advanced Regulatory Control, System Design and Application*, ISA. 2004.

Other, more comprehensive references are:

> Camancho, E.F. and C. Bordons, *Model Predictive Control*. Springer-Verlag, 1999.
> Rossier, J.A., *Model-Based Predictive Control, A Practical Approach*. CRC Press, 2003

1. PREPARATORY

From the Windows Start menu, select Run. Type in (or Browse to)

> *C:\ Program Files \ PC-ControLAB 3 \ MPC-LAB.EXE*

Once the program starts, it automatically reads in the “Generic” process model.

2. TESTING THE PROCESS TO DETERMINE STEP RESPONSES

2.1. Testing the response to OUT-1.

READ ALL OF SECTION 2.1 BEFORE TAKING ANY ACTION

- Be sure [**SP-1 or OUT-1**] is selected. (There should be a red LED next to the command button.)
- From the Menu Bar, select **View**, then **Variable Plot Selection**. Select “Yes” for PV-2, PV-3, PV-4, and OUT-2. (All variables should now be selected “Yes.”). Press **Clear**.
- Be sure that data has moved across the screen at least once before proceeding.
- Press the button labeled **Out**. Increase OUT-1 by 10% (to 45%). Note that several PV s are affected.
- From the Menu Bar, select **Response** and highlight (but do not click on) **Capture**.

- When the data (including the output change) has moved at least 40 (simulated) minutes across the screen, but no more than 55 minutes (within the "red" zone), click on **Response I Capture**.

- If you do not receive an error message, you can presume that you have successfully determined the response of PV-1, PV-2, PV-3 and PV-4 to a step |change of OUT-1. To view these responses, select **Response | View**. Select any button in the top row of the button matrix to view the response of that PV to OUT-1. Note that the response has been normalized to reflect a 1 unit step of OUT- 1, even though that may not be what you made.

- Select a button on any other row. Since you have not determined the step response to any other output or load change, there is no response data to be displayed. **Clear**.

- Select [**SP-1 or OUT-1**] and return OUT-1 to its initial value. When the variables have lined out, proceed with the next test.

2.2. Testing the response to OUT-2, LOAD-1, and LOAD-2.

- You could proceed in the similar manner and test responses to OUT-2, LOAD-1 and LOAD-2. To save time, however, you can simply read in a data file containing the responses that have previously been captured.

- Select **Response I Retrieve**.

- Highlight ***generic4.rsp*** and click on **OK**.

2.3. Verifying that all responses have been determined.

- Select **Response I View** and check to see that all responses have been determined. (Some response data curves may be flat, indicating that that output or load has no effect on that PV.)

- Press the button for OUT-1 and PV-1. On the lab exercise worksheet (at back of this exercise) , record the first six values of the step response.

- Press the button for LOAD-1 and PV-1. On the lab exercise worksheet, record the first six values of the step response in the columns labeled “PV STEP INPUT RESPONSES.”

(Note: If for any reason you have to restart your program, you must again determine the responses, or re-read the data file.)

3. SETUP FOR SISO OPERATION

- Select **Control I Control Options.**

- Confirm the following: No of CVs = 1
No of MVs = 1

  Press **Clear**.

- To reduce unnecessary traces recorded on the screen, select **View I Variable Plot Selection**. Select “No” for PV-2, PV-3, PV-4, OUT-2 and LOAD-2.

Terminology Explanation

Process Variables (PV's) can either be controlled or merely monitored. If a PV is controlled, it is called a Controlled Variable (CV); if it is merely monitored, it is called an Auxiliary Variable (AV). Therefore

CV-1 is the same as PV-1
CV-2 is the same as PV-2.
etc.

PC-ControLAB, and this exercise, tend to use PV and CV interchangeably.

4. MPC OPERATION

- Press **AUTO** to start the model predictive control algorithm. Notice that the *predicted future values* of PV-1 is displayed. However, if the PV was initially at SP, and if there are no load changes, then the predicted future profile will be flat.
- Press **SP-1 or OUT-1**, then press **SP**. Change the SP to 375^{o} Observe the predicted future profile and compare it with the present behavior.
- Does the actual behavior follow the predicted behavior? ______________________________
- Does the predicted behavior approach the SP? ______________________________________
- Select **Load-1** then press **Incr**.
- Does the PV (actual) behavior remain approximately on SP? _____________________
- Does the MV (output) change to compensate for this load change? _________________ (That is the *feedforward* effect*.)*
- Press **AutoLoadOn**. This creates a randomly varying load which should be compensated for by feedforward action. Is it? ____
- Select **Load-1** and press **AutoLoadOff**.
- Press **Incr** or **Decr** until Load-1 (grey trace) is between 70% and 80%. (Read LH scale.)
- Press [**SP-1 or OUT-1**] and change the SP to 275^{o} . Let the process come to equilibrium.

5. DETAILED ANALYSIS

Now that we have observed the overall operation of the MPC control algorithm, let's take a closer look at what is actually happening.

- Confirm that the MPC operation is in AUTO. (Status indicated beneath the grid.)

- Click in the circle labeled **Step** in the Calculation Cycle panel – RH side of screen.

- Note you must step through each phase of the calculation cycle manually by pressing the **STEP** button. Notice:

  That red LEDs indicate the phase of the calculation cycle you are in;

  That the chart advances only at the end of a calculation cycle;

- Try these until you are comfortable with how this part of the program works.

- **STEP** through the calculation cycle until the LEDs indicate that you are at the *Control Move Correction* step.

- Click the small square labeled **List Profile**, then press **STEP**. You should see a table listing values of the predicted PV profiles at the end of a calculation cycle. (Since we are controlling one PV with one MV, we are only interested in the predicted profile of PV-1.) The values for PV-1 should all be 275.00. If not, click in the circle labeled **Auto**. Let the system run with automatic stepping for a little while, then click in the circle labeled **Step** and return to this condition. When you are at the *End Cycle* step, with the predicted profile on display and all values for PV-1 at 275.00, then proceed.

- Change the set point to 375^0.

- Press STEP until you have gone through the calculation cycle exactly twice, stopping at the *End Cycle* step.

End of Cycle

- On your laboratory exercise worksheet, column 1 (end of last cycle), copy down the first six predicted values of PV-1.

Beginning of Cycle

- Press STEP to start the next cycle. In column 2, copy the first six predicted values of PV-1. How do these compare with the values in column 1?

  ____

Feedback Correction

- The first value in column 2 (step #0) is the predicted value of what the PV should be right now. We will read the transmitter output and see how the actual value compares with the prediction. Select **View | Data Monitor** and read the current value of PV-1. Write this in column 3.

- If the predicted and actual values of PV do not agree, then the entire predicted profile, including the prediction of the current value, must be adjusted upward or downward to make the current prediction agree with the actual value. On the line above column 3, write the value of

  Actual PV (col #3, step #0) - Predicted PV (col #2, step #0)

  This is the feedback correction required. Now add this to each value in column #2 and write the results in column #4. This *is your prediction* of what the future profile should be after feedback correction.

- Click **STEP**. (The LED labeled *"Feedback Correction"* should now be lit.) Copy the computer's predicted profile into column #5. How well do columns #4 and #5 agree?

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Feedforward Correction

- On the dotted line above column #6, write the amount of *load change* since the last calculation step. (This first time through; it should be zero.)

- Multiply that figure by each value of the PV-1 response to a unit step of LOAD-1. Write this in column #6.

- Add column #6 to column #5 and write the results in column #7. This is *your prediction* of what the future profile should be, after feedforward correction.

- Press **STEP.** (The LED beside "Feedforward Correction" should be lit.) Copy the computer's predicted profile into column #8. How well do columns #7 and #8 agree?

____

Control Calculation

- Press **STEP** (The LED beside "Control Calculation" should be lit.) The current control move (change in OUT-1) calculated by the MPC algorithm is displayed. Write this value above column #9.

Control Move Correction

- Now multiply this value by each value in the table PV-1 Response of Unit Step of OUT- 1. Enter these values in column #9. This is the amount of correction to the predicted profile to be made for the current control move.

- Add columns #8 and #9 and write the results in column #10. This is *your prediction* of what the future profile should be, after feedback correction.

- Press **STEP** (The LED beside "Control Move Correction" should be lit.) Copy the computer's predicted profile into column #11. How well do columns #l0 and #11 agree?

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End of Cycle

- Before the end of this cycle, select **Load-1** and then press **Incr**.

- Press **STEP** to go to end of cycle. (The LED beside “End cycle” should be lit.) Copy the computer's predicted profile into column #12. (This should be the same as column #11.)

6. ANOTHER CALCULATION CYCLE, FOLLOWING A LOAD CHANGE

- Take a new worksheet and copy column #12 from the completed worksheet into column #1 of the new worksheet.

- Press **STEP** to go to the start of a new cycle. Fill in columns #2 through #12 the way you did before. Note that there has been a 5% load increase since the beginning of the last cycle. Therefore the figure to be written above column #6 is “5”. Review the above instructions if necessary.

After you have gone through two calculation cycles, you should be comfortable with the knowledge of what is going on behind the scenes. You can now take off the "List Profile" and return to "Auto " Calculation Cycle.

7. OTHER EXPLORATION (Optional)

At this point, we're going to let you explore a lot of effects on your own, with only minimal guidance, but a lot of suggestions.

7.1. Tuning

- Press **TUNE.** Notice that the reference trajectory time constant is 6.0 minutes and the move suppression factor is 0.25. Try other values of these, both for set point changes and for random load changes. Try reference trajectory time constants between 3 and 12, and move suppression factors between 0.15 and 1.0.

7.2. Multiple-Input, Multiple-Output

- Press **MAN**. Select **Control | Control Options**.
  Set:

  No of CVs = 2
  No of MVs = 2

  Then select **View I Variable Plot Selection.** Enable all traces.

- Press **AUTO** to restart the MPC control algorithm. Let the PV's come to equilibrium.

- One at a time, change the set points for PV- I and PV-2. Do both outputs change?
  Does the other PV stay approximately on SP? ________________

  If so, you have just observed the decoupling effect.

- Press **Load-1** then **AutoLoadOn**. Press Load-2 then **AutoLoadOn**. You should be seeing a random load change of both disturbance variables. Do both PV's stay approximately on SP?
  ____

  If so, you have just observed the multivariable feedforward effect.

7.3. Insufficient Degrees of Freedom

- Press **Load-1**, **AutoLoadOff**, then **Load-2**, **AutoLoadOff**.

- Change to **MAN**, then select **Control I Control Options.** Set

  No of MVs = 1
  Leave No of CVs = 2

You are now trying to control two measurements with one valve. Change set points, make manual load changes, etc. and observe the effect. Notice that both PVs stay in the region of their SP, but neither meets it exactly.

- Select **SP-1 or OUT-1** then press **TUNE**.

- Note that there is a new entry, labeled "Priority" and that it currently has a value of 0.5. This is the relative priority currently assigned to PV-1.
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- Press **Clear**, then select **SP-2**, then **TUNE**. This shows the relative priority currently assigned to PV-2. Notice that PV-2 also has a priority of 0.5, same as PV-1. *If you change either priority, the other will automatically be adjusted so that the sum equals 1.0.*

- For PV-2, enter a priority of 0.05. (This will give PV-1 a priority of 0.95. You can check that if you wish.) With a higher priority give to PV-1, it will control closer to its set point, but at the expense of more deviation at PV-2. Is this what you observe?_______________________

- Now, enter a priority for PV-2 of 0.95. Do the PVs move in a way that you would expect?

___

You have observed the behavior of a "thin" system," where the number of PVs is greater then the number of MVs. One way of handling this is to assign priorities to each of the variables. The variable with the higher priority will control closer to set point.

7.4 Output Limiting

MPC-ControLAB permits setting limits for control outputs, both in terms of absolute values and rates of change (slew limits). MPC-ControLAB does not support limits on PVs or auxiliary variables (AVs), although that is a very important feature of commercial systems.

- Press **MAN**, then select **Control | Control Options**.

- Set: No of CVs = 1
  No of MVs = 1

  Press **Clear**.

- Set the SP for CV-1 to 275^{o}.

- Press **TUNE** and return the tuning parameters to their initial values.

Ref Traj	6.0
Move Suppr	0.25

- When the PV comes to equilibrium, put the MPC algorithm in AUTO. and change the SP to 325^{o}. Observe the controller output. What is the largest move (change) that it makes in any one calculation cycle?_________%

- Return the SP to 275^{o}. When the PV lines out, select **LIMITS.**

- In the "Rate of Change" field, click in the MV-1 square under "APPLY". Then enter a value of 3.0 (%). (That should be significantly less than the maximum move you observed.) Press **Clear**.

- Change the SP to 325^{o}**.** The controller output should now show the effects of limiting the size of the move. Do you observe that?___________________________________

You have observed the effect of limiting the rate of change of controller output. You may also wish to experiment with limiting the maximum and minimum value of the controller output. The default values are 0 and 100%, but through the LIMITS table, you can reduce these limits further.

PV STEP INPUT
RESPONSE PROFILES

Sample No.	PV-1 RESPONSE TO UNIT STEP OF: OUT-1	LOAD-1
0		
1		
2		
3		
4		
5		

Worksheet No. ______

MODEL PREDICTIVE CONTROL
Demonstration

for use with
MPC-ControLAB **for Windows**
from
Wade Associates, Inc.
Houston, TX

PV RESPONSE DURING MPC CALCULATION CYCLE

Step No.	END OF LAST CYCLE	BEGIN-ING OF CYCLE	Feedback Corr Required ____	FEEDBACK CORRECTION		Load Change ____	FEEDFORWARD CORRECTION		Control Move: ____	CONTROL MOVE CORRECTION		END OF CYCLE	Step No.
	1	2	3	4	5	6	7	8	9	10	11	12	
			ACTUAL PV	Your Predicted Profile	MPC's Predicted Profile	Load Change Effect	Your Predicted Profile	MPC's Predicted Profile	Control Move Effect	Your Predicted Profile	MPC's Predicted Profile		
0													0
1			Read Actual PV from View - Data Monitor										1
2													2
3													3
4													4
5													5

PV STEP INPUT RESPONSE PROFILES

Sample No.	PV-1 RESPONSE TO UNIT STEP OF: OUT-1	LOAD-1
0		
1		
2		
3		
4		
5		

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	1	2	3	4	5	6	7	8	9	10	11	12	
			ACTUAL PV	Your Predicted Profile	MPC's Predicted Profile	Load Change Effect	Your Predicted Profile	MPC's Predicted Profile	Control Move Effect	Your Predicted Profile	MPC's Predicted Profile		
0													0
1			Read Actual PV from View - Data Monitor										1
2													2
3													3
4													4
5													5