QNET-011 ROTPEN Trainer

Quanser Engineering Trainer for NI-ELVIS

QNET Rotary Pendulum Trainer

Student Manual

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1. Introduction

This manual contains experimental procedures and lab exercises for the QNET Rotary Pendulum Trainer (ROTPENT). The ROTPENT is depicted in Figure 1 and the hardware of the device is explained in Reference [1].

Figure 1: QNET rotary pendulum trainer on ELVIS II.

The prerequisites to run the LabVIEW Virtual Instruments (VIs) for the ROTPENT are listed in Section 2 and described in Section 3. The in-lab procedures are given in Section 4 and split into three sections: simple modeling, balance control design, and swing-up control. In Section 4.1, the coupling and friction of the system are assessed and the moment of inertia is found. The controller that balances the inverted pendulum is designed in Section 4.2 and then implemented in Section 4.3. In addition to running the balance controller, the energy-based swing-up control is implemented in Section 4.3. The exercises are given within the lab procedures and labeled "**Exercise**". In that case, enter your answer in the exercises number in the corresponding section.

2. Prerequisites

The following system is required to run the QNET ROTPENT virtual instruments:

- ✔ PC equipped with either:

  - ✔ NI-ELVIS I and an NI E-Series or M-Series DAQ card.
  - ✔ NI ELVIS II
- ✔ Quanser Engineering Trainer (QNET) module.
- ✔ LabVIEW 8.6.1 with the following add-ons:
  - ✔ DAQmx
  - ✔ Control Design and Simulation Module
  - ✔ *When using ELVIS II*: ELVISmx installed for required drivers.
  - ✔ *When using ELVIS I*: ELVIS CD 3.0.1 or later installed.

If these are not all installed then the VI will not be able to run! Please make sure all the software and hardware components are installed. If an issue arises, then see the troubleshooting section in Reference [1].

3. ROTPENT Virtual Instruments

3.1. Summary

Table 1 below lists and describes the ROTPENT LabVIEW VIs supplied with the **QNET CD**.

VI	*Description*
QNET_ROTPENT_Simple_Modeling.vi	Apply voltage to DC motor and examine the arm and pendulum responses.
QNET_ROTPENT_Control_Design.vi	Design and simulate LQR-based balance controller.
QNET_ROTPENT_Swing_Up_Control.vi	Swing-up and balance pendulum.

Table 1: ROTPENT VIs supplied with the QNET CD.

3.2. Description

3.2.1. Simple Modeling

The QNET-ROTPENT Simple Modeling VI is shown in Figure 2. It runs the DC motor connected to the pendulum arm in open-loop and plots the corresponding pendulum arm and link angles as well as the applied input motor voltage. Table 2 lists and describes the main elements of the ROTPENT Simple Modeling virtual instrument front panel. Every element is uniquely identified through an ID number and located in Figure 2.

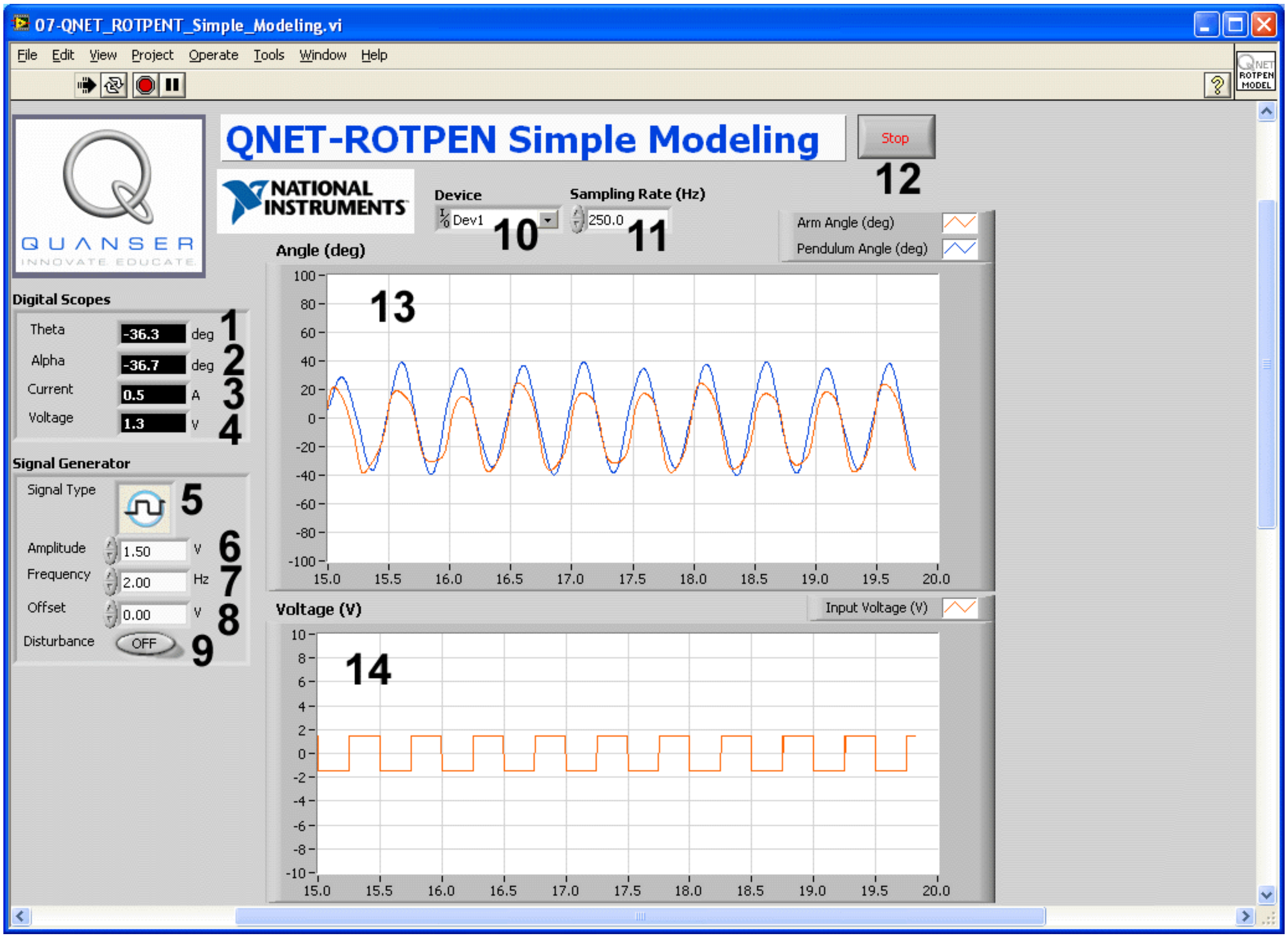

Figure 2: QNET-ROTPENT Simple Modeling VI.

ID #	***Label***	***Parameter***	***Description***	***Unit***
1	Theta	θ	Arm angle numeric display measured by encoder on motor.	deg
2	Alpha	α	Pendulum angle numeric display measured by encoder on pendulum pivot.	deg
3	Current	I_m	Motor armature current numeric display.	A
4	Voltage	V_m	Motor input voltage numeric display.	V
5	Signal Type		Type of signal generated for the input voltage signal.	
6	Amplitude		Generated signal amplitude input box.	V
7	Frequency		Generated signal frequency input box.	Hz
8	Offset		Generated signal offset input box.	V

9	Disturbance	V_{sd}	Apply simulated disturbance voltage.	V
10	Device		Selects the NI DAQ device.	
11	Sampling Rate		Sets the sampling rate of the VI.	Hz
12	Stop		Stops the LabVIEW VI from running.	
13	Scopes: Angle	θ,α	Scope with measured arm angle (in red) and pendulum angle (in blue).	deg
14	Scopes: Voltage	V_m	Scope with applied motor voltage (in red).	V

Table 2: Nomenclature of QNET-ROTPENT Simple Modeling VI

3.2.2. Control Design

The QNET ROTPENT Control Design VI enables users to design a balance controller and simulate its response. The matrices for the state-space model of the rotary inverted pendulum system is shown in the *Symbolic Model* tab and illustrated in Figure 4. The values of the variables used in the state-space model can be changed. In the *Open Loop Analysis* tab, shown in Figure 5, the numerical state-space model is displayed and the resulting open-loop poles are plotted on a phase plane. Based on this model, a controller to balance the rotary inverted pendulum system can be designed using the Linear-Quadratic Regulator (LQR) optimization technique, as shown in the *Simulation* tab in Figure 6. The resulting closed-loop inverted pendulum system can be simulated. Table 3 lists and describes the main elements of the ROTPENT Control Design virtual instrument user interface. Every element is uniquely identified through an ID number and located in figures 4, 5, and 6.

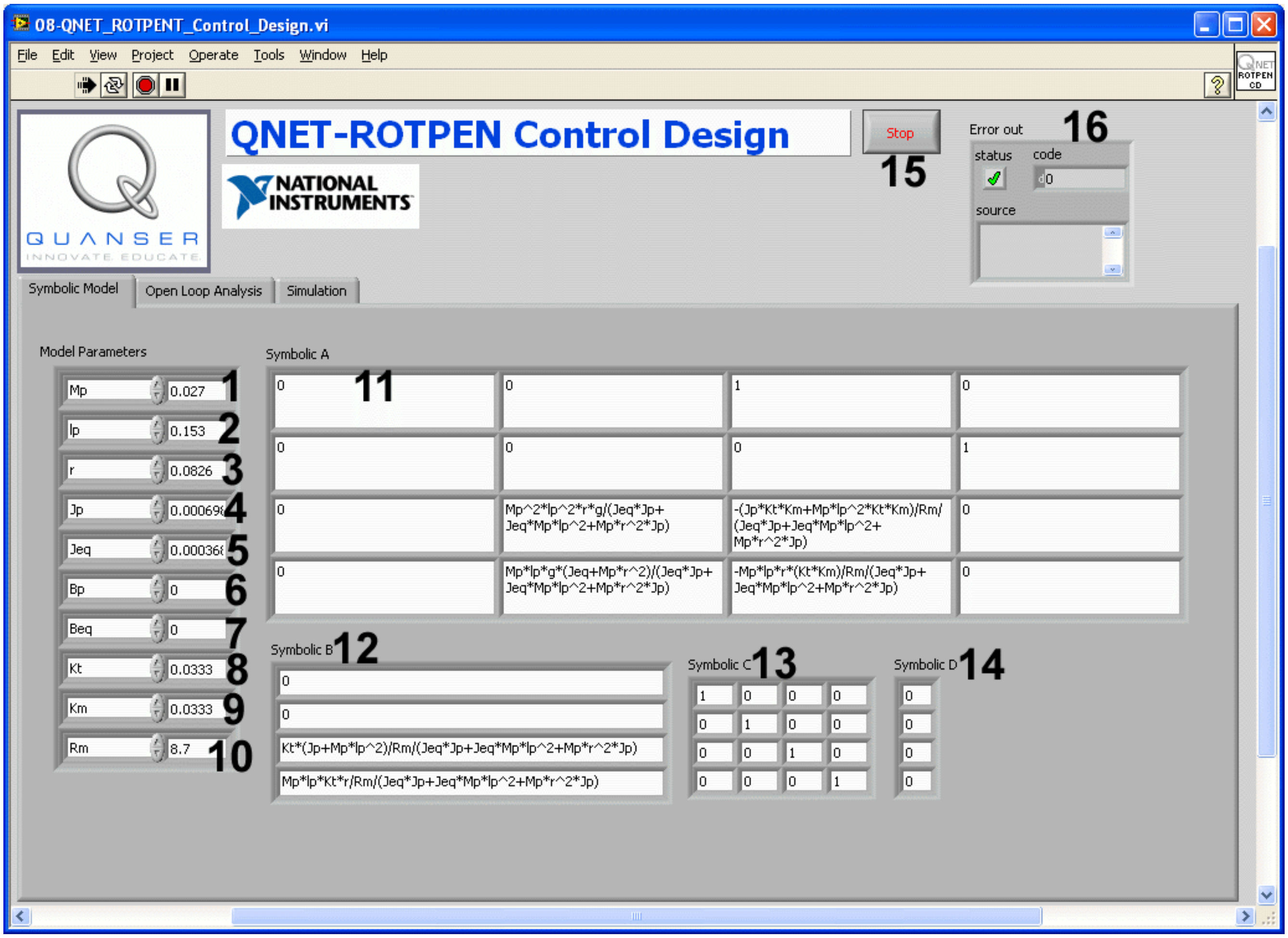

Figure 3: QNET ROTPENT Control Design VI: "Symbolic Model" tab.

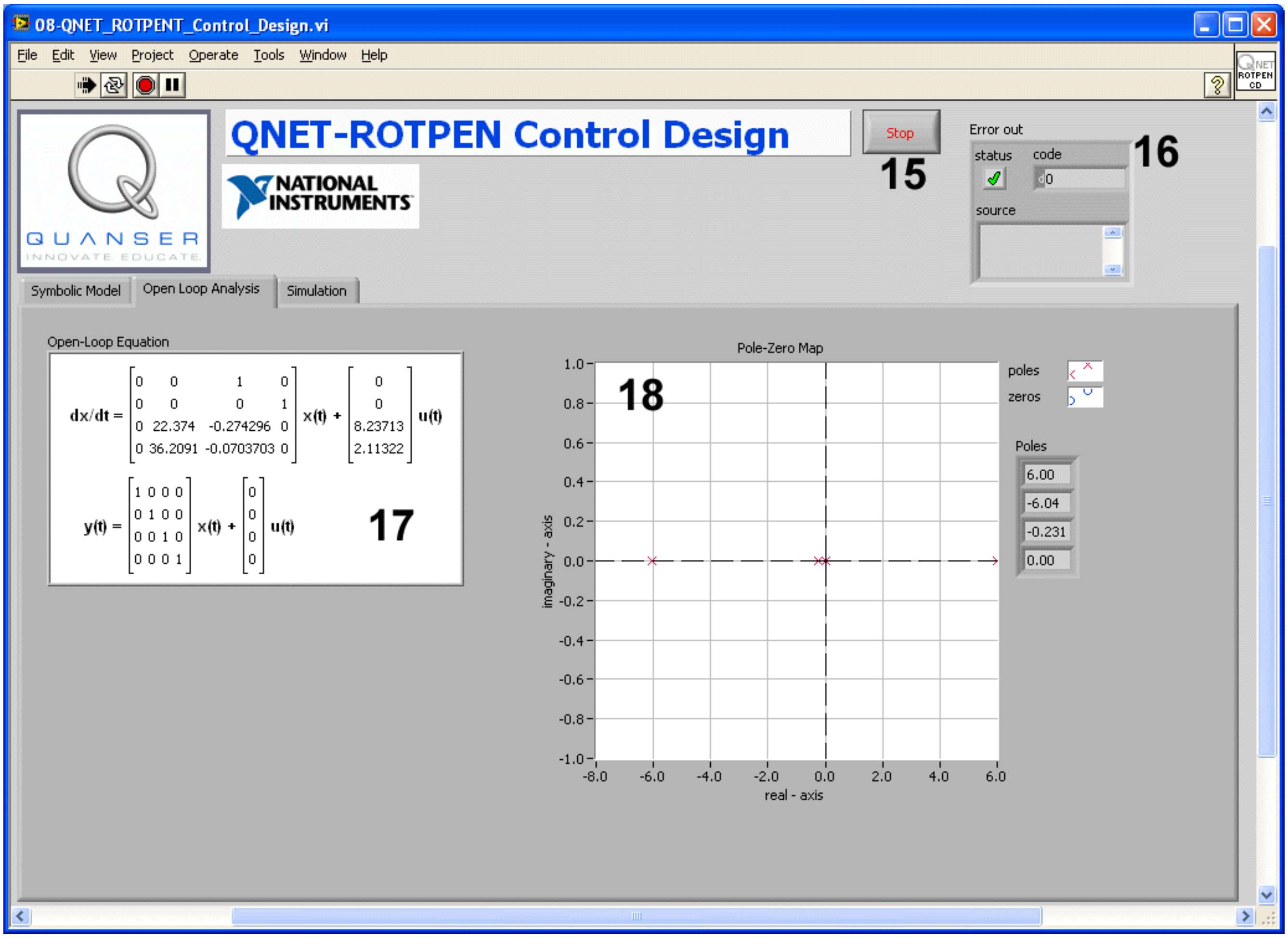

Figure 4: QNET ROTPENT Control Design VI: "Open Loop Analysis" tab.

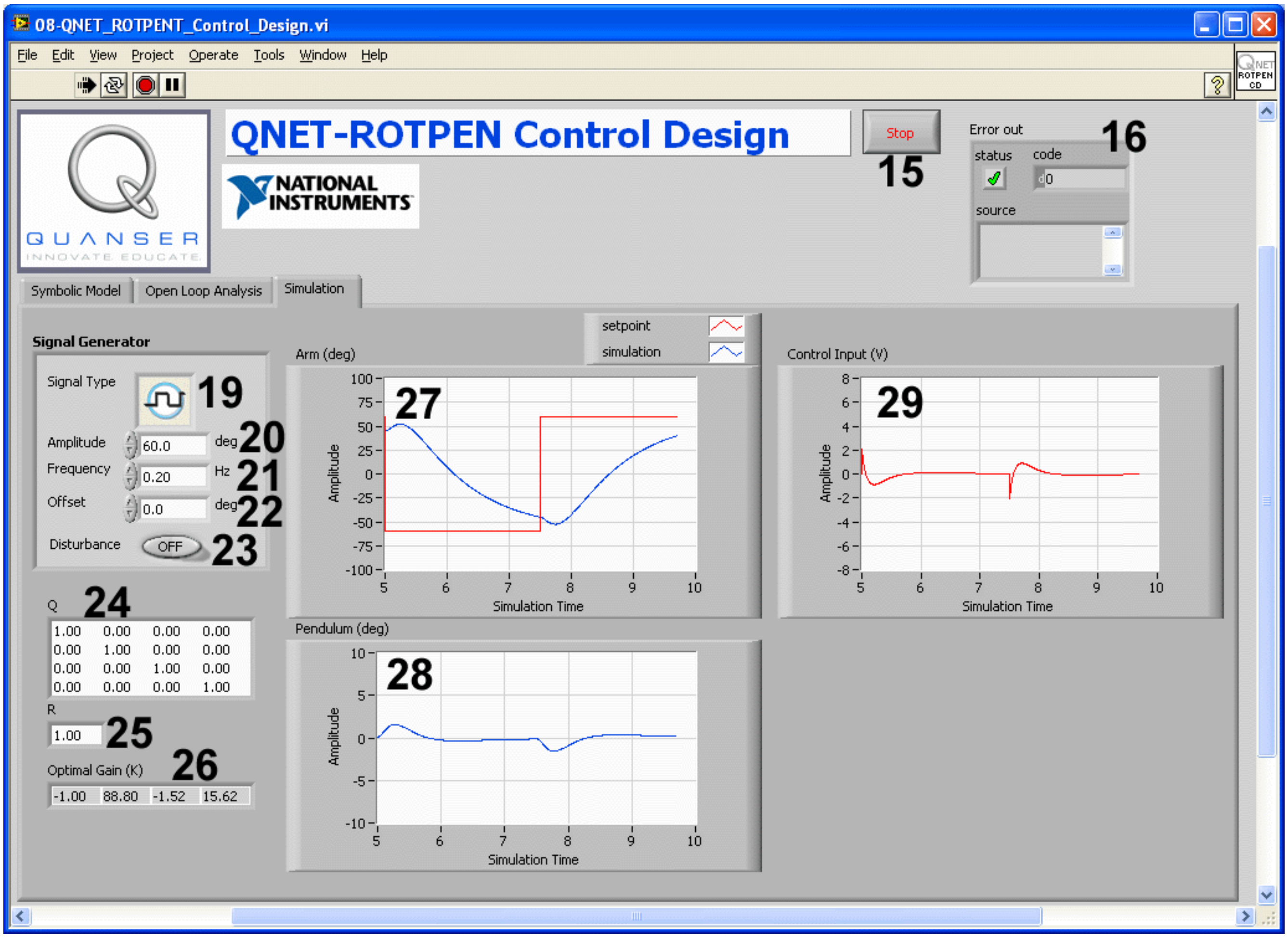

Figure 5: QNET ROTPENT Control Design VI: "Simulation" tab.

ID #	*Label*	*Parameter*	*Description*	*Unit*
1	Mp	M_p	Mass of pendulum assembly (link + weight).	kg
2	lp	l_p	Center of mass of pendulum assembly (link+weight) input box.	m
3	r	r	Length from motor shaft to pendulum pivot.	m
4	Jp	J_p	Pendulum moment of inertia relative to pivot.	$kg.m^2$
5	Jeq	J_{eq}	Equivalent moment of inertia acting on the DC motor shaft.	$kg.m^2$
6	Bp	B_p	Viscous damping about the pendulum pivot.	N.m.s/rad
7	Beq	B_{eq}	Equivalent viscous damping acting on the	N.m.s/ra

			DC motor shaft.	d
8	Kt	K_t	DC motor current-torque constant.	N.m/A
9	Km	K_m	DC motor back-emf constant.	V.s/rad
10	Rm	R_m	Electrical resistance of the DC motor armature.	ohm
11	Symbolic A	A	Rotary pendulum linear state-space matrix A.	
12	Symbolic B	B	Rotary pendulum linear state-space matrix B.	
13	Symbolic C	C	Rotary pendulum linear state-space matrix C.	
14	Symbolic D	D	Rotary pendulum linear state-space matrix D.	
15	Stop		Stops the LabVIEW VI from running.	
16	Error Out		Displays any error encountered in the VI.	
17	Open-Loop Equation		Numeric linear state-space model of rotary pendulum.	
18	Pole-Zero Map		Maps pole and zeros of open-loop rotary pendulum system.	
19	Signal Type		Type of signal generated for the arm position reference.	
20	Amplitude		Generated signal amplitude input box.	V
21	Frequency		Generated signal frequency input box.	Hz
22	Offset		Generated signal offset input box.	V
23	Disturbance	V_{sd}	Apply simulated disturbance voltage.	V
24	Q	Q	Linear-quadratic weighting matrix that defines a penalty on the state.	
25	R	R	Linear-quadratic weighting matrix that defines a penalty on the control action.	
26	Optimal Gain (K)	K	State-feedback control gain calculated uisng LQR.	
27	Arm	θ	Scope with reference (in blue) and measured (in red) arm angles.	deg
28	Pendulum	α	Scope with inverted pendulum angle (in blue).	deg
29	Control Input	V_m	Scope with applied motor voltage (in red).	V

Table 3: Nomenclature of QNET-ROTPENT Control Design VI.

3.2.3. Swing-Up Control

The QNET rotary pendulum trainer swing-up control VI implements an energy-based control that swings up the pendulum to its upright vertical position and a state-feedback controller to balance the pendulum when in its upright position. The main elements of the VI front panel are summarized in Table 4 and identified in Figure 6 through the corresponding ID number.

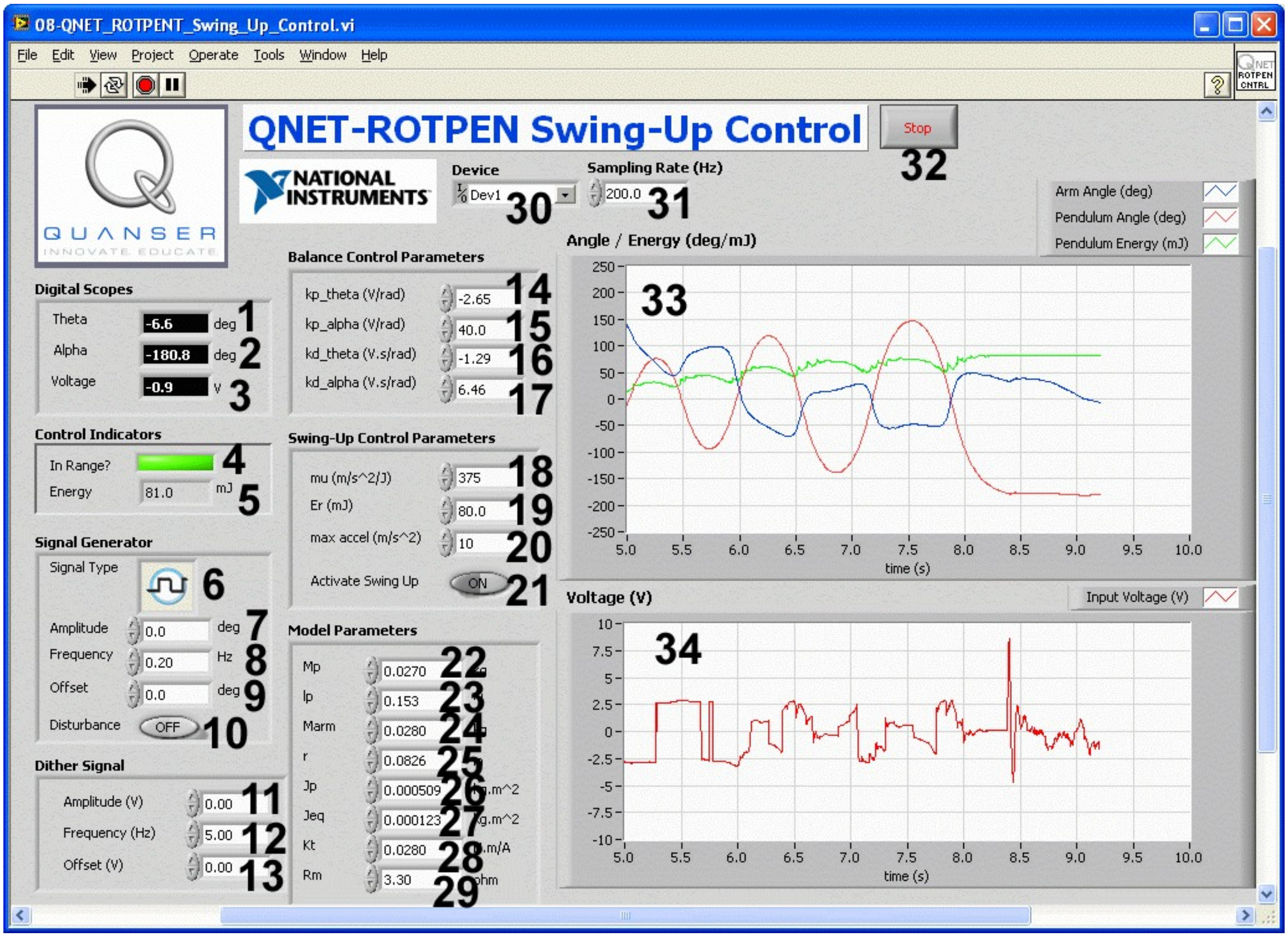

Figure 6: QNET ROTPENT Swing-Up Control.

#	*Label*	*Parameter*	*Description*	*Unit*
1	Theta	θ	Arm angle measured by encoder on motor.	deg
2	Alpha	α	Pendulum angle measured by encoder on pendulum pivot.	deg
3	Current	I_m	Motor armature current numeric display.	A
4	In Range?		Balance controller is engaged when this LED is turns bright green.	
5	Energy		Numeric display of the pendulum energy.	mJ
6	Signal Type		Type of signal generated for the input voltage.	
7	Amplitude		Generated signal amplitude input box.	V
8	Frequency		Generated signal frequency input box.	Hz
9	Offset		Generated signal offset input box.	V
10	Disturbance	V_{sd}	Apply simulated disturbance voltage.	V
11	Amplitude	A_d	Dither signal amplitude input box.	V
12	Frequency	f_d	Dither signal frequency input box.	Hz
13	Offset	V_{d0}	Dither signal offset input box.	V
14	kp_theta	$k_{p,\theta}$	Arm angle proportional gain input box.	V/rad
15	kp_alpha	$k_{p,\alpha}$	Pendulum angle proportional gain input box.	V/rad
16	kd_theta	$k_{d,\theta}$	Arm angle derivative gain input box.	V.s/rad
17	kd_alpha	$k_{d,\alpha}$	Pendulum angle derivative gain input box.	V.s/rad
18	mu	μ	Proportional gain for energy controller.	$m/(s^2.J)$
19	Er	E_r	Reference energy for energy controller.	mJ
20	Max accel	u_{max}	Maximum acceleration	m/s^2
21	Activate Swing Up		When pressed down the energy controller that swings-up the pendulum is engaged.	
22	Mp	M_p	Mass of pendulum assembly (link + weight).	kg
23	lp	l_p	Center of mass of pendulum assembly (link+weight) input box.	m
24	Marm	M_{arm}	Mass of rotary arm.	kg
25	r	r	Length from motor shaft to pendulum pivot.	m

26	Jp	J_p	Pendulum moment of inertia relative to pivot.	$kg.m^2$
27	Jeq	J_{eq}	Equivalent moment of inertia acting on the DC motor shaft.	$kg.m^2$
28	Kt	K_t	Current-torque or back-emf constant: they are equivalent in SI units.	N.m/A
29	Rm	R_m	Electrical resistance of the DC motor armature.	ohm
30	Device		Selects the NI DAQ device.	
31	Sampling Rate		Sets the sampling rate of the VI.	Hz
32	Stop		Stops the LabVIEW VI from running.	
33	Angle / Energy	θ, α, E	Scope with measured arm angle (in red), measured pendulum angle (in blue), and pendulum energy (in green).	deg/mJ
34	Voltage	V_m	Scope with applied motor voltage (red).	V

Table 4: Nomenclature of QNET ROTPENT Swing-Up Control VI.

4. In-Lab Experiments

4.1. Simple Modeling

4.1.1. Dampening

1. Open the QNET_ROTPENT_Simple_Modeling.vi.
2. Ensure the correct *Device* is chosen, as shown in Figure 7

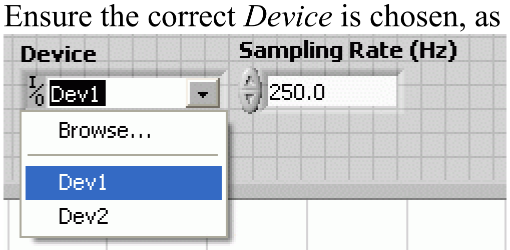

Figure 7: Selecting correct device.

3. Run the QNET_ROTPENT_Simple_Modeling.vi, shown in Figure 8.
4. Hold the arm of the rotary pendulum system stationary and manually perturb the pendulum.
5. While still holding the arm, examine the response of *Pendulum Angle (deg)* in the *Angle (deg)* scope. This is the response from the **pendulum** system.
6. Repeat Step 3 above and release the arm after several swings.

7. **Exercise 1**: Examine the *Pendulum Angle (deg)* response when the arm is not fixed. This is the response from the **rotary pendulum** system. Given the response from these two systems - **pendulum** and **rotary pendulum** – which converges faster towards angle zero? Why does one system dampen faster than the other?
8. Stop the VI by clicking on the *Stop* button.

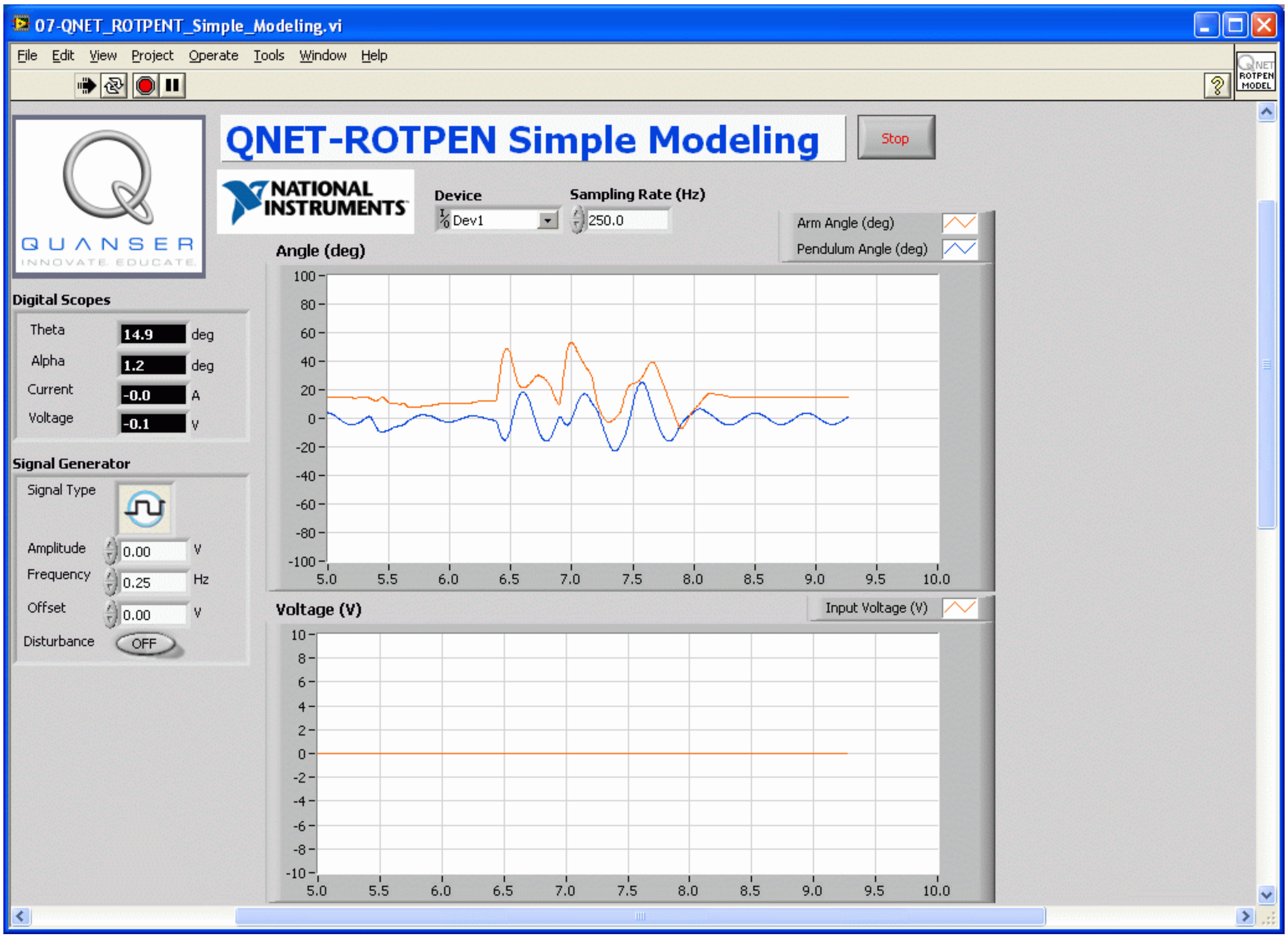

Figure 8: QNET ROTPEN Simple Modeling VI.

4.1.2. Friction

1. Run the QNET_ROTPENT_Simple_Modeling.vi.
2. In the *Signal Generator* section set:
   - *Amplitude* = 0.00 V
   - *Frequency* = 0.25 Hz
   - *Offset* = 0.00 V
3. Change the *Offset* in steps of 0.10 V until the pendulum begins moving. Record the voltage at which the pendulum moved.
4. Repeat Step 3 above for steps of -0.10 V.

5. **Exercise 2**: Enter the positive and negative voltage values needed to get the pendulum moving in . Why does the motor need a certain amount of voltage to get the motor shaft moving?
6. Stop the VI by clicking on the *Stop* button.

4.1.3. Moment of Inertia

1. **Exercise 3**: Using references [1] and [2], calculate the moment of inertia acting about the pendulum pivot.
2. Run the QNET_ROTPENT_Simple_Modeling.vi
3. In the *Signal Generator* section set:
    - *Amplitude* = 1.00 V
    - *Frequency* = 0.25 Hz
    - *Offset* = 0.00 V
4. Click on the *Disturbance* toggle switch to perturb the pendulum and measure the amount of time it takes for the pendulum to swing back-and-forth in a few cycles (e.g. 4 cycles).
5. **Exercise 4:** Find the frequency and moment of inertia of the pendulum using the observed results. See Reference [2] to see how to calculate the inertia experimentally and make sure you fill in Table 5.
6. **Exercise 5**: Compare the moment of inertia calculated analytically in Exercise 3 and the moment of inertia found experimentally. Is there a large discrepancy between them?
7. Stop the VI by clicking on the *Stop* button.

4.1.4. Exercises

Exercise 1: Dampening

0	1	2

Exercise 2: Friction Analysis

Description	***Symbol***	***Value***	***Unit***
Positive Coulomb Friction Voltage	V_{fp}		V
Negative Coulomb Friction Voltage	V_{fn}		V

0	1	2

0	1	2

Exercise 3: Calculate Moment of Inertia

0	1	2

Exercise 4: Measure Moment of Inertia

Description	Symbol	Value	Unit
Cycles	n_{cyc}		
Duration	Δt		s
Frequency	f		Hz
Pendulum moment of inertia	$J_{p,exp}$		$kg.m^2$

0	1	2

Table 5: Measure pendulum moment of inertia.

Exercise 5: Comparing Pendulum Inertia

0	1	2

4.2. Balance Control Design

4.2.1. Model Analysis

1. Open the QNET_ROTPENT_Control_Design.vi, shown in Figure 9.
2. Run the QNET_ROTPENT_Control_Design.vi.
3. Select the *Symbolic Model* tab.
4. The *Model Parameters* array includes all the rotary pendulum modeling variables that are used in the state-space matrices A, B, C, and D.
5. Select the *Open Loop Analysis* tab.
6. **Exercise 1**: This shows the numerical linear state-space model and a pole-zero plot of the open-loop inverted pendulum system. What do you notice about the location of the open-loop poles?
   Recommended: In the *Model Parameters* section, it is recommend to enter the pendulum moment of inertia, *Jp*, determined experimentally in Section 4.1.3.
7. In the *Symbolic Model* tab, set the pendulum moment of inertia, *Jp,* to 1.0e-5 $kg.m^2$.

8. **Exercise 2**: Select the *Open Loop Analysis* tab. How did the locations of the open-loop poles change with the new inertia? Enter the pole locations of each system with a different moment of inertia in Table 6. Are the changes of having a pendulum with a lower inertia as expected?
9. Reset the pendulum moment of inertia, *Jp*, back to 1.77e-4.
10. Stop the VI by clicking on the *Stop* button.

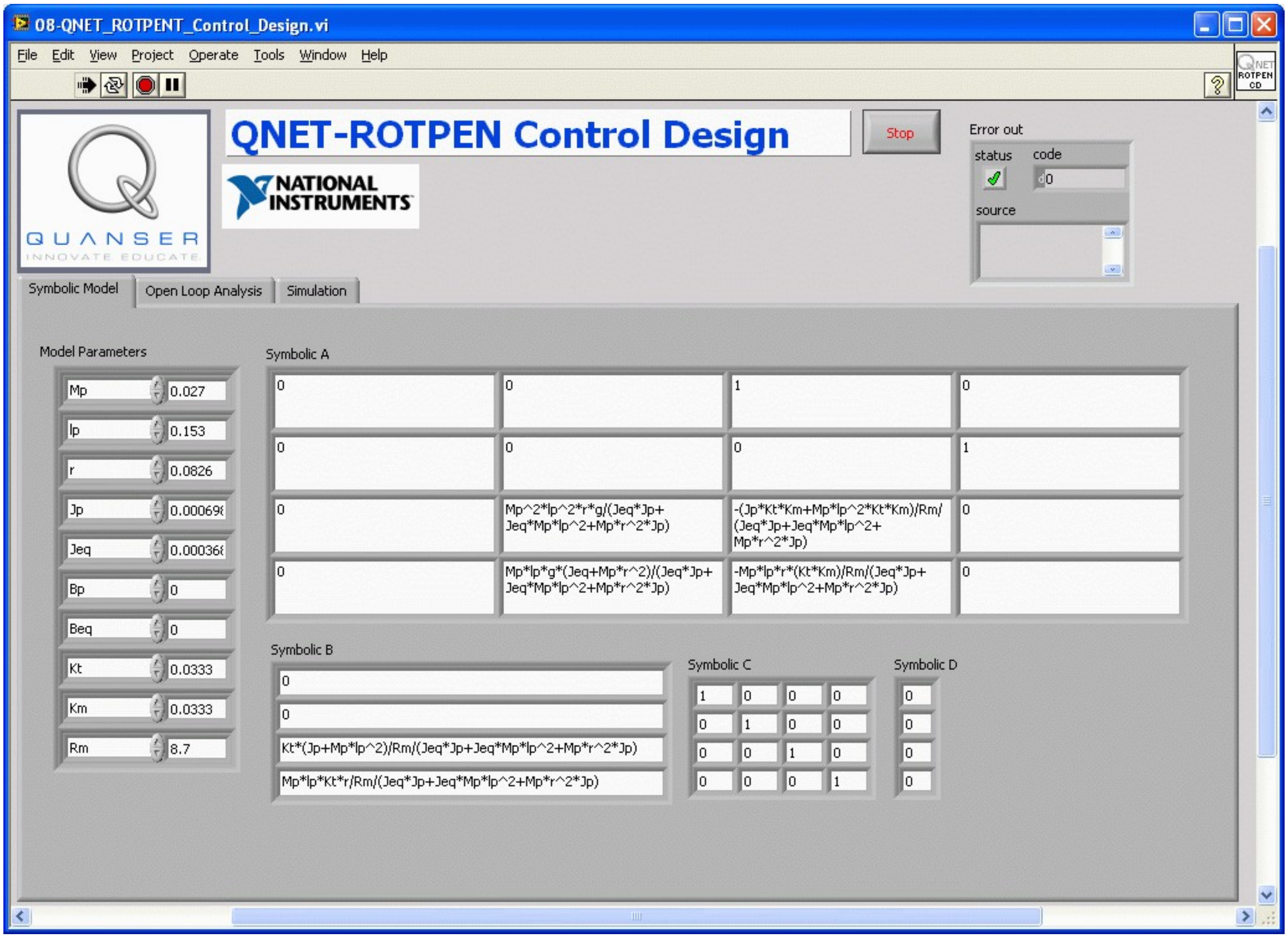

Figure 9: QNET ROTPEN trainer control design VI: Symbolic Model tab.

4.2.2. Control Design and Simulation

1. Open the QNET_ROTPENT_Control_Design.vi, shown in Figure 10.
2. Select the *Simulation* tab.
3. Run the QNET_ROTPENT_Control_Design.vi.
4. In the *Signal Generator* section set:
   - *Amplitude* = 45.0 deg
   - *Frequency* = 0.20 Hz
   - *Offset* = 0.0 deg

5. Set the *Q* and *R* LQR weighting matrices to the following:
    - *Q(1,1)* = 10, i.e. set first element of *Q* matrix to 5.
    - *R* = 1.00
6. Changing the *Q* matrix generates a new control gain.
7. **Exercise 3**: The arm reference (in red) and simulated arm response (in blue) are shown in the *Arm (deg)* scope. How did the arm response change? How did the pendulum response change in the *Pendulum (deg)* scope.
8. Set the third element in the *Q* matrix to 0, i.e. *Q(3,3)* = 0.
9. **Exercise 4**: Examine and describe the change in the *Arm (deg)* and *Pendulum (deg)* scope.
10. By varying the diagonal elements of the *Q* matrix, design a balance controller that adheres to the following specifications:
    - Arm peak time less than 0.75 seconds: $t_p \leq 0.75$ s
    - Motor voltage peak less than ± 12.5 V: $|V_m| \leq 12.5$ V
    - Pendulum angle less than 10.0 degrees: $|\alpha| \leq 10.0$ deg
11. **Exercise 5**: Enter the *Q* and *R* matrices along with and control gain used to meet the specifications.
12. **Exercise 6**: Attach the responses from the *Arm (deg)*, *Pendulum (deg)*, and *Control Input (V)* scopes when using your designed balance controller.
13. Stop the VI by clicking on the *Stop* button.

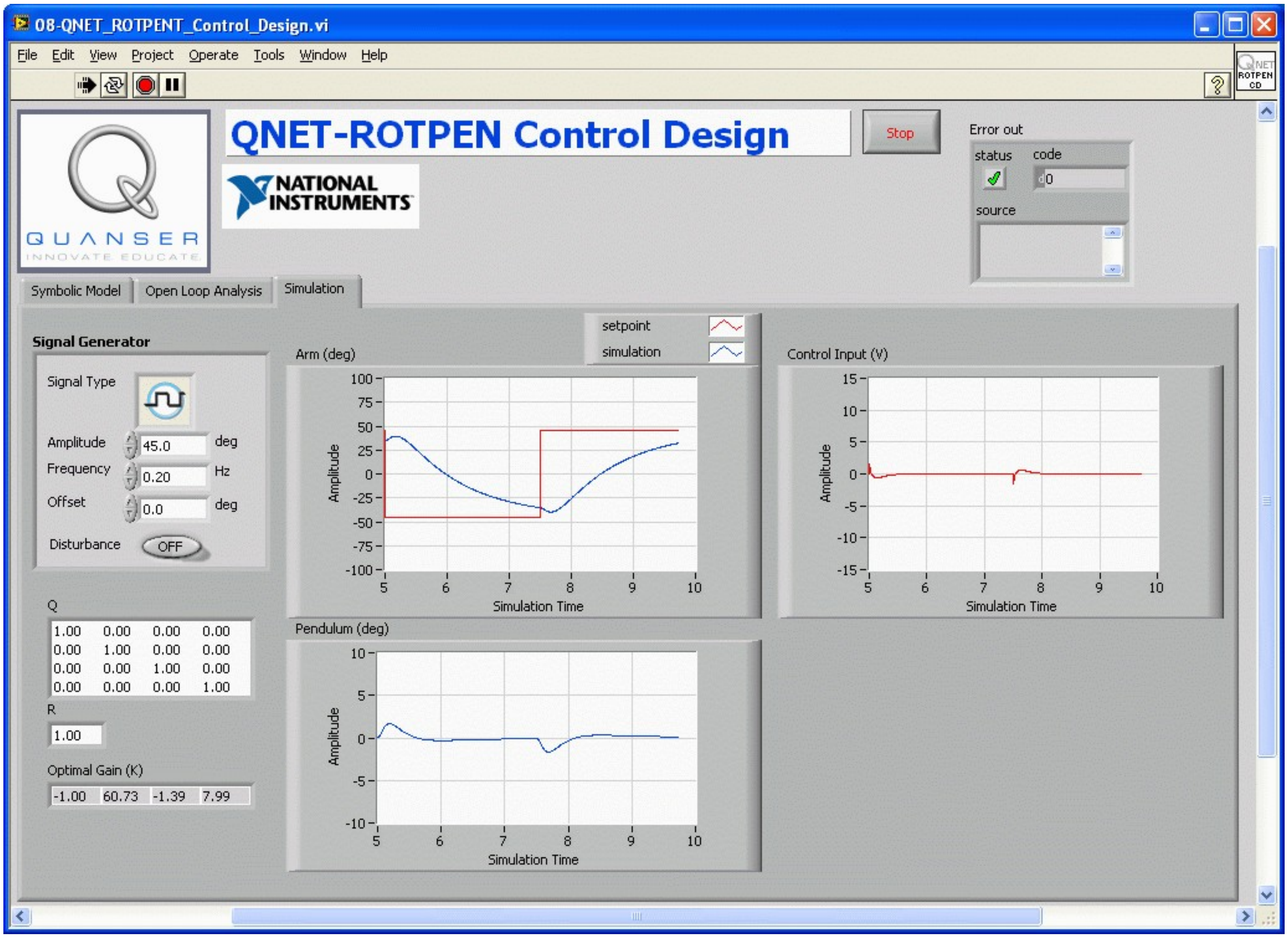

Figure 10: QNET ROTPEN trainer control design VI: Simulation tab.

4.2.3. Exercises

Exercise 1: Open-Loop Poles

0 1 2

Exercise 2: Effect of Changing Inertia on Poles

Description	***Symbol***	***Value***	***Unit***
System w/ *Jp* = 1.7e-4	p_0		rad/s
	p_1		rad/s
	p_2		rad/s
	p_3		rad/s
System w/ *Jp* = 1.00e-5	p_0		rad/s
	p_1		rad/s
	p_2		rad/s
	p_3		rad/s

0 1 2

Table 6: Effect on poles when changing moment of inertia.

Exercise 3: Arm Response with Q(1,1)=10

0	1	2

Exercise 4: Arm Response with Q(3,3)=0

0	1	2

Exercise 5: Designed Balance Controller

Description	*Symbol*	*Value*	*Unit*
Q(1,1)	$Q_{1,1}$		
Q(2,2)	$Q_{2,2}$		
Q(3,3)	$Q_{3,3}$		
Q(4,4)	$Q_{4,4}$		
R	R		
K(1)	$k_{p,\theta}$		V/rad
K(2)	$k_{p,\alpha}$		V/rad
K(3)	$k_{d,\theta}$		V.s/rad
K(4)	$k_{d,\alpha}$		V.s/rad

0	1	2

Table 7: Designed balance controller.

Exercise 6: Balance Control Responses

0	1	2

4.3. Swing-Up Control

4.3.1. Default Balance Control

1. Open the QNET_ROTPENT_Swing_Up_Control.vi, shown in Figure 11.
2. Ensure the correct *Device* is chosen.
3. Run the QNET_ROTPENT_Swing_Up_Control.vi.
4. In the *Signal Generator* section set:
   - *Amplitude* = 0.0 deg
   - Frequency = 0.10 Hz
   - *Offset* = 0.0 deg
5. In the *Balance Control Parameters* section set:
   - *kp_theta* = -6.50 V/rad
   - *kp_alpha* = 80 V/rad
   - *kd_theta* = -2.75 V/(rad/s)
   - *kd_alpha* = 10.5 V/(rad/s)
6. In the *Swing-Up Control Parameters* section set:
   - *mu* = 55 m/s^2/J
   - *Er* = 20.0 mJ
   - *max accel* = 10 m/s^2
   - *Activate Swing-Up* = OFF (de-pressed)
7. Adjust the *Angle/Energy (deg/mJ)* scope scales to see between -250 and 250 (see Reference [1] for help).
8. Manually rotate the pendulum in the upright position until the *In Range?* LED in the *Control Indicators* section turns bright green. **Ensure the encoder cable does not interfere with the pendulum arm motion.**
9. **Exercise 1**: Vary *Offset* and observe the *Arm Angle (deg)* response in the *Angle/Energy (deg/mJ)* scope. **Do not set the *Offset* too high or the encoder cable will interfere with the pendulum arm motion.**
10. **Exercise 2**: As the pendulum is being balanced, examine the red *Arm Angle (deg)* and blue *Pendulum Angle (deg)* responses in the *Angle/Energy (deg/mJ)* scope.
11. In the *Signal Generator* section set:
    - *Amplitude* = 45.0 deg
    - *Frequency* = 0.10 Hz
    - *Offset* = 0.0 deg
12. **Exercise 3**: Observe the behaviour of the system when a square wave command is given to the arm angle. Why does the arm initially move in the wrong direction?
13. Click on the *Stop* button to stop running the VI.

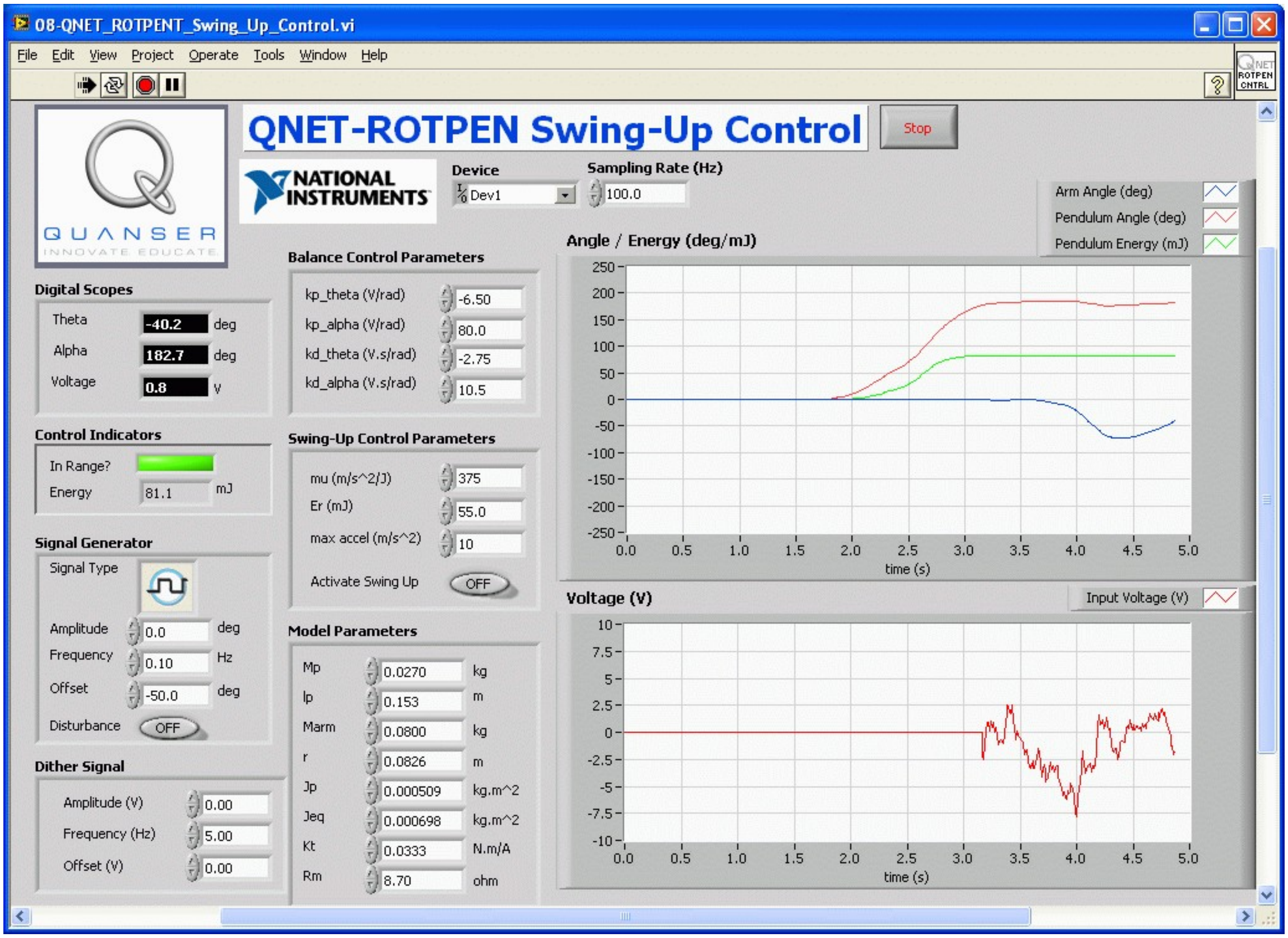

Figure 11: QNET rotary pendulum trainer swing-up VI.

4.3.2. Implement Designed Balance Controller

1. Go through Section 4.2.2 and design a balance control according to the given specifications. *Remark*: It is recommended to use the experimental determined pendulum moment of inertia that was found in Section 4.1.3.
2. Open the QNET_ROTPENT_Swing_Up_Control.vi.
3. Ensure the correct *Device* is chosen.
4. Run the QNET_ROTPENT_Swing_Up_Control.vi.
5. In the *Signal Generator* section set:
    - *Amplitude* = 45.0 deg
    - *Frequency* = 0.20 Hz
    - *Offset* = 0.0 deg
6. To implement your balance controller, enter the control gain found in Section 4.2.2 in *kp_theta*, *kp_alpha*, *kd_theta*, and *kd_alpha* in the *Control Parameters* section.
7. Manually rotate the pendulum in the upright position until the *In Range?* LED in the *Control Indicators* section turns bright green. **Ensure the encoder cable does not interfere with the**

pendulum arm motion.

8. **Exercise 4**: Attach the response found *Angle/Energy (deg/mJ)* and the *Voltage (V)* scopes. Does your system meet the specifications given in Section 4.2.2?
9. Click on the *Stop* button to stop running the VI.

4.3.3. Balance Control with Friction Compensation

1. Go through steps 1-8 in Section 4.3.1 to run the default balance control.
2. In the *Signal Generator* section set:
   - *Amplitude* = 0.0 deg
   - Frequency = 0.10 Hz
   - *Offset* = 0.0 deg
3. In the *Dither Signal* section set:
   - *Amplitude* = 0.00 V
   - *Frequency* = 2.50 Hz
   - *Offset* = 0.00 V
4. **Exercise 5**: Observe the behaviour of *Arm Angle (deg)* in the *Angle/Energy (deg/mJ)* scope. Intuitively speaking, can you find some reasons why the arm is oscillating?
5. Increase the *Amplitude* in the *Dither Signal* section by steps of 0.1 V until you notice a change in the arm angle response.
6. **Exercise 6**: From the *Voltage (V)* scope and the pendulum motion, what is the Dither signal doing? Compare the response of the arm with and without the Dither signal.
7. Increase the *Frequency* in the *Dither Signal* section starting from 1.00 to 10.0 Hz.
8. **Exercise 7**: How does this effect the pendulum arm response?
9. ***Optional*** **Exercise 8**: Set the *Dither Signal* properties according to the friction measured in Exercise 2 of the *QNET-ROTPEN: Simple Modeling* experiment. How does this effect the pendulum arm response?
10. Click on the *Stop* button to stop running the VI.

4.3.4. Energy Control

1. Open the QNET_ROTPENT_Swing_Up_Control.vi.
2. Ensure the correct Device is chosen.
3. Run the QNET_ROTPENT_Swing_Up_Control.vi.
4. In the *Balance Control Parameters* section ensure the following parameters are set:
   - *kp_theta* = -6.50 V/rad
   - *kp_alpha* = 80.0 V/rad
   - *kd_theta* = -2.75 V/(rad/s)
   - *kd_alpha* = 10.5 V/(rad/s)
5. In the *Swing-Up Control Parameters* section set:
   - *mu* = 55 $m/s^2/J$
   - *Er* = 20.0 mJ
   - *max accel* = 10 m/s^2
   - *Activate Swing-Up* = OFF (de-pressed)

6. Adjust the *Angle/Energy (deg/mJ)* scope scales to see between -250 and 250 (see Reference [1] for help).
7. Manually rotate the pendulum at different levels and examine the blue *Pendulum Angle (deg)* and the green *Pendulum Energy (mJ)* in the *Angle/Energy (deg/mJ)* scope. The pendulum energy is also displayed numerically in the *Control Indicators* section.
8. **Exercise 9**: What do you notice about the energy when the pendulum is moved at different positions? Record the energy when the pendulum is being balanced (i.e. fully inverted in the upright vertical position).
9. Click on the *Stop* button to bring the pendulum down to the gantry position and re-start the VI.
10. In the *Swing-Up Control Parameters* section, set the *Activate Swing-Up* = ON (pressed) switch.
11. If the pendulum is stationary, click on the *Disturbance* button in the *Signal Generator* section to perturb the pendulum.
12. **Exercise 10**: In *Swing-Up Control Parameters*, change the reference energy *Er* between 5.0 mJ and 50.0 mJ. As it is varied, examine the control signal in the *Voltage (V)* scope as well as the blue *Pendulum Angle (deg)* and the red *Pendulum Energy (mJ)* in the *Angle/Energy (deg/mJ)* scope. Attach the response of the *Angle/Energy (deg/mJ)* and *Voltage (V)* scopes.
13. **Exercise 11**: In *Control Parameters* fix *Er* to 20.0 mJ and vary the swing-up control gain *mu* between 10 and 100 $m/s^2/J$. Describe how this changes the performance of the energy control.
14. Click on *Stop Control* to disable the energy and balance controllers.

4.3.5. Hybrid Swing-Up Control

1. Open the QNET_ROTPENT_Swing_Up_Control.vi.
2. Ensure the correct Device is chosen.
3. Run the QNET_ROTPENT_Swing_Up_Control.vi.
4. In the *Balance Control Parameters* section verify the following parameters are set:
    - *kp_theta* = -6.50 V/rad
    - *kp_alpha* = 80.0 V/rad
    - *kd_theta* = -2.75 V/(rad/s)
    - *kd_alpha* = 10.5 V/(rad/s)
5. In the *Swing-Up Control Parameters* section set:
    - *mu* = 55 $m/s^2/J$
    - *Er* = 20.0 mJ
    - *max accel* = 10 m/s^2
    - *Activate Swing-Up* = OFF (de-pressed)
6. Adjust the *Angle/Energy (deg/mJ)* scope scales to see between -250 and 250 (see Reference [1] for help).
7. Make sure the pendulum is hanging down motionless and the encoder cable is not interfering with the pendulum.
8. Set the *Activate Swing-Up* = ON (pressed) switch in the *Swing-Up Control Parameters*.
9. The pendulum should begin going back and forth. If not, click on the *Disturbance* button in the *Signal Generator* section to perturb the pendulum. **Turn off the** *Active Swing-Up* **switch if the pendulum goes unstable or if the encoder cable interferes with the pendulum arm**

motion.

10. Gradually increase the reference energy *Er* in the *Control Parameters* section to the energy read when the pendulum is vertically upwards (Exercise 9 in Section 4.3.4). When that reference energy is reached, the pendulum should swing-up to the inverted position.
11. Click on the *Stop* button to stop running the VI.

4.3.6. Exercises

Exercise 1: Varying Offset

0	1	2

Exercise 2: Arm and Pendulum Motions when Balancing

0	1	2

Exercise 3: Behaviour of Arm

0	1	2

Exercise 4: Response using Designed Controller

0	1	2

Exercise 5: Arm Oscillation

0	1	2

Exercise 6: Adding Dither Signal

0	1	2

Exercise 7: Effect of Increasing Dither Frequency

0	1	2

Exercise 8: Setting Dither to Measured Friction

0	1	2

Exercise 9: Energy Level at Different Pendulum Positions

0	1	2

Exercise 10: Changing Reference Energy

0	1	2

Exercise 11: Changing Swing-Up Gain

0	1	2

5. References

[1] QNET User Manual
[2] QNET Practical Control Guide