QUANSER
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Specialty Plant: 3 DOF Crane

3 DOF Crane

User Manual

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1. Introduction

The Quanser 3 DOF Crane pictured in Figure 1 is a compact version of a tower crane. Like an actual crane it has three degrees of freedom: the tower can rotate in both directions, the trolley can move back-and-forth along the horizontal member, and the height of the payload can be changed.

Figure 1: Quanser 3 DOF Crane

The crane tower, also known as a *mast*, holds up the bulk of this system's structure while also containing an electrical input/output circuit board near its base. This circuit board interfaces with a data-acquisition terminal board to allow sensor signals and motor actuator signals to travel back and forth between the crane and a PC.

The horizontal member, mounted atop the tower, can rotate clockwise and counterclockwise by using a motor for actuation. This horizontal member is called the *jib* or *boom* of the crane. This jib has a trolley that has a cable to lift the payload up or to set it down by using another motor for actuation. This trolley, in turn, travels along a portion of the length of the jib by using another motor for actuation. Each of the motorized shafts are instrumented with optical encoders. The motors are driven by linear current control amplifiers with the capability of 100 Watts each.

This system can be used to teach fundamentals of the control of tower cranes, as well as advanced topics such as efficient and reasonably fast load transportation that simultaneously employs load swing minimization.

2. Prerequisites

To successfully carry out this laboratory, the prerequisites are:

i) To be familiar with your 3-DOF Crane main components (e.g. actuator, sensors), your data acquisition card (e.g. HIL), and your power amplifier (e.g. AMPAQ), as described in this document, Reference [1], and Reference [2], respectively.
ii) To be familiar in using QUARC to control and monitor the plant in real-time, as detailed in Reference [3], and use Simulink to design a controller.
iii) To be familiar with proportional-integral-derivative (PID) family of compensators and the linear-quadratic regulator (LQR) method enough to design a controller.

3. References

[1] Data-Acquisition User Manual
[2] AMPAQ User Manual
[3] QUARC User Manual (type `doc quarc` in Matlab to access)

4. Experiments Design Files

Table 1, below, lists and describes the various computer files coming with the experiment.

File Name	***Description***
3-DOF Crane User Manual.pdf	The user manual for the Quanser 3-DOF Crane system. It contains information about the hardware components, specifications, information to setup and configure the laboratory hardware, system modeling, control design, as well as the experimental procedure to implement the controller.

File Name	***Description***
3-DOF Crane Payload Position Equations.mws	Maple worksheet used to derive the Laplace equations used to describe the motions of the payload subsystem. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
3-DOF Crane Jib Equations.mws	Maple worksheet used to analytically derive the state-space model describing the position of the trolley and the payload angle that is inline with the jib, i.e. linear gantry. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
3-DOF Crane Tower Equations.mws	Maple worksheet used to analytically derive the state-space model describing the motions of the rotating tower and the payload angle that is perpendicular to the jib, i.e. rotary gantry. Waterloo Maple 9, or a later release, is required to open, modify, and execute this file.
3-DOF Crane Payload Position Equations.html	HTML presentation of the *3-DOF Crane Payload Position Equations.mws* file. It allows users to view the content of the Maple file without having Maple 9 installed. No modifications to the equations can be performed when in this format.
3-DOF Crane Jib Equations.html	HTML presentation of the *3-DOF Crane Jib Equations.mws* file. It allows users to view the content of the Maple file without having Maple 9 installed. No modifications to the equations can be performed when in this format.
3-DOF Crane Tower Equations.html	HTML presentation of the *3-DOF Crane Tower Equations.mws* file. It allows users to view the content of the Maple file without having Maple 9 installed. No modifications to the equations can be performed when in this format.

File Name	***Description***
quanser_tools.mws	Executing this worksheet generates the *quanser* repository containing the *Quanser_Tools* package. The two package files are named: *quanser.ind* and *quanser.lib*. The *Quanser_Tools* module defines the generic procedures used in Lagrangian mechanics and resulting in the determination of a given system's equations of motion and state-space representation. It also contains data processing routines to save the obtained state-space matrices into a Matlab-readable file.
quanser_tools.rtf	Rich Text Format presentation of the quanser_tools.mws file. It allows to view the content of the Maple worksheet without having Maple 8 installed. No modifications to the Maple procedures can be performed when in this format.
setup_3d_crane.m	The main Matlab script that calls *setup_3d_crane_configuration.m*, *CRANE_JIB_ABCD_eqns.m*, *CRANE_TOWER_ABCD_eqns.m*, and *d_payload_piv_controller.m* to set the model, control, and configuration parameters. **Run this file only to setup the laboratory.**
setup_3d_crane_configuration.m	Returns the model parameters and encoder calibration constants *g, Kt_t, Kt_j, Kt_y, eff_m_t, eff_m_j, eff_m_y, Kg_t, Kg_j, Kg_y, eff_g_t, eff_g_j, eff_g_y, J_theta, J_psi, J_phi, J_alpha, J_gamma, lj, lp, mp, m_trolley, r_y_reel, r_j_pulley, K_ENC_THETA, K_ENC_X, K_ENC_Z, K_ENC_ALPHA,* and *K_ENC_GAMMA*. These are explained in Table 8.
CRANE_JIB_ABCD_eqns.m	Matlab script file generated using the Maple worksheet *3-DOF Crane Jib Equations.mws.* It sets the *A*, *B*, *C*, and *D* state-space matrices of the 3-DOF Crane Jib open-loop system that is used to its LQR controller and for simulating the system in the Simulink model *s_3d_crane_jib_pos_cntrl.mdl*.

File Name	***Description***
CRANE_TOWER_ABCD_eqns.m	Matlab script file generated using the Maple worksheet *3-DOF Crane Tower Equations.mws*. It sets the *A*, *B*, *C*, and *D* state-space matrices of the 3-DOF Crane Tower open-loop system that is used to design its LQR controller and for simulating the system in the Simulink model *s_3d_crane_tower_pos_cntrl.mdl*.
d_payload_piv_controller.m	Matlab function that designs the PIV controller gains *kp*, *ki*, and *kv* based on payload model parameters and the following specifications: peak time *tp*, percentage overshoot *PO*, and pole location *p0* . It is used in the Simulink model *s_3d_crane_payload_pos_cntrl_lqr.mdl* and *q_3d_crane.mdl*.
callback_clear_setpoints	Sets the tower, trolley, and payload setpoint in q_3d_crane.mdl to zero when its corresponding QUARC Controller is stopped.
calc_conversion_constants.m	Loads various conversion factors.
s_3d_crane_payload_pos_cntrl.mdl	Simulink file that simulates the closed-loop 3-DOF Crane Payload Position system using its developed linear equations of motion and a PIV controller.
s_3d_crane_jib_pos_cntrl.m-dl	Simulink file that simulates the closed-loop 3-DOF Crane Jib system, i.e. controlling the position of the trolley, using its derived state-space representation and a PID controller.
s_3d_crane_tower_pos_cntrl.mdl	Simulink file that simulates the closed-loop 3-DOF Crane Tower system, i.e. controlling rotation of tower, using its derived state-space representation and a PV controller.
q_3d_crane.mdl	Simulink file that implements the payload, jib, and tower position controller in real-time on the actual 3-DOF Crane device.
q_3d_crane_cal.mdl	Simulink file that calibrates the 3-DOF Crane to its home position.

Table 1 Supplied laboratory design files.

5. 3 DOF Crane Component Description

5.1. Component Nomenclature

Table 2, below, provides a list of all the principal components comprising the 3 DOF Crane package. Every component has a unique identification (ID) number that corresponds to a label in figures 2, 4, 3, 5, 6, 7, 8, and 9.

ID #	Description	ID #	Description
1	Base plate	21	Payload Motor
2	Tower	22	Payload Encoder
3	Jib	23	Payload motor pinion pulley
4	Cart	24	Payload motor output pulley
5	Steel Cable	25	Belt
6	Payload	26	Gimbal
7	Tower motor	27	Gimbal Y Encoder (γ)
8	Harmonic drive	28	Gimbal X Encoder (α)
9	Tower encoder	29	Payload limit switch
10	CCW tower limit switch	30	Steel Cable Sleeve (not shown)
11	CW tower limit switch	31	I/O Plate
12	CCW tower rocker safety switch	32	Tower Encoder Connector
13	CW tower rocker safety switch	33	Cart Encoder Connector
14	Cart Motor	34	Payload Encoder Connector
15	Cart Encoder	35	Gimbal X Encoder (α) Connector
16	Linear Guide	36	Gimbal Y Encoder (γ) Connector
17	CCP-RET Limit Switch (for cart)	37	Tower Motor Connector
18	CCP-EXT Limit Switch (for cart)	38	Jib Motor Connector
19	Payload Circuit Case	39	Trolley Motor Connector
20	Payload Pulley/Spool	40	Limit Switches Digital Connector

Table 2 3-DOF Crane Component Nomenclature.

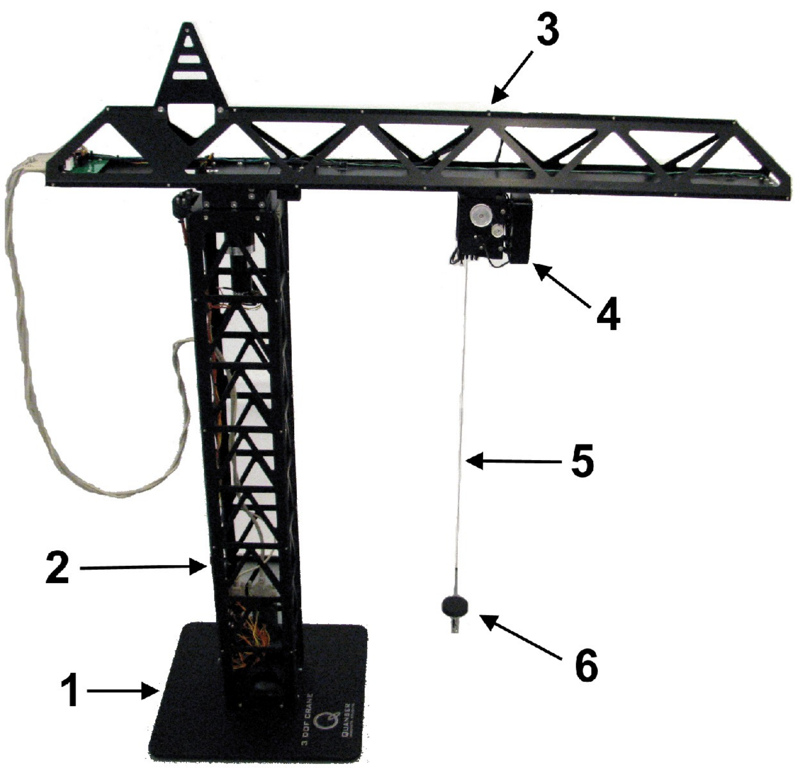


Figure 2: Main components on 3 DOF crane

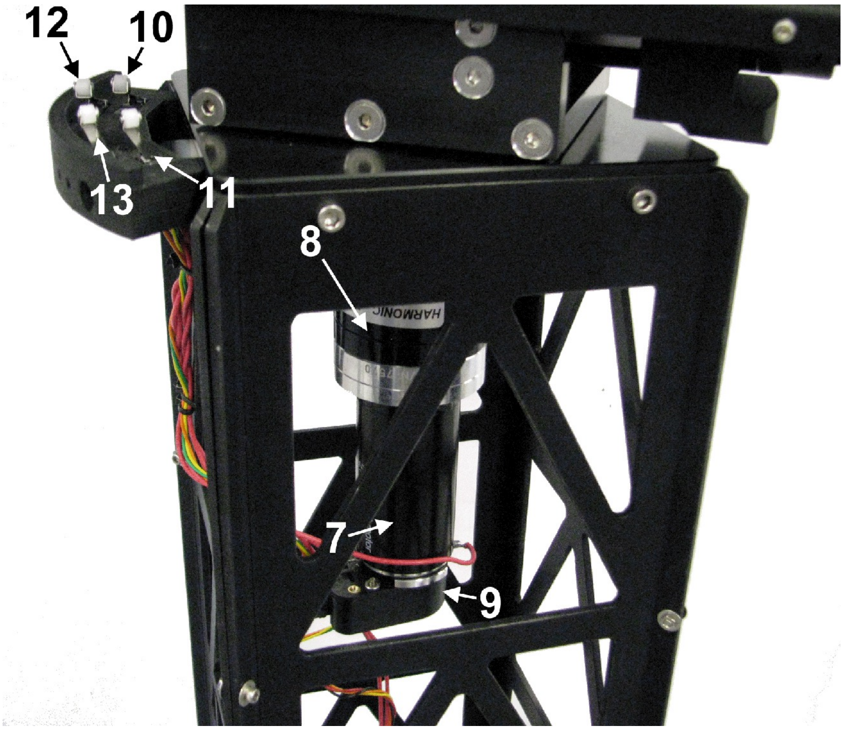


Figure 3: Tower motor and limits switches

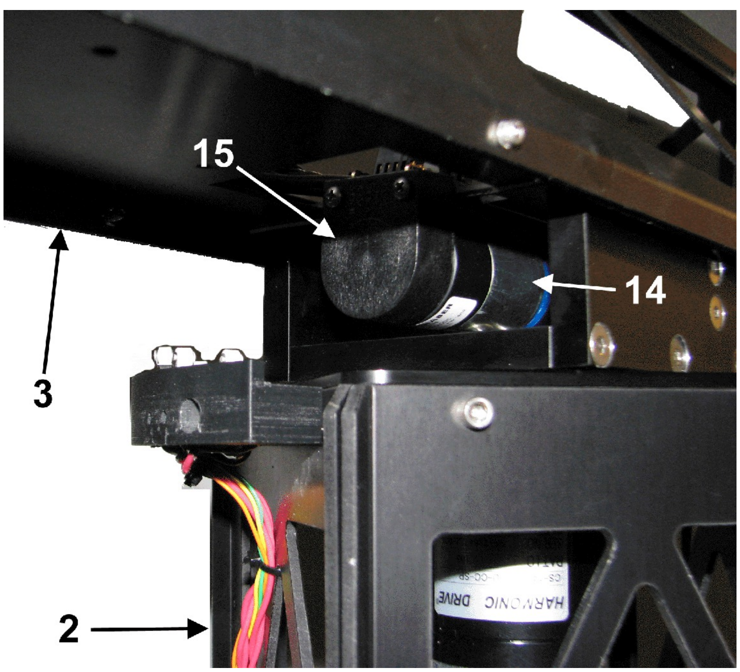


Figure 4: Trolley motor

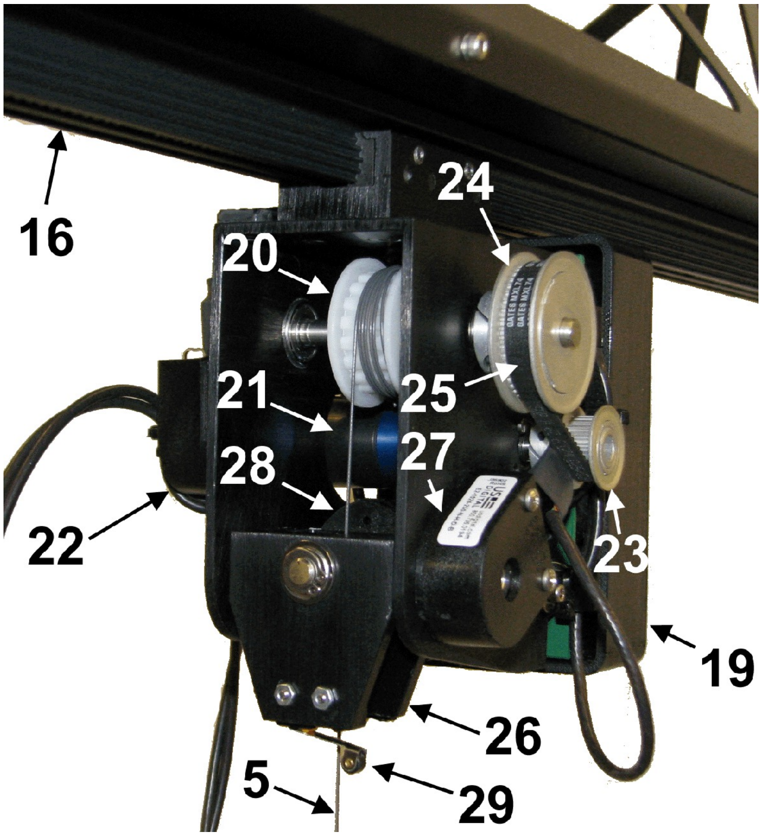


Figure 5: Components on cart

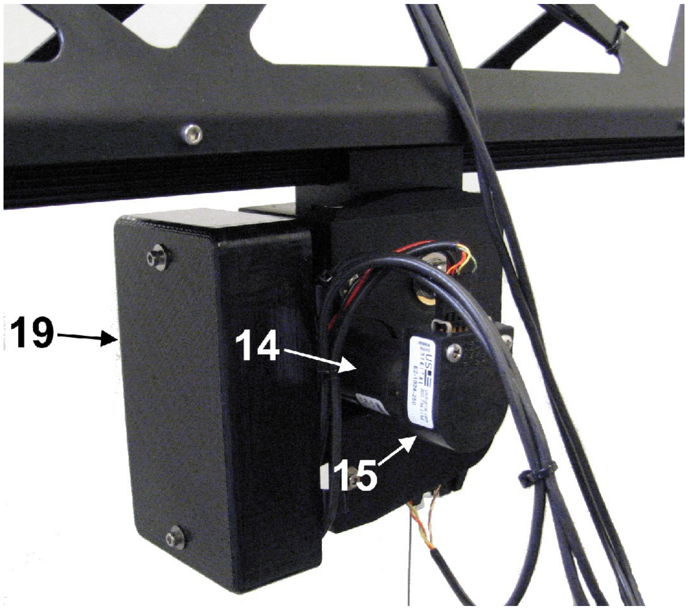


Figure 6: Components on motor-side of trolley

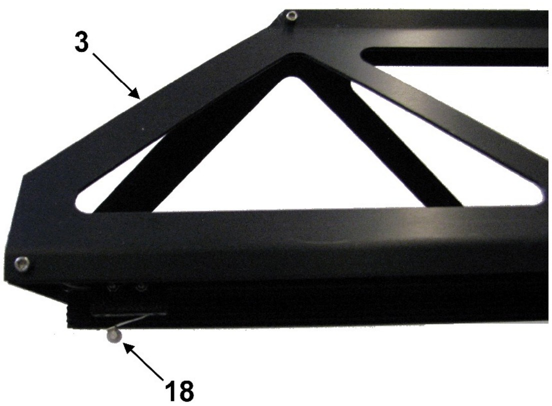


Figure 7: EXT limit switch

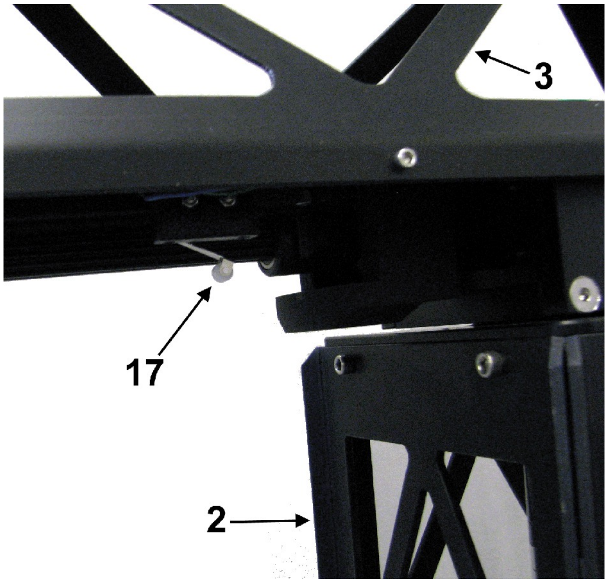


Figure 8: RET limit switch

Figure 9: Connector board

5.2. Component Description

The following is a brief description of the system components with the label IDs that are referenced in Table 2 with respect to figures 2, 4, 3, 5, 6, 7, 8, and 9. Table 8 lists and characterizes some of the components of the 3 DOF Crane system.

5.2.1. Tower

5.2.1.1. Motor and Encoder

The tower, or mast, of the 3 DOF Crane is the structure that stands vertically upright, perpendicular to the floor, as shown by ID #2 in Figure 2. It sits on top of a square baseplate, ID #1, that provides extra support to allow the tower to stand vertically upright. At the top end of the tower is a slewing unit that consists of a high quality dc motor (ID #7) a harmonic drive (ID #8), and an optical encoder (ID #9). The horizontal member that mounts on top of the slewing unit (discussed in the next subsection) is called the jib, ID #3. The motorized gear box actuates the jib to rotate either clockwise or counterclockwise by any amount, while the optical encoder measures angular rotation of the jib.

5.2.1.2. Tower Limit Switches

The tower had two limit switches that are shown in Figure 3: the counter-clockwise switch (ID #10) and the clockwise switch (ID #11). Each gets triggered when the mast rotates over and presses down on the switch. This is a digital signal that can be used by software for calibration and safety.

5.2.1.3. Tower Cut-Off Diodes

Furthermore, as shown in Figure 3, the tower has a clockwise (CW) rocker switch, ID #12, and a counter-clockwise (CCW) rocker switch, ID #13, that behave as a current cut-off diodes. These are hardware safety limiters. If the tower rotates and presses down on one of these switches the AMPAQ will stop supplying current to the tower motor in that direction. Thus if the tower is rotating CW and presses down on the CW switch then the tower will be unable to move further in the CW direction. However, the user can supply the opposite current to move the tower in the CCW direction. Remark that these are software-independent.

5.2.1.4. Cables

Cables and wires, that carry signals between the PC and the 3 DOF Crane, are mostly contained inside the tower. These cables and wires are primarily connected to the various motors and encoders on the horizontal member, located near the top of the tower. Most of the other ends of these cables and wires are connected to an input/output interface circuit board that is attached to the tower near its base.

5.2.2. Jib

The horizontal member that mounts on top of the tower is called the jib and is shown in Figure 2 by ID #3. As illustrated in Figure 4, the jib has a dc motor, ID #14, with an encoder, ID #15. The motor is drives a ball screw which used to position the cart, ID #4, along linear guide. The cart is anchored along the underside of the jib.

A stopping block at the tip of the jib is armed with a limit switch called the *CCP-Ext* limit switch, ID #18 in Figure 7. The block prevents the trolley from traveling off the guide and the limit switch can be used as a trigger to stop the controller or for calibration. The *CCP-Ret* limit switch, see component #17 pictured in Figure 8, is the return proximity sensor that detects if the trolley is at the starting point of the jib.

5.2.3. Cart

As shown in Figure 6, the cart (ID #6 in Figure 2) is equipped with a dc motor (ID #22) and an encoder (ID #6) to move the payload up and down. As depicted in Figure 5, the motor output shaft is connected to a pinion pulley, ID #23, that drives an output pulley, ID #24, through a belt, ID #25. This rotates the pulley or spools shown in Figure 5 by ID #20. The pulley is wound with a cable, ID #5, and the bottom of the cable is attached to a payload, ID #6. The pulley therefore acts as a spool that can reel in or reel out and thus change the height of the payload.

A gimbal, ID #26 in Figure 5, is attached near the bottom of the cart and it allows the cable to sway in any direction. There is a limit switch, shown by ID #29 in Figure 5, that is fastened to the bottom of gimbal. The sensor is triggered when the payload pressed down on the switch. This signal can be used to prevent the load from not being risen any further and for calibration.

The optical encoder shown by ID #27 in Figure 5 measures the swing of the cable when it swings lengthwise with the jib. The optical encoder identified by #28, measures the swing of the cable when the payload moves perpendicularly to the jib.

5.2.4. Input/Output Interface Plate (I/O Plate)

The I/O plate is shown in Figure 9. It is attached near the base of the crane's tower and has connector sockets that allow the 3 DOF Crane to interface directly with the data-acquisition terminal board and a Quanser AMPAQ Power Module.

5.2.5. AMPAQ Power Module

The AMPAQ Power Module, shown in Figure, is a pulse-width modulated current amplifier. It is used to drive the motors of the 3 DOF Crane. The power module's specifications are given in Table 3. The signal from the data-acquisition board are to be connected to the *Input* connector. The *Sense* connector outputs the current measured in the attached DC motor. The *Enable* connector socket of the AMPAQ receives digital input signals from the PC in order to enable or disable the power module. Finally, the amplified current is sent from the *Output* connector.

Each motor-driving amplified current signal from each *Output* socket of the AMPAQ has its own indicator LED. When a particular *Output* signal is enabled, such that that its corresponding crane motor, to which it is connected, can be actuated, then its corresponding LED lights up. When a particular *Output* signal is disabled, that is its connected crane motor cannot be actuated, then its corresponding LED stays shut off. For example, if the AMPAQ's *Output* #2 is enabled, then a crane motor that is connected to the *Output* 2 socket will be actuated; furthermore, the *Normal* #2 LED will become lit. If, however, *Output* #2 is disabled, then LED 2 will not light up, and the crane motor that is connected to the *Output* #2 socket will not be actuated.

Symbol	***Description***	***Value***	***Unit***
	AMPAQ Maximum Input Voltage Range Note: This value is for reference only; particular control signal levels will result in unique voltage input levels.	±10	V
	AMPAQ Maximum Input Current Note: This value is for reference only; particular loading will result in unique electrical current use.	25	mA
	AMPAQ Enable Ribbon Cable Signals' Voltage Range	0 to 5	V
	AMPAQ Enable Ribbon Cable Signals Electrical Current (Absolute Maximum Value)	1	mA
	External Power Source RMS Voltage Required to Operate AMPAQ.	120/240	V
	External Power Source Voltage Frequency Required to Operate AMPAQ	60/50	Hz
V_{A_SUP}	AMPAQ Supply Voltage	27	V
V_{A_RNG}	AMPAQ Voltage Input Range	±10	V
K_a	AMPAQ Gain	0.5	A/V

Symbol	Description	Value	Unit
I_{MAX}	AMPAQ Maximum Peak Output Note: This value is for reference only; particular motor resistance and loading will result in unique electrical current sourcing levels.	7	A
$I_{MAX,CONT}$	AMPAQ Continuous Output Current	2.15	A
B	Current Amplifier Bandwidth (in Current Mode, with 3 DOF Crane Motor Stalled; for 0, 1, or 2; inside AMPAQ)	500	Hz
S_{AMP_SEN}	Current Sensor Sensitivity (for 0, 1, or 2; inside AMPAQ)	2.0	A/V

Table 3 AMPAQ specifications.

5.2.6. Cables

The various cables in the 3-DOF Crane package are described in Table 9.

⚠ **Many of the components that are included with your 3 DOF Crane package have screws that allow you to attach them securely to the shafts of the 3 DOF Crane. Be sure to use the supplied set of Allen keys (that are included with you 3 DOF Crane package) to securely attach these components to the 3 DOF Crane shafts, for the various experiments. These components include pulleys, tensioners, inertia masses, hubs and hub flanges.**

6. 3-DOF Crane Modeling and System Parameters

The tower, cart/jib, and payload related specifications of the 3 DOF Crane system are listed in tables 4, 5, and 6. The moment of inertia about the pivots is given in Table 7 and the dimensions of various components is listed in Table 8.

Symbol	Matlab Notation	Description	Value	Unit
$K_{t,t}$	Kt_t	Tower Motor Torque Constant (before Gear Ratio)	8.93	N.m/A

Symbol	*Matlab Notation*	*Description*	*Value*	*Unit*
K_{emb}		Tower Motor Back-Emf Constant	0.119	V.s/rad
$R_{m,t}$		Tower Motor Terminal Resistance	11.5	Ω
$L_{m,t}$		Tower Motor Terminal Inductance	3.16	mH
Jm		Rotor Moment of Inertia	1.02e-6	$kg.m^2$
$J_{m,t}$	Jm_t	Equivalent Rotor Moment Of Inertia (after Gear Ratio)	0.0102	$kg.m^2$
$T_{max,c}$		Max Continuous Torque (at Gearbox Output)	8.6	N.m
$T_{max,p}$		Peak Torque (at Gearbox Output)	22.6	N.m
$K_{g,t}$	Kg_t	Tower Motor Gearbox Gear Ratio	100:1	
$\mu_{g,t}$	eff_g_t	Tower Motor Gearbox Efficiency	1.00	
$I_{m,c}$		Tower Motor Maximum Continuous Current	0.943	A
$I_{m,p}$		Tower Motor Maximum Peak Current	4.1	A
$S_{PPR,\theta}$		Tower encoder resolution (quadrature)	4096	counts/rev
$K_{enc,\theta}$	K_ENC_THETA	Tower position sensitivity gain	1.534e-5	m/rev

Table 4: Tower motor and encoder specifications

Symbol	*Matlab Notation*	*Description*	*Value*	*Unit*
$K_{t,j}$	Kt_j	Cart Motor Torque Constant (before Gear Ratio)	0.0396	N.m/A
$R_{m,j}$		Cart Motor Terminal Resistance	6.8	Ω
$L_{m,j}$		Cart Motor Terminal Inductance	0.620	mH
$J_{m,j}$	Jm_j	Cart Motor Rotor Inertia	1.63e-07	$kg.m^2$
$K_{g,j}$	Kg_t	Cart Motor Gearbox Gear Ratio	3.7:1	
$\eta_{g,j}$	eff_g_j	Cart Motor Gearbox Efficiency	0.95	

Symbol	Matlab Notation	Description	Value	Unit
$V_{m,j}$		Cart Motor Rated Voltage	12	V
P_t	Pt	Ball screw pitch	0.0127	m/rev
$S_{PPR,J}$		Cart encoder resolution (quadrature)	4096	counts/rev
$K_{enc,x}$	K_ENC_X	Cart position sensitivity gain (with direction convention)	-8.38e-07	m/rev
l_j	lj	Max distance of trolley from pivot	0.8065	m

Table 5: Cart related specifications

Symbol	Matlab Notation	Description	Value	Unit
$K_{t,y}$	Kt_y	Payload Motor Torque Constant (before Gear Ratio)	0.0261	N.m/A
$\mu_{m,y}$	eff_m_y	Payload Motor Efficiency	1.00	
$K_{g,y,i}$	Kg_y_i	Motor gearbox (internal gear ratio)	14:1	
$K_{g,y,e}$	Kg_y_e	Motor to pulley gear ratio (external)	2:1	
$K_{g,y}$	Kg_y	Equivalent gear ratio from motor to pulley	28:1	
$\mu_{g,y}$	eff_y_t	Payload Motor Gearbox Efficiency	1.00	
$J_{m,y}$	Jm_y	Equivalent Rotor Moment Of Inertia (after Gear Ratio)	5.8e-7	$kg.m^2$
$r_{y,reel}$	r_y_reel	Radius of payload reel (moves payload up and down)	0.0148	m
$m_{y,reel}$	m_y_reel	Mass of payload reel (moves payload up and down)	0.030	kg
$S_{PPR,Z}$		Payload encoder resolution (quadrature)	4096	counts/rev
$K_{enc,z}$	K_ENC_Z	Payload position sensitivity gain (with direction convention)	-7.83e-07	m/rev

Symbol	Matlab Notation	Description	Value	Unit
$S_{PPR,\alpha}$		Gimbal X encoder resolution (quadrature)	4096	counts/rev
$K_{enc,\alpha}$	K_ENC_ALPHA	Gimbal X position sensitivity gain	0.0015	m/rev
$S_{PPR,\gamma}$		Gimbal Y encoder resolution (quadrature)	4096	counts/rev
$K_{enc,\gamma}$	K_ENC_GAMMA	Gimbal Y position sensitivity gain	0.0015	m/rev
l_p	lp	Vertical distance of payload from jib arm	0.8636	m
m_p	mp	Mass of the payload (each weight is 0.12 kg).	0.147	kg

Table 6: Payload related specifications

Symbol	Matlab Notation	Description	Value	Unit
J_θ	J_theta	Tower motor equivalent moment of inertia.	0.8872	$kg.m^2$
J_ψ	J_psi	Jib motor equivalent moment of inertia.	9.14e-7	$kg.m^2$
J_ϕ	J_phi	Trolley motor equivalent moment of inertia.	3.64e-6	$kg.m^2$
J_α	J_alpha	Equivalent moment of inertia acting at gimble angle α.	0.00	$kg.m^2$
J_γ	J_gamma	Equivalent moment of inertia acting at gimble angle γ.	0.00	$kg.m^2$

Table 7: Moment of inertia about each pivot

Symbol	Matlab Notation	Description	Value	Unit
L_S		Length of one side of Tower (base of Tower forms a Square, so all sides are of same length)	0.1475	m
L_B		Length of one side of Square Baseplate	0.405	m
L_E		Effective (Available) Length of Trolley Track	0.75	m
L_W		Length of Tower (i.e. Vertical Member) (excluding thickness of Baseplate + Rubber Feet)	1.202	m
H_T		Thickness of Baseplate	0.01	m
H_F		Thickness of one Rubber Foot (total of four Rubber Feet mounted at bottom near each corner of Baseplate)	0.00735	m
W_J		Width of Jib's Base	0.12	m
H_J		Height of Jib (from Base to Top)	0.115	m
L_J		Total Length of Jib (i.e. Horizontal Member)	1.205	m
L_Y		Length of Trolley's Side (this side is parallel to the track and travels along it)	0.0575	m
W_K		Width of Track under Jib (outer Rail to outer Rail)	0.04845	m

Table 8 3 DOF Crane component dimensions

7. Hardware Setup Procedure

This section describes the standard procedure to safely set up the mechanical components of the 3 DOF Crane system. The 3 DOF Crane is packaged essentially as two members: the *tower* (vertical member) and the *jib* (horizontal member). Follow the steps described below to set up the 3 DOF Crane's electromechanical assembly:

1. As shown in Figure 10, there are four screw holes at the bottom of the base plate. Align the holes near the center of the base plate with those at the bottom of the tower structure and tighten the screws to fasten the base plate to the tower.

Figure 10 Screws at the bottom of the base plate.

2. Place the 3 DOF Crane's tower on its base plate, such that it stands vertically upright, on a **very smooth, sturdy and flat floor that can safely handle the weight of the complete 3 DOF Crane system plus the weight of the supplied accessories and components that came with the system**. The 3 DOF Crane and its components are heavy; therefore, a very smooth, sturdy and flat horizontal floor surface should be used to set up this system, and perform experiments on it.
3. The top of tower without the jib is shown in Figure 11. Notice there are 3x screw holes on each side of the square motor flange.

Figure 11: Top of tower shown without the jib installed.

4. The underside of the jib is shown in Figure 12. The jib motor is encased in the chassis with 3x screw holes on each side.

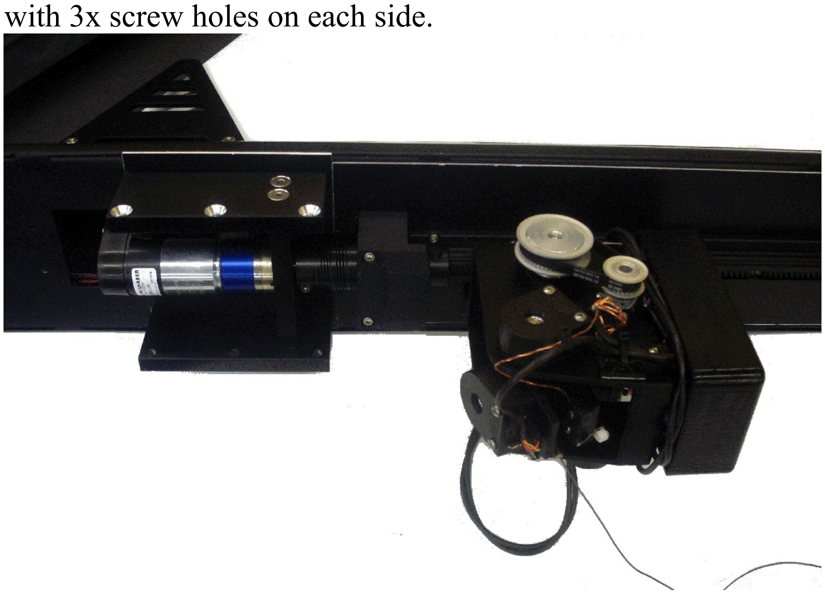


Figure 12: Underside of jib.

5. Mount the jib onto the tower. **Make you have two people doing this**. One person to support the jib and the other to align the jib chassis onto the square motor flange of the

tower. Make sure the trolley motor is closes to the limit switches on the tower.

6. Use the provided 1/8 inch Allen key and the tighten the 3x screws on each side of the jib to fasten the jib onto the tower, as depicted in Figure 13.

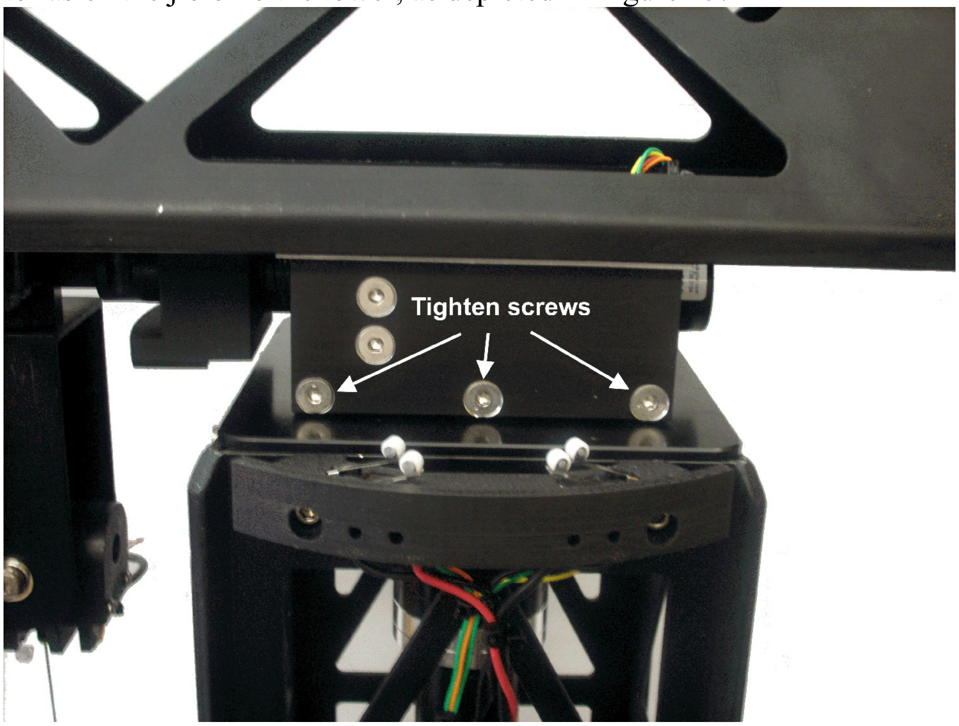


Figure 13: Tighten the jib screws.

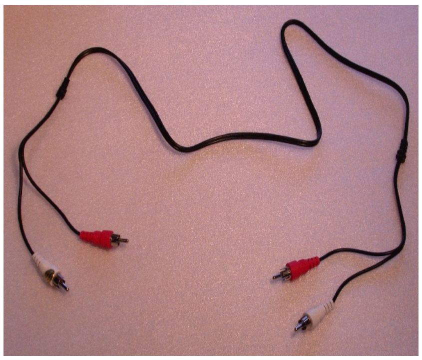
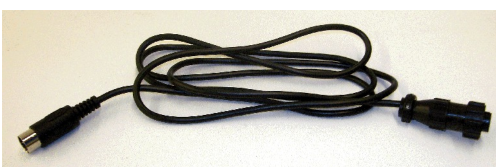
7. Thereafter, make sure the all 6x screws are tightened on each side of the jib (i.e. the 2x top screws that were not used previously may need to be tightened).
8. **Clear all space, on the floor, around the 3-DOF Crane, and never attach or place any things, other than the intended components, near or on the 3 DOF Crane itself.**
9. Four screws or nails can be used to further secure the baseplate of the crane's tower to the floor by using each of the four holes near the base plate’s rounded corners. This step is optional.

8. 3 DOF Crane Wiring Procedure

This section describes the standard wiring procedure for the 3 DOF Crane system.

8.1. Cable Nomenclature

Table 9, below, provides a description of the standard cables used in the wiring of the 3 DOF Crane system.

Cable	*Description*
 Figure 14 Analog Input/Output Cable.	The "Analog Input/Output Cable" is actually two separate RCA cables. Each of these separate cables has a male connector at both ends. One of these separate cables has red connectors while the other has white connectors, to distinguish them from one another and to emphasize their independence. An analog signals from the HIL terminal board to the AMPAQ is carried through one of these separate cables, while another analog signal from the AMPAQ is carried through the other separate cable to the DAQ terminal board. In other commercial or industrial applications, the Analog Input/Output cable is sometimes referred to as "Stereo RCA Cables".
 Figure 15: AMPAQ to Motor Cable	This is a Motor Cable. It has a 4-pronged male connector at one end and a 4-pin male DIN connector at the other end. The AMPAQ-side connector is keyed so that they can be plugged in only one way. It also has a screw-able rotating cover that allows it to be screwed securely to its corresponding mating connector. Each Motor Cable is meant to carry a current amplified signal from the AMPAQ to one of the motors of the 3 DOF Crane.

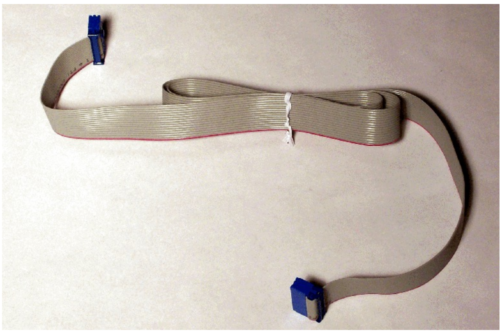
Cable	Description
 Figure 16 Ribbon cable.	Two 16 wire ribbon cables are supplied. The cables have identical female connectors at both ends and are keyed such that it can be plugged in only one way. One cable connects the AMPAQ to the DAQ terminal board. This carries the enable signals from the PC to the AMPAQ to allow and disallow the amplified motor signals to be available at the output sockets. The other cable connects the DAQ terminal board to the 3 DOF Crane and it carries the limit switch signals: *BCP L/R*, *Jib Ret*, *Jib Ext*, and *Payload*.
 Figure 17 Encoder cable.	The Encoder cable is a 5-pin-stereo-DIN-to-5-pin-stereo-DIN cable. It can directly connect the 3 DOF Crane's encoders to the data-acquisition terminal board. This cable carries the encoder signals and encoder DC power supply.

Table 9 Cable Nomenclature

8.2. Typical Connections for the 3-DOF Crane System

This section goes through the procedure to to set up the 3 DOF Crane system. Figures 18, 19, and 36 illustrate the connections needed. The labels used in these figures are explained in Table 10, which provides a summary of the 3 DOF Crane wiring. The steps below provide more information about the various connections. After the wiring and cabling connections are made, the 3 DOF Crane system can be used to perform the control experiments that are described in this manual.

1. **Ensure the PC and the AMPAQ are powered off prior to making these connections!** In particular, never attempt to hot swap encoder signals. Encoder signals carry power from the PC to the encoder and thus are susceptible to current surge that could potentially damage the encoder, HIL card or the PC.
2. Connect the DB-9 and DB-25 connectors from the jib to the female DB-9 and DB-25 connectors mounted on the black tower cable, as depicted in Figure 18.
3. The connections between the Quanser 3 DOF Crane, the data-acquisition terminal board, and the AMPAQ power amplifier are depicted in Figure 19 and summarized in Table 10.

This shows how to connect the 2 ribbon cables, the 5 Encoder cables, the 3 Analog Output cables, and the 3 Analog Input cables.

Cable #	*Cable Type*	*From*	*To*	*Signal*
1	DB-9 cable	Jib	DB-9 Connector on Tower	Trolley and payload motor signals.
2	DB-25 cable	Jib	DB-25 Connector on Tower	Trolley, payload, and gimbal encoder signals as well as the *Tower CW, Tower CCW*, *Jib Ret*, *Jib Ext*, and *Payload* limit switches.
3	Ribbon cable	DIO0 on Terminal Board	*Enable* on AMPAQ	Enable/disable motors
4	Ribbon cable	DIO1 on Terminal Board	*Limit Switches* on Crane	Reads limit switches on crane.
5	RCA Cable	Analog Output #0 on Terminal Board	*Input #0* on AMPAQ	Tower motor amplifier command.
6	RCA Cable	Analog Output #1 on Terminal Board	*Input #1* on AMPAQ	Cart motor amplifier command.
7	RCA Cable	Analog Output #2 on Terminal Board	*Input #2* on AMPAQ	Payload motor amplifier command.
8	RCA Cable	Analog Input #0 on Terminal Board	*Sense #0* on AMPAQ	Measured current in tower motor.
9	RCA Cable	Analog Input #1 on Terminal Board	*Sense #1* on AMPAQ	Measured cart motor current.
10	RCA Cable	Analog Input #2 on Terminal Board	*Sense #2* on AMPAQ	Measured payload motor current.

Cable #	Cable Type	From	To	Signal
11	Encoder Cable	*Tower Encoder* Connector on 3 DOF Crane	Encoder Input #0 on Terminal Board	Tower motor encoder used to measure angle of rotating tower, θ.
12	Encoder Cable	*Cart Encoder* Connector on 3 DOF Crane	Encoder Input #1 on Terminal Board	Cart motor encoder used to measure cart displacement, x.
13	Encoder Cable	*Payload Encoder* Connector on 3 DOF Crane	Encoder Input #2 on Terminal Board	Payload motor encoder used to measure height of payload, z.
14	Encoder Cable	*Gimbal X Encoder* Connector on 3 DOF Crane	Encoder Input #3 on Terminal Board	Measures angle of load swinging transversely with jib, γ.
15	Encoder Cable	*Gimbal Y Encoder* Connector on 3 DOF Crane	Encoder Input #4 on Terminal Board	Measures angle of load swinging inline with jib, α.
16	Motor Cable	*Output #0* on AMPAQ	*Tower Motor* Connector on 3 DOF Crane	Amplified signal to tower motor.
17	Motor Cable	*Output #1* on AMPAQ	*Cart Motor* Connector on 3 DOF Crane	Amplified signal to cart motor.
18	Motor Cable	*Output #2* on AMPAQ	*Payload Motor* Connector on 3 DOF Crane	Amplified signal to payload motor.

Table 10 3 DOF Crane System Wiring Summary

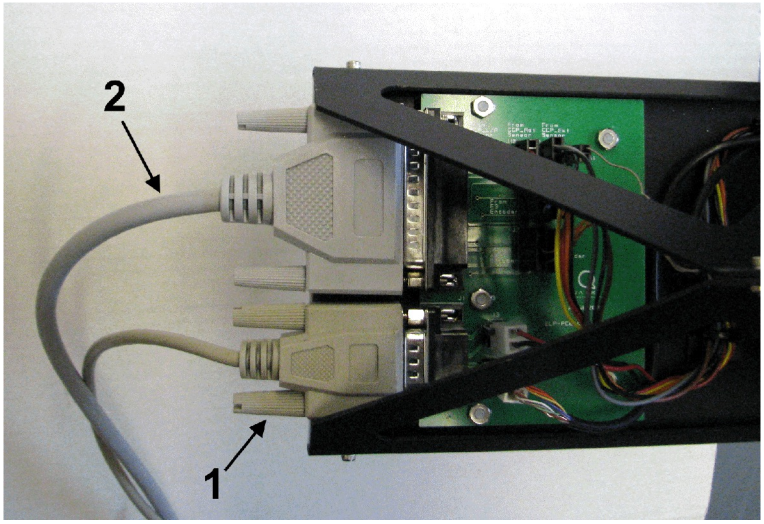


Figure 18: 3 DO Crane tower to jib connections.

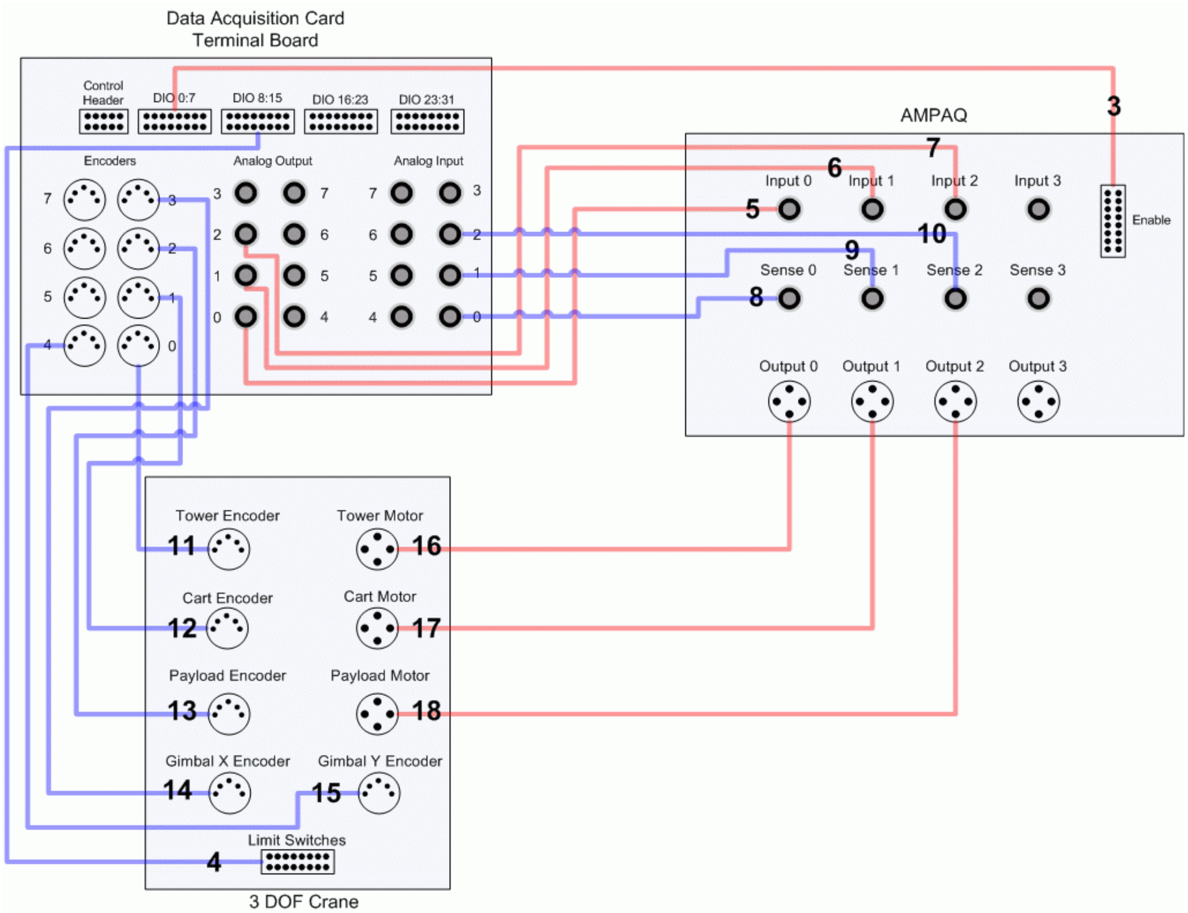


Figure 19: Connections between 3 DOF Crane, AMPAQ, and data-acquisition board.

9. System Modeling and Control Design

In this section, a decoupled joint-based position control is developed for the 3-DOF Crane plant. The 3-DOF Crane plant is separated into three subsystem: payload, jib, and tower.

The payload subsystem includes the trolley motor assembly and the payload mass. In Section 9.1, a feedback system is designed to control the height of the payload. The jib is discussed in Section 9.2. It develops a control system to control the position of the trolley while keeping the swings of the payload, that are inline with the jib, at a minimum. In Section 9.3, a feedback algorithm is designed to rotate the tower to a desired angle, i.e. move the jib, and try to maintain the swings that are perpendicular to the jib in the payload small.

9.1. Payload Subsystem

9.1.1. Modeling the Payload Position

In this section, an open-loop transfer function describing the relationship between the input current of the trolley motor and the vertical position of the payload is developed. The free-body diagram of the system is depicted in Figure 20. The top circle represents the pulley or the reel that is mounted on the trolley motor. When a positive current is applied to the trolley motor, the reel rotates clockwise and lifts the payload. The vertical position of the payload is zero when the cable is fully extended and increases positively as the payload elevates. The distance between the pivot where the encoder measurement is made and the center of mass of the payload is l_p.

As described by Figure 20, the equation representing the motions of the payload is

$$m_p \left(\frac{d^2}{dt^2} \mathrm{z}(t) \right) + f_{ai}(t) = f_y(t) - m_p\, g - B_y \left(\frac{d}{dt} \mathrm{z}(t) \right) - f_{coulomb}(t) \qquad [1]$$

where m_p is the mass of the payload, z is the vertical position of the payload, f_{ai} is the force generated by the inertia of the spinning reel, f_y is the force generated by the trolley motor, g is the gravitational acceleration constant, B_y is the viscous damping parameter, $f_{coulomb}$ is the force from the Coulomb friction, i.e. dry friction.

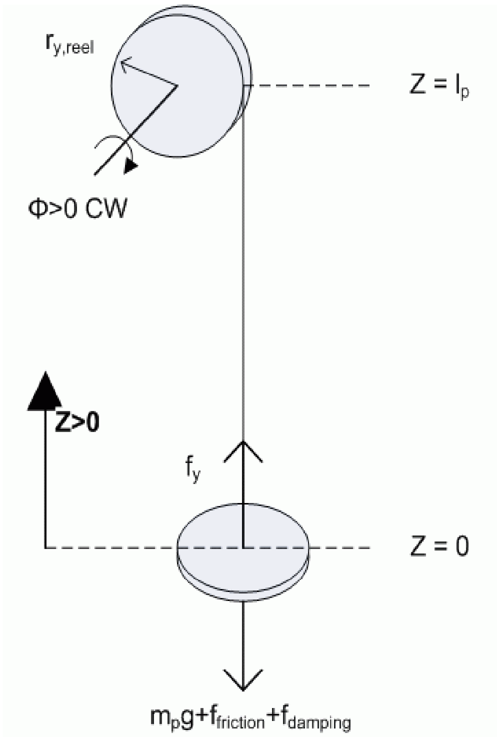


Figure 20 Modeling the payload position.

The Coulomb friction is discontinuous about zero and will be neglected in order to construct a continuous Laplace model of the system, thus set

$$f_{coulomb}(t) = 0 \quad . \tag{2}$$

In addition, the viscous damping is assumed to be negligible

$$B_y = 0 \quad . \tag{3}$$

The equation of motion given in [1] therefore simplifies to

$$m_p \left(\frac{d^2}{dt^2} z(t) \right) + f_{ai}(t) = f_y(t) - m_p\, g \tag{4}$$

and its corresponding Laplace transform is

$$m_p\, s^2\, Z + F_{ai} = F_y - \frac{m_p\, g}{s} \tag{5}$$

where $Z=Z(s)$, F_y, and F_{ai} are the Laplace representations of z, f_y, and f_{ai}, respectively. For the trolley motor parameters $\eta_{g,y}$, $K_{g,y}$, $\eta_{m,y}$, and $K_{t,y}$ defined in Table 8, the linear force generated by the trolley motor with respect to its input current $I_{m,y}$ is

$$F_y = \frac{\eta_{g,y} K_{g,y} \eta_{m,y} K_{t,y} I_{m,y}}{r_{y,\,wheel}}. \tag{6}$$

The force from the inertia of the reel on the trolley needs to be defined with respect to Z(s). Consider the torque generated by the inertia of the spool

$$\tau_{ai} = J_\phi \left(\frac{d^2}{dt^2} \phi(t) \right), \tag{7}$$

where $\phi(t)$ is the angle of the reel and J_ϕ is the moment of inertia of the reel. From the sector formula, the relationship between the linear position of the payload and the angle of the reel is

$$\phi(t) = \frac{z(t)}{r_{y,\,reel}}. \tag{8}$$

Given the torque, the linear force acting on the mass is

$$f_{ai} = \frac{\tau_{ai}}{r_{y,\,reel}}. \tag{9}$$

Substitute Equation [8] into [7] and the resulting expression into [9] to obtain the linear force due to the rotation of the reel with respect to z(t),

$$f_{ai} = \frac{J_\phi \left(\frac{d^2}{dt^2} z(t) \right)}{{r_{y,\,reel}}^2}. \tag{10}$$

The corresponding Laplace transform of this force is

$$F_{ai} = \frac{J_\phi s^2 Z}{{r_{y,\,reel}}^2}. \tag{11}$$

Substitute motor force expression [6] and the reel inertia force [11] into [5] to get the final payload equation of motion

$$\left(m_p + \frac{J_\phi}{r_{y,\,reel}^{\;2}}\right) Z\,s^2 = \frac{\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,I_{m,\,y}}{r_{y,\,reel}} - \frac{m_p\,g}{s} \qquad [12]$$

The open-loop trolley motor input current to payload position transfer function is therefore

$$\mathrm{Z}(s) = \frac{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,I_{m,\,y}(s)}{s^2\,(m_p\,r_{y,\,reel}^{\;2} + J_\phi)} - \frac{r_{y,\,reel}^{\;2}\,m_p\,g}{s^3\,(m_p\,r_{y,\,reel}^{\;2} + J_\phi)} \qquad [13]$$

9.1.2. PIV Control Design

The position of the payload is controlled using a proportional-integral-velocity compensator, or PIV. It is described by the feedback loop shown in Figure 21. The PIV loop differs from the more common PID compensator by using only the velocity of the state instead of using the velocity, or derivative, of the error.

The PIV compensator enters the trolley motor input current $I_{m,y}$ and is written

$$I_{m,\,y}(s) = \left(k_p + \frac{k_i}{s}\right)(Z_d(s) - \mathrm{Z}(s)) - k_v\,s\,\mathrm{Z}(s) \qquad [14]$$

where $Z_d(s)$ is the Laplace of the payload position setpoint, k_p is the proportional gain k_p, k_i is the integral gain, and k_v is the velocity gain.

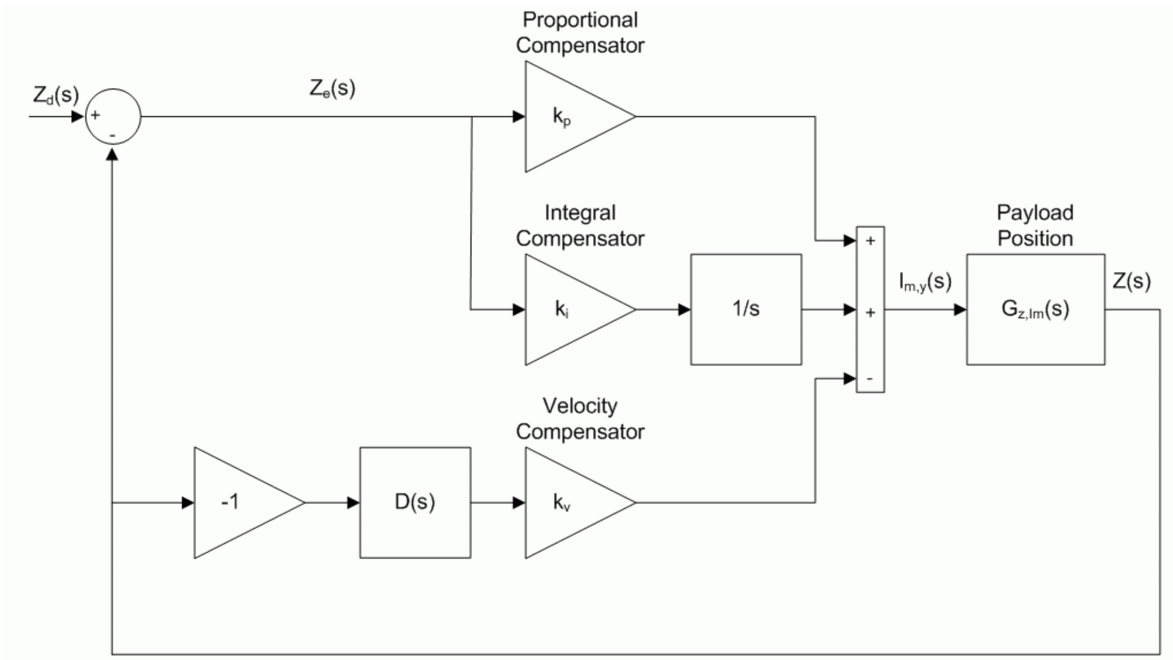


Figure 21 PIV control loop to control position of payload.

Since there is no sensor measuring the speed of the payload directly, it must be derived using the measured position. For control design purposes, the straight derivative is used. However as depicted in Figure 21 with D(s) and when implementing the controller, a high-pass filter is used to obtain the velocity from the encoder. Taking the straight derivative of an encoder measurement can result in a very noisy velocity calculation. The transfer function of the first-order high-pass filter is of the form

$$V_z(s) = \frac{\omega_f^2 \, s \, Z(s)}{s + \omega_f} \qquad [15]$$

where $V_z(s)$ is the filtered derivative of the measured payload position Z(s) and ω_f is the cutoff frequency. This high-gain observer method is used to obtain the velocity of all the position measurements in the 3 DOF Crane system.

Substitute the controller into open-loop transfer function [13] and solve for Z(s) to get the $Z(s)/Z_d(s)$ closed-loop model of the payload position

$$\begin{aligned} Z(s) = {} & r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,(k_p\,s + k_i) \Big/ (s^3\,(m_p\,r_{y,\,reel}^{\;2} + J_\phi) \\ & + r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,k_v\,s^2 + r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,k_p\,s \\ & + r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,k_i) \end{aligned} \qquad [16]$$

This does not include the unactuated part from gravity. The characteristic equation of this system is

$$s^3 + \frac{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,k_v\,s^2}{m_p\,r_{y,\,reel}^{\;\;2} + J_\phi} + \frac{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,k_p\,s}{m_p\,r_{y,\,reel}^{\;\;2} + J_\phi} + \frac{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}\,k_i}{m_p\,r_{y,\,reel}^{\;\;2} + J_\phi}. \qquad [17]$$

The general third-order characteristic equation is

$$(s^2 + 2\,\zeta\,\omega_0\,s + \omega_0^{\;2})\,(s + p_0) = s^3 + (2\,\zeta\,\omega_0 + p_0)\,s^2 + (\omega_0^{\;2} + 2\,\zeta\,\omega_0\,p_0)\,s + \omega_0^{\;2}\,p_0 \qquad [18]$$

where ω0 is the natural frequency, ζ is the damping ratio, and p_0 the location of a pole. These three parameters are the specifications of the controller. The natural frequency primarily affects the speed of the response and the damping ratio affects the amount of overshoot. The pole location generally determines the amount of integral action used. For the obtained characteristic equation in [17] to match the generalized equation in [18], the PIV gains must be

$$k_p = \frac{\omega_0\,(2\,\zeta\,p_0\,J_\phi + \omega_0\,m_p\,r_{y,\,reel}^{\;\;2} + \omega_0\,J_\phi + 2\,\zeta\,p_0\,m_p\,r_{y,\,reel}^{\;\;2})}{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}}, \qquad [19]$$

$$k_i = \frac{\omega_0^{\;2}\,p_0\,(m_p\,r_{y,\,reel}^{\;\;2} + J_\phi)}{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}} \qquad [20]$$

and

$$k_v = \frac{p_0\,J_\phi + 2\,\zeta\,\omega_0\,m_p\,r_{y,\,reel}^{\;\;2} + 2\,\zeta\,\omega_0\,J_\phi + p_0\,m_p\,r_{y,\,reel}^{\;\;2}}{r_{y,\,reel}\,\eta_{g,\,y}\,K_{g,\,y}\,\eta_{m,\,y}\,K_{t,\,y}}. \qquad [21]$$

The next step is to calculate the PIV gains needed to satisfy a set of time-domain requirements. Consider the following maximum peak time, maximum percentage overshoot, and pole location closed-loop response specifications:

$t_p = 0.02$, $PO = 10$, and $p_0 = 0.125$. [22]

Given the peak time equation

$$t_p = \frac{\pi}{\omega_0 \sqrt{1-\zeta^2}} \qquad [23]$$

and percentage overshoot equation

$$PO = 100\, \mathbf{e}^{\left(-\frac{\zeta \pi}{\sqrt{1-\zeta^2}}\right)} \qquad [24]$$

it can be found that the minimum damping ratio and natural frequency required to meet these requirements are

$$\omega_0 = 194.8 \left[\frac{rad}{s}\right] \qquad [25]$$

and

$$\zeta = 0.591 \, . \qquad [26]$$

Substituting the p_0 specification in [22], the natural frequency in [25], the damping ratio in [26], and the various model parameters in Table 8 into the equations [19], [20], and [21] gives the PIV gains needed to meet the closed-loop specifications

$$k_p = 151.1 \left[\frac{A}{m}\right] , \qquad [27]$$

$$k_i = 18.9 \left[\frac{A}{m\, s}\right] \qquad [28]$$

and

$$k_v = 0.917 \left[\frac{A\, s}{m}\right] . \qquad [29]$$

9.2. Jib System

9.2.1. Modeling the Jib Plant

The jib is modeled as a two-dimensional linear gantry by assuming the payload is at a fixed height and is also fixed about the α gimble angle, which is the motion perpendicular to the jib length. In other words, it is assumed the payload only rotates about gimble angleγ. In this section, the linear state-space representation of the 3 DOF Crane Jib subsystem is only summarized. For the complete details of the derivation, see the Maple worksheet called *3D Crane Jib Equations.mws* or its corresponding HTML output *3D Crane Jib Equations.html*.

As explained in Section 5, the jib is the horizontal member of 3 DOF crane. The trolley is suspended on a linear guide and is fastened to a motorized belt-pulley device. When the current in the DC motor, $I_{m,j}$, is positive the trolley moves away from the tower and towards the end of the jib. This is defined as positive velocity. Thus the position of the trolley, x_j, increases positively as it goes towards the right of the free-body diagram shown in Figure 22.

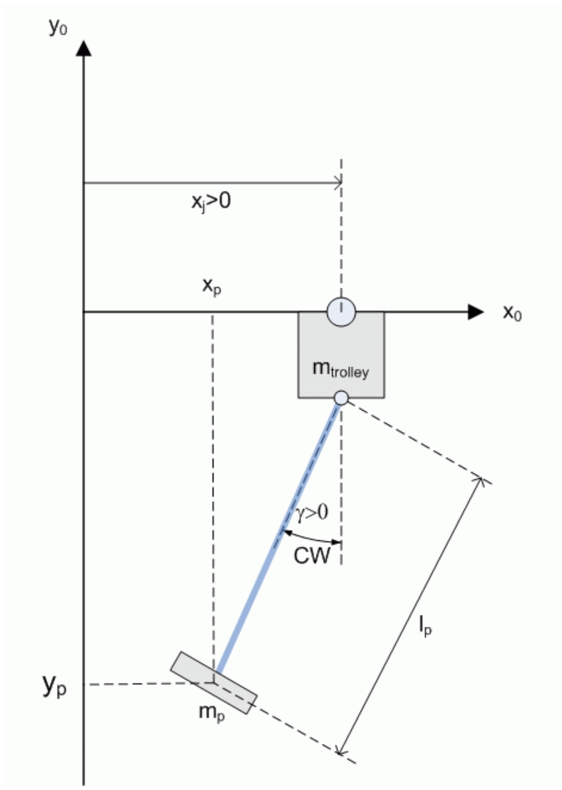


Figure 22 Free-body diagram of jib system.

The payload is connected to the trolley with a steel cable. Assuming the cable remains rigid, the payload is modeled as a suspended pendulum. As illustrated in Figure 22, when the trolley goes positive towards the right the pendulum angle, γ, turns clockwise. This is defined as positive rotational velocity.

Using Figure 22, the position of the payload's center of mass with respect to the Cartesian coordinate system Ox_0y_0 is

$$x_p := x_j(t) - l_p \sin(\gamma(t)) \qquad [30]$$

and

$$y_p := -l_p \cos(\gamma(t)) \qquad [31]$$

The system is modeled as a cart with a suspended pendulum, i.e. linear gantry plant. As detailed in the Maple worksheet, the Lagrange method is used to find the nonlinear dynamics of the system. The nonlinear system of equations are also linearized and represented in state-space format. When ignoring the rotational kinetic energy from the pendulum, i.e. effectively setting $J_\gamma = 0$, the linear state-space system of the 3 DOF Crane Jib system is

$$\frac{\partial}{\partial t} x = A\,x + Bu \qquad [32]$$

$$y = C\,x + \mathrm{D}\,u \qquad [33]$$

where

$$x^T = \left[x_j(t), \gamma(t), \frac{d}{dt} x_j(t), \frac{d}{dt}\gamma(t) \right] \qquad [34]$$

and the matrices are

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\dfrac{m_p\, r_{j,pulley}^2\, g}{m_{trolley}\, r_{j,pulley}^2 + J_\psi\, K_{g,j}^2} & 0 & 0 \\ 0 & -\dfrac{g\,(m_{trolley}\, r_{j,pulley}^2 + m_p\, r_{j,pulley}^2 + J_\psi\, K_{g,j}^2)}{(m_{trolley}\, r_{j,pulley}^2 + J_\psi\, K_{g,j}^2)\, l_p} & 0 & 0 \end{bmatrix}, \qquad [35]$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \dfrac{r_{j,pulley}\, \eta_{g,j}\, K_{g,j}\, \eta_{m,j}\, K_{t,j}}{m_{trolley}\, r_{j,pulley}^2 + J_\psi\, K_{g,j}^2} \\ \dfrac{r_{j,pulley}\, \eta_{g,j}\, K_{g,j}\, \eta_{m,j}\, K_{t,j}}{(m_{trolley}\, r_{j,pulley}^2 + J_\psi\, K_{g,j}^2)\, l_p} \end{bmatrix}, \qquad [36]$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad [37]$$

and

$$D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \qquad [38]$$

The parameters used in the model are given in Table 8. This system can then be used to developed an state-feedback control system. As described by the C matrix, the only measured states are the trolley position, x_j, and the angle of the pendulum, γ. The remaining velocity states are calculated using high-gain observers as will be explained in the next section.

9.2.2. PID using LQR Control Design

The feedback loop used to control the position of the trolley while dampening the motions of the payload is shown in Figure 23. A proportional-integral-derivative, or PID, compensator is used to regulate the position. Assuming full-state feedback the linear-quadratic regulator, or LQR, algorithm is used to calculate the PID control gains.

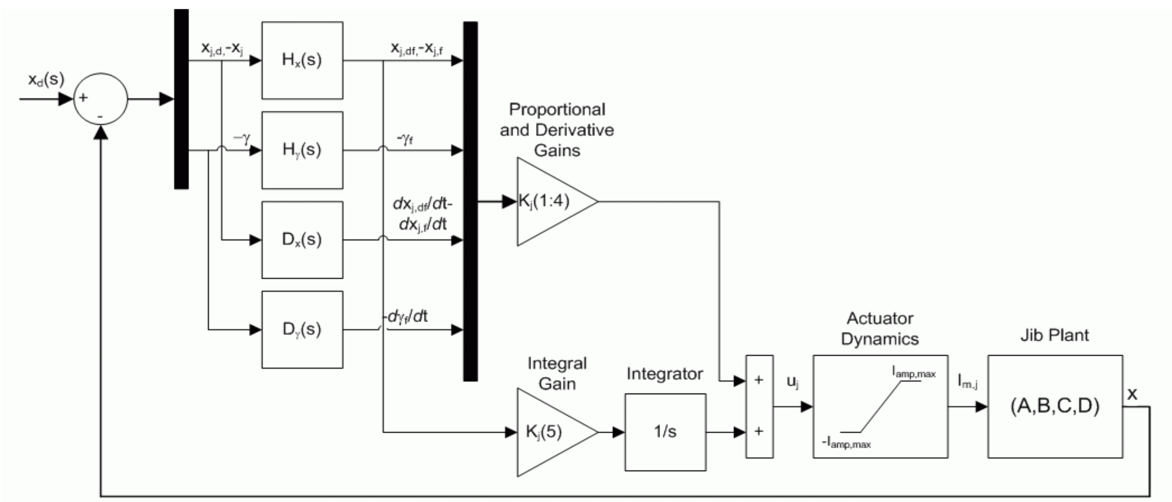


Figure 23 Jib closed-loop position control feedback loop.

Augment the Jib system state in [34] as follows

$$\zeta^T = \left[x_j(t), \gamma(t), \frac{d}{dt}x_j(t), \frac{d}{dt}\gamma(t), \int x_j(t)\,dt \right] \qquad [39]$$

to include a cart position integrator. Next, using the control law

$$u_j = -K_j\,\zeta \qquad [40]$$

the LQR method is used to minimize the cost function

$$J = \int_0^\infty x(t)^T\,Q\,x(t) + u_j(t)^T\,R\,u_j(t)\,dt \qquad [41]$$

,

where Q and R are weighting matrices that are specified by the user. When the weighting matrices are set to

$$Q = \begin{bmatrix} 5 & 0 & 0 & 0 & 0 \\ 0 & 5 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad [42]$$

and

$$R = 0.1 \qquad [43]$$

the LQR algorithm calculates the control gain

$$K_j = [14.1 \quad 34.7 \quad 11 \quad 1.46 \quad 4.47] \qquad [44]$$

.

Thus the trolley has a proportional control gain of 9.96 A/m, a derivative gain of 7.77 A.s/V, and an integral gain of 3.16 A/m/s. The proportional and derivative gains for the pendulum are 24.4 A/rad and 1.08 A.s/rad, respectively.

However as previously mentioned, there are only two measured states in the jib system- the linear trolley position and the pendulum angular position. Therefore, as illustrated in Figure 23, the actual implemented controller is of the form

$$u_j = -K_j\,\zeta_{j,\,e}^{\;T} \qquad [45]$$

where

$$\zeta_{j,\,e}^{\;T} = \left[x_{j,f}(t) - x_{j,\,df}(t),\ \gamma_f(t),\ \left(\frac{d}{dt}x_{j,f}(t)\right) - \left(\frac{d}{dt}x_{j,\,df}(t)\right),\ \frac{d}{dt}\gamma_f(t),\ \int x_{j,f}(t) - x_{j,\,df}(t)\,dt \right] \qquad [46]$$

is the estimated error state.

The $x_{j,f}$ and $x_{j,df}$ states are the filtered measured position of the trolley and the filtered trolley position setpoint. These are both passed through the low-pass filter called $H_x(s)$, as shown in Figure 23. This low-pass filter is first-order and has the same form as the transfer function given [15] without the Laplace operator in the numerator. The $dx_{j,f}/dt$ state is the filtered derivative of the trolley position after being processed by the high-pass filter $D_x(s)$. The filtered trolley velocity setpoint, $dx_{j,df}/dt$, is actually a calculated trajectory that is only passed through a low-pass filter, i.e. it is *not* derived applying a high-pass filter to the desired position as indicated in Figure 23. Similarly for the pendulum, the states $\gamma_f(t)$ and $d\gamma_f/dt$ are the filtered pendulum angle and the filtered pendulum velocity after being passed through the low-pass filter $H_\gamma(s)$ and the high-pass filter $D_\gamma(s)$, respectively.

The measured position and velocity states as well as the set-points are filtered to help smooth trolley motions. Other measures taken to make the trolley movements smooth are using a velocity setpoint for the trolley and avoiding large control gains.

9.3. Tower System

9.3.1. Modeling the Tower Plant

The tower subsystem is modeled as a rotary gantry crane by assuming the trolley position is fixed, the γ gimble deflection angle is always 0, and the payload height is fixed. Thus the only moving joints are the jib pivoting about the tower and gimble angle α. In this section, the linear state-space representation of the 3 DOF Crane Tower subsystem is only summarized. For complete details, see the Maple worksheet called *3D Crane Tower Equations.mws* or its corresponding HTML output *3D Crane Tower Equations.html*.

As shown in Figure 24, the jib is modeled as a rigid rotary arm and it is assumed that the trolley remains stationary at the end of the jib, a distance of l_j from the vertical tower. The payload is assumed to be fixed at a height of l_p from the trolley pulley and is modeled as a suspended pendulum. The Tower system has two measured states: the rotary arm angle, θ, and the pendulum deflection angle, α, and the payload moves about a three-dimensional space. When the tower motor input current is positive, $I_{m,t} > 0$, the rotary arm angle moves in the counter-clockwise direction. This is defined as positive velocity. As shown in Figure 24, the pendulum angle is defined as positive when rotating in the counter-clockwise direction.

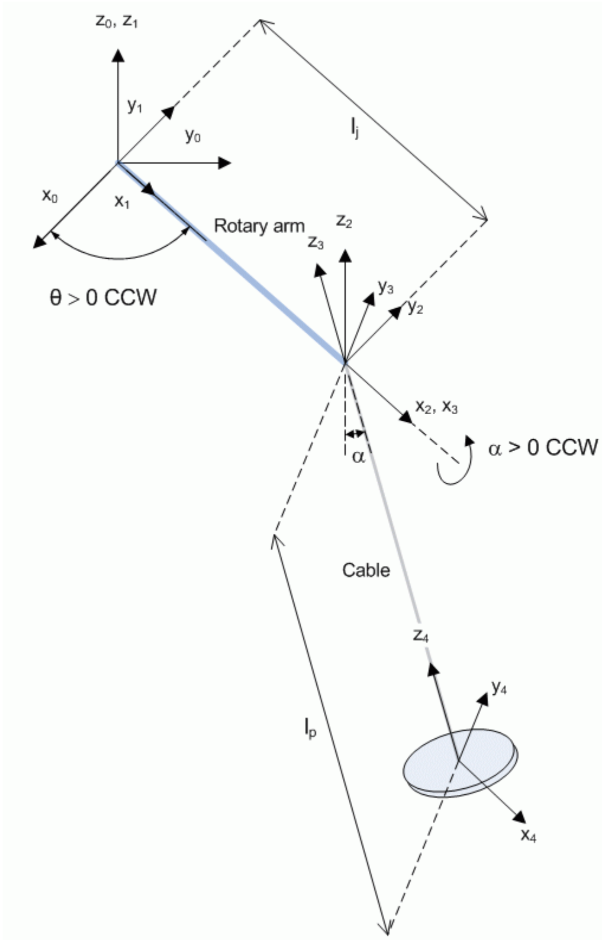


Figure 24 Kinematics of tower system.

The transformation matrices used to define the payload center of mass in terms of $Ox_0y_0z_0$ is

$$T_{0,\,4} = \mathrm{trans}(Z_3, -l_p)\ \mathrm{rot}(X_2, \alpha)\ \mathrm{trans}(X_1, l_j)\ \mathrm{rot}(Z_0, \theta) \qquad [47]$$

where *trans* stands for translation matrix and *rot* is rotational matrix. The Cartesian coordinates of the payload center of mass are

$$x_2 := -\sin(\theta(t))\sin(\alpha(t))\, l_p + \cos(\theta(t))\, l_j, \qquad [48]$$

$$y_2 := \cos(\theta(t))\sin(\alpha(t))\, l_p + \sin(\theta(t))\, l_j, \qquad [49]$$

and

$$z_2 := -\cos(\alpha(t))\, l_p. \qquad [50]$$

The system is modeled as a rotary arm with a suspended pendulum, i.e. rotary gantry plant. As described in the Maple worksheet, the nonlinear equations of motion are obtained using the Euler-Lagrange technique. With the state

$$x^T = \left[\theta(t),\, \alpha(t),\, \frac{d}{dt}\theta(t),\, \frac{d}{dt}\alpha(t) \right] \quad [51]$$

the motion equations are used to find the tower linear state-space matrices

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{m_p^2 l_p^2 l_j g}{J_\alpha J_\theta + J_\theta m_p l_p^2 + m_p l_j^2 J_\alpha} & 0 & 0 \\ 0 & -\dfrac{m_p l_p g (m_p l_j^2 + J_\theta)}{J_\alpha J_\theta + J_\theta m_p l_p^2 + m_p l_j^2 J_\alpha} & 0 & 0 \end{bmatrix}, \quad [52]$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \dfrac{\eta_{g,t} K_{g,t} \eta_{m,t} K_{t,t} (J_\alpha + m_p l_p^2)}{J_\alpha J_\theta + J_\theta m_p l_p^2 + m_p l_j^2 J_\alpha} \\ -\dfrac{m_p l_p \eta_{g,t} K_{g,t} \eta_{m,t} K_{t,t} l_j}{J_\alpha J_\theta + J_\theta m_p l_p^2 + m_p l_j^2 J_\alpha} \end{bmatrix}, \quad [53]$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad [54]$$

and

$$\mathrm{D} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad [55]$$

See Table 8 for the values of the parameters used in the model. Notice that as with the Jib system, only the tower and pendulum positions are being measured. The velocity states are obtained with high-pass filters.

9.3.2. PV using LQR Control Design

To control the angle of the jib while dampening the motions of the payload, a proportional-velocity, or PV, compensator is designed. Figure 25 illustrates the feedback loop that is implemented. The PV controller is

$$u_t = -K_t \zeta_{t,e} \tag{56}$$

where for the high-pass filters $D_\theta(s)$ and $D_\alpha(s)$ the error state is

$$\zeta_{t,e}^T = [\theta_d - \theta, -\alpha, -D_\theta(s)\,\theta, -D_\alpha(s)\,\alpha] \tag{57}$$

The velocity states are not directly measured and are instead obtained using high-gain observers. The filtered derivative of the tower position, $d\theta_f/dt$, and the filtered derivative of the pendulum angle, $d\alpha_f/dt$, are found using the high-pass filters $D_\theta(s)$ and $D_\alpha(s)$, respectively.

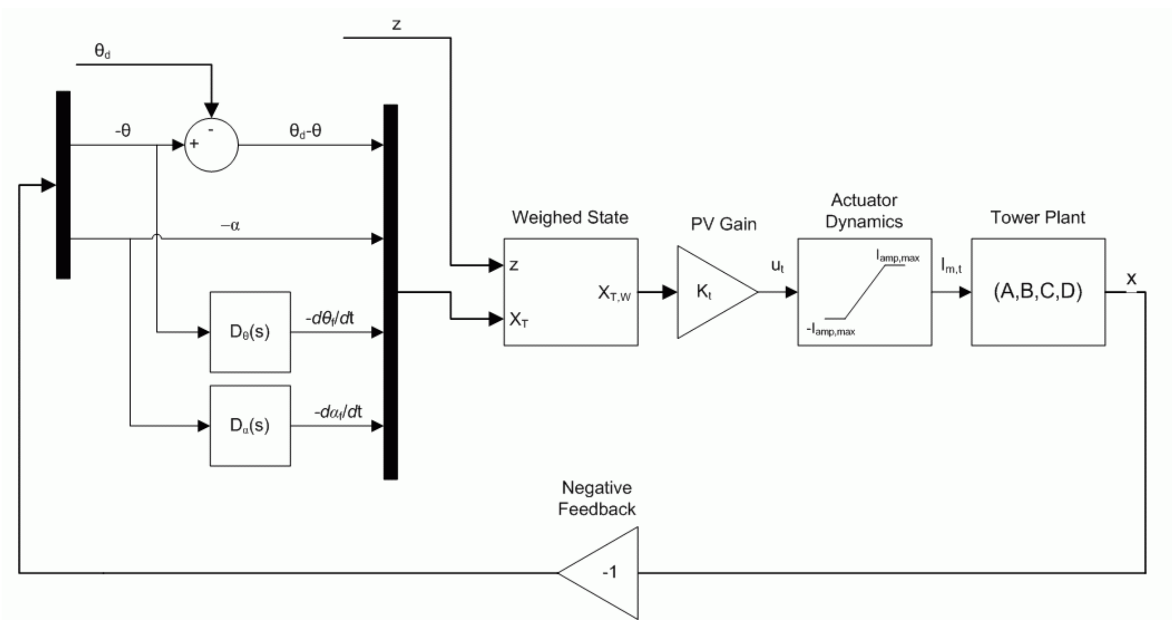


Figure 25 Tower control system.

Assuming full-state feedback, the PV control gains are found using the LQR method. With the A, B, C, and D state-space matrices found in Section 9.3.1 and the weighting matrices

$$Q = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0.25 & 0 \\ 0 & 0 & 0 & 0.25 \end{bmatrix} \quad [58]$$

and

$$R = 0.05 \quad [59]$$

the LQR algorithm calculates the control gain

$$K_t = [6.32 \quad -8.44 \quad 3.71 \quad 0.70]. \quad [60]$$

As the payload is being lifted, the cable shortens and the mass tends to swing at a much higher frequency (i.e. lower moment of inertia). Recall that the control gains are designed based on a mathematical model that assumes the payload is at a fixed distance of l_p. When the payload is at the bottom, it moves more slowly and the gains that were generated do well to compensate for its motions. However, as the payload beings swinging more rapidly the high gains originally generated cause the tower oscillate back and forth very rapidly until it almost goes unstable.

This is why the *Weighed State* system is introduced. This transforms the estimated error state in [57] to

$$\zeta_{t,\,e,\,w}^{\ T} = [\,\theta_d - \theta, -b_\alpha(z)\,\alpha, -D_\theta(s)\,\theta, -b_\alpha(z)\,D_\alpha(s)\,\alpha\,] \quad [61]$$

where

$$b_\alpha(z) = k_w\,(1 - z) \quad [62]$$

is called the weighing factor. The weighing factor is a function of the payload height, *z*, and $k_w > 0$ is called the weighing gain. As the payload raises the $b_\alpha(z)$ factor decreases and lowers the proportional and velocity gimble α angle gains. This prevents the tower from overcompensating for the small swinging motions of the payload.

10. In-Lab Procedure

10.1. Controller Simulation

Each 3D Crane subsystem has its own Simulink model that can be used to simulate the closed-loop response.

10.1.1. Payload Position using PIV

The procedure to simulate the closed-loop position of the payload when using the PIV controller designed in Section 9.1.2 is given in this section.

Follow these steps:

1. Open the Simulink model named *s_3d_crane_payload_pos_cntrl.mdl* that is shown in Figure 26.

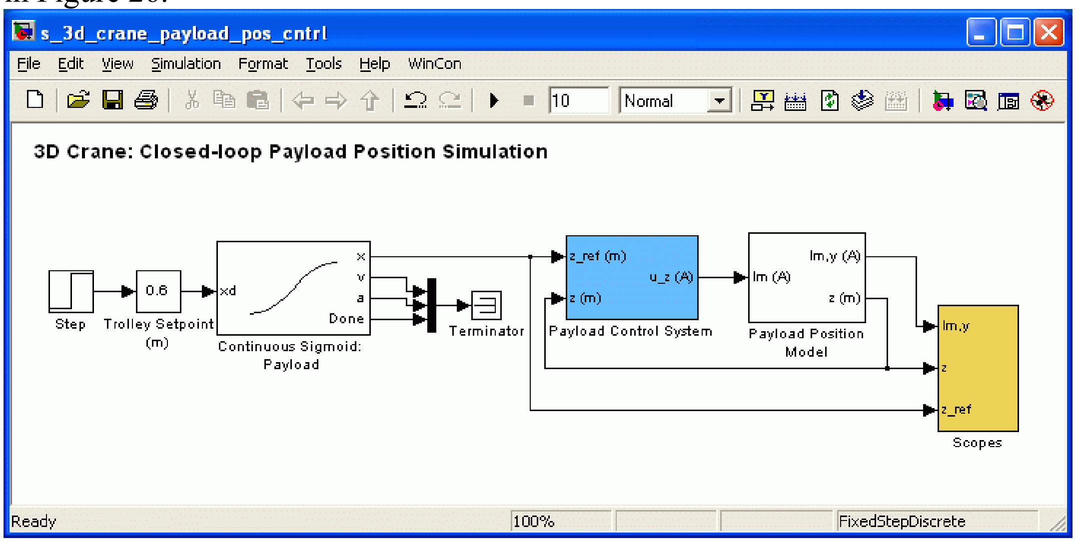


Figure 26 Simulink model used to simulate payload controller.

2. Run the Matlab script called *setup_3d_crane.m* to set the model parameters and the control gains *kp*, *ki*, and *kv*.
3. Set the Payload Setpoint (m) Slider Gain block to 0.6 and ensure the Step block generates 1 at 1 second. The desired or reference payload position trajectory is passed though a Sigmoid block to smooth out the step command. The Payload Control System subsystem resembles the control loop shown in Figure 21 in Section 9.1.2. The PIV control is implemented using discrete blocks: the Discrete Integrator block is used from the Discrete Simulink library and the Discretized Transfer Function block is used from the Quanser Toolbox to implement the high-pass filter. The Payload Position Model block contains the dynamics presented in Section 9.1.1.
4. Click on start simulation to simulate the closed-loop response using the PIV controller. The *z_sim (m)* scope displays the reference position and the simulated position of the payload. The yellow line is the reference and the purple is the simulated trajectory. The $I_{m,y}$ (A) scope displays the current used to control the position of the payload. It should be smooth and within ±7 A to ensure the amplifier is not saturated.
5. Close the Simulink model and Matlab when done.

10.1.2. Trolley Position on Jib using PID

In this section, the steps to simulate the closed-loop position of the trolley on the jib when using the PID controller designed in Section 9.2.2 is given.

Here is the procedure:

1. Open the Simulink model named *s_3d_crane_jib_pos_cntrl.mdl* that is shown in Figure 27.

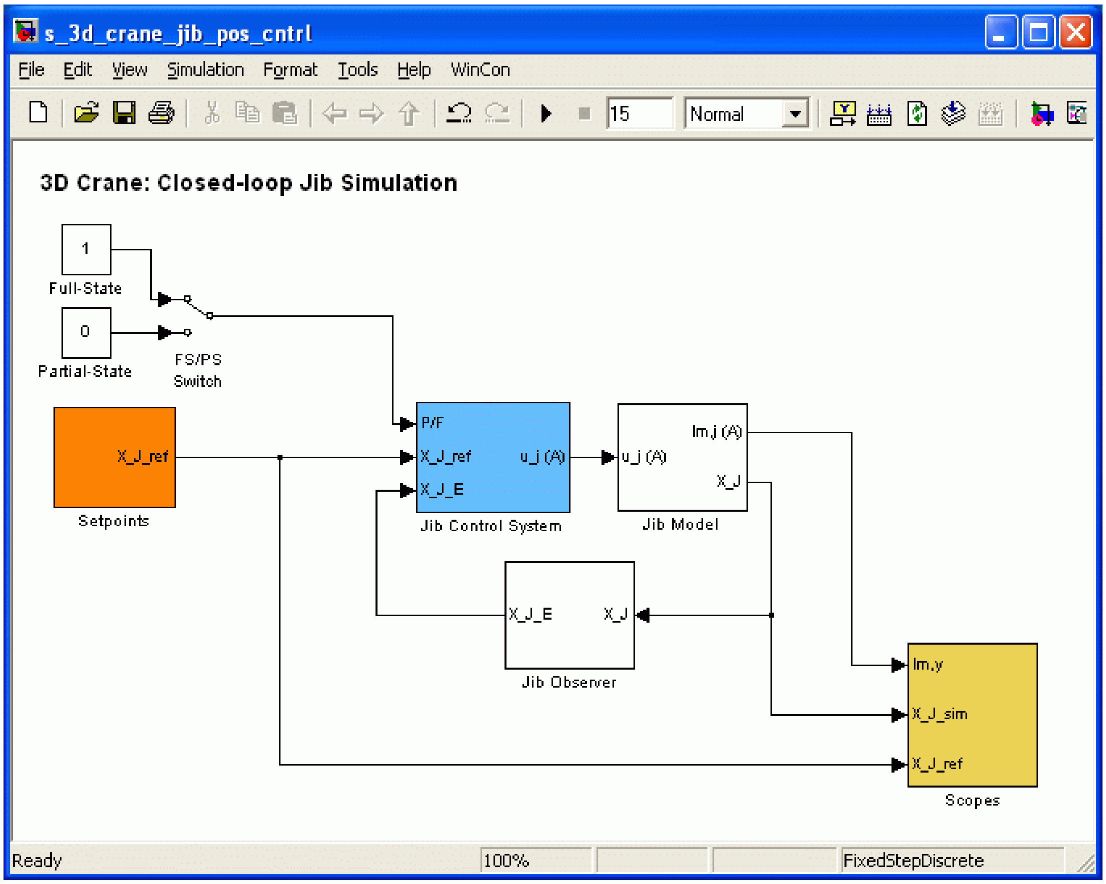


Figure 27 Simulink model used to simulate the jib controller.

2. Run the Matlab script called *setup_3d_crane.m* to set the model parameters and the Jib control gain K_J.
3. In the orange *Setpoints* subsystem, set the *Trolley Setpoint (m)* Slider Gain block to 0.4 m and ensure the *Step* block generates 1 at 1 second. The reference position trajectory is passed though a Sigmoid block to smooth out the step command. The computed velocity trajectory from the Sigmoid block is processed by a low-pas filter

and used as the velocity setpoint, as discussed in Section 9.2.2. The *Jib Control System* and the *Tower Observer* subsystems resemble the control loop in Figure 23 of Section 9.2.2. The integrator in the PID control is implemented using the Discrete Integrator block from the Discrete Simulink library. In the *Jib Model* subsystem, the *Discretized State-Space* block from the Quanser Toolbox is used to model the plant. The resulting positions states x_j and γ are then passed through low-pass and high-pass filters to obtain smooth positions and velocities, as discussed in Section 9.2.2. The filters are contained in the the *Observer* subsystem and the resulting state estimate, X_J_E, is used in the feedback.

4. Set the *FS/PS Switch* to the down position to simulate the Partial-State response, i.e. when the pendulum angle position and velocity states are not included in the feedback.
5. Click on start simulation to simulate the partial-state closed-loop response using the PIV controller. The *xj (m)* scope displays the reference position and the simulated position of the payload. The simulated purple trajectory should be tracking the yellow reference trolley position. The *gamma (deg)* scope displays the simulated pendulum angle. Given that this is partial-state feedback, the pendulum angle should be oscillating somewhere between ±20 degrees. The $I_{m,j}$ (A) scope displays the jib motor input current. It should be smooth and within ±7 A to ensure the amplifier is not saturated.
6. Set the *FS/PS Switch* to the up position to simulate the full-state response.
7. Click on start simulation to simulate the full-state closed-loop response. Now, the pendulum angle shown in *gamma (deg)* should stabilize to zero. Notice that trolley position in the *xj (m)* scope has a larger overshoot to compensate for the pendulum rotating in the negative direction.
8. Close the Simulink model and Matlab when done.

10.1.3. Tower Position using PV

The procedure to simulate the closed-loop tower position with the PV controller summarized in Section 9.2.2 is given in this section.

Follow these steps:

1. Open the Simulink model named *s_3d_crane_tower_pos_cntrl.mdl* that is shown in Figure 28.

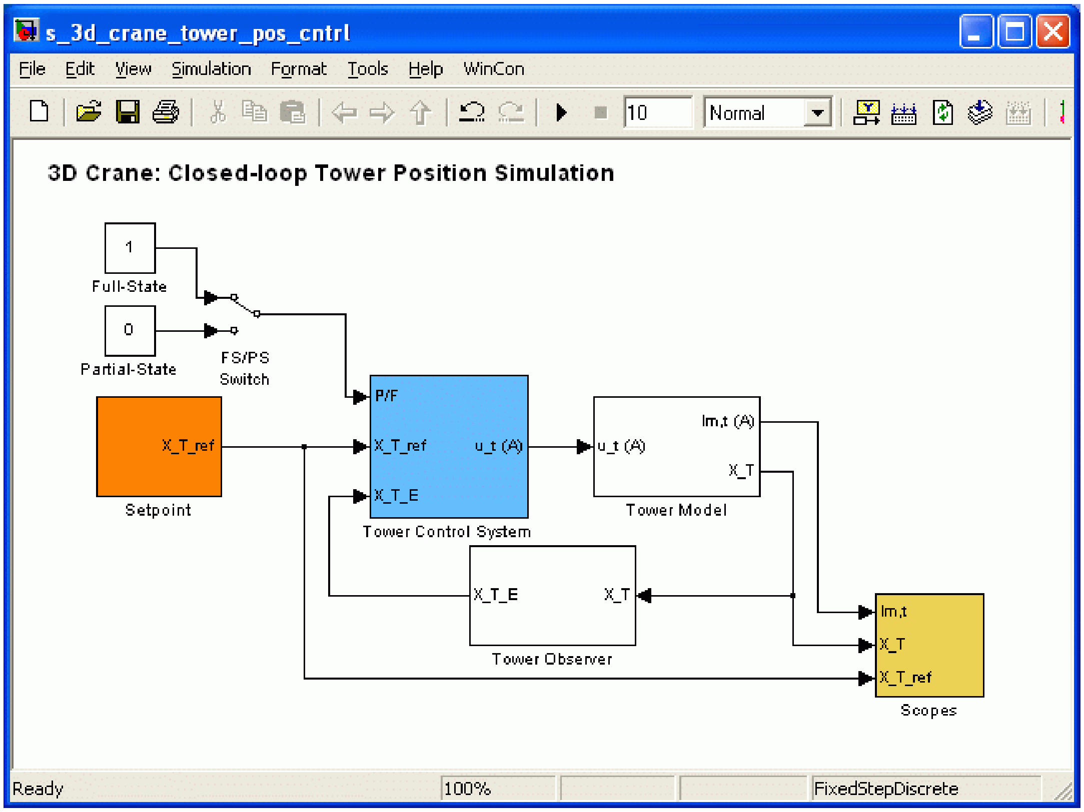


Figure 28 Simulink model used to simulate the tower controller.

2. Run the Matlab script called *setup_3d_crane.m* to set the model parameters and the Tower control gain K_T.
3. In the *Setpoint* subsystem, set the *Tower Setpoint (m)* Slider Gain block to 60 degrees and ensure the *Step* block generates 1 at 1 second. The reference position trajectory is passed though a Sigmoid block to smooth out the step command. The *Tower Control System* and the *Tower Observer* together resemble the control loop illustrated in Figure 25 of Section 9.2.2. In the *Tower Observer* subsystem, the positions θ and α are passed through high-pass filters to obtain smooth velocities, as discussed in Section 9.3.2. The tower state estimate, X_T_E, is used in the feedback.
4. Set the *FS/PS Switch* to the down position to simulate the partial-state response, i.e. when the pendulum angle position and velocity states are not included in the feedback.
5. Click on start simulation to simulate the partial-state closed-loop response using the PIV controller. The *theta (deg)* scope displays the reference position and the simulated position of the payload. The simulated purple trajectory should be tracking the yellow reference trolley position. The *alpha (deg)* scope displays the simulated pendulum angle. This is partial-state feedback so the pendulum should be

swinging between ±10 degrees with little decay. The $I_{m,t}$ (A) scope displays the tower motor input current. It should be smooth and within ±7 A to ensure the amplifier is not saturated.

6. Set the *FS/PS Switch* to the upward position to simulate the full-state response.
7. Click on start simulation. Now the pendulum angle shown in *alpha (deg)* should stabilize to zero. Notice that tower angle in the *theta (deg)* scope has a larger overshoot to compensate for the pendulum rotating in the positive direction.
8. Close the Simulink model and Matlab when done.

10.2. Controller Implementation

The objectives of the sample experiments are briefly outlined in Section 10.2.1. In Section 10.2.2, the Simulink diagram that implements the designed position controller is described. This Simulink model is used to generate real-time code using QUARC in order to control the position of the 3-DOF Crane device. The procedure to initialize the system in order to perform the various control experiments is introduced in Section 10.2.3. Section 10.2.4 gives a sample experiment to control the position of the tower. Similarly in sections 10.2.5 and 10.2.6, sample procedures are given to control the position of the trolley position and control the height of the payload, respectively.

10.2.1. Objectives

- Implement with QUARC the previously designed feedback system in order to control the tower, trolley, and payload positions while keeping the swinging motions of the payload at a minimum.
- Verify the behaviour seen in the simulation when using partial-state and full-state feedback.

10.2.2. 3-DOF Crane Position Control Simulink Model Description

The Simulink model *q_3d_crane_pos_cntrl.mdl* shown in Figure 29 implements the payload, jib, and tower position controllers described in sections 9.1.2, 9.2.2, and 9.3.2. It runs the actual 3-DOF Crane plant by directly interfacing with your hardware through the *QUARC Targets* blocks, discussed in Reference [3].

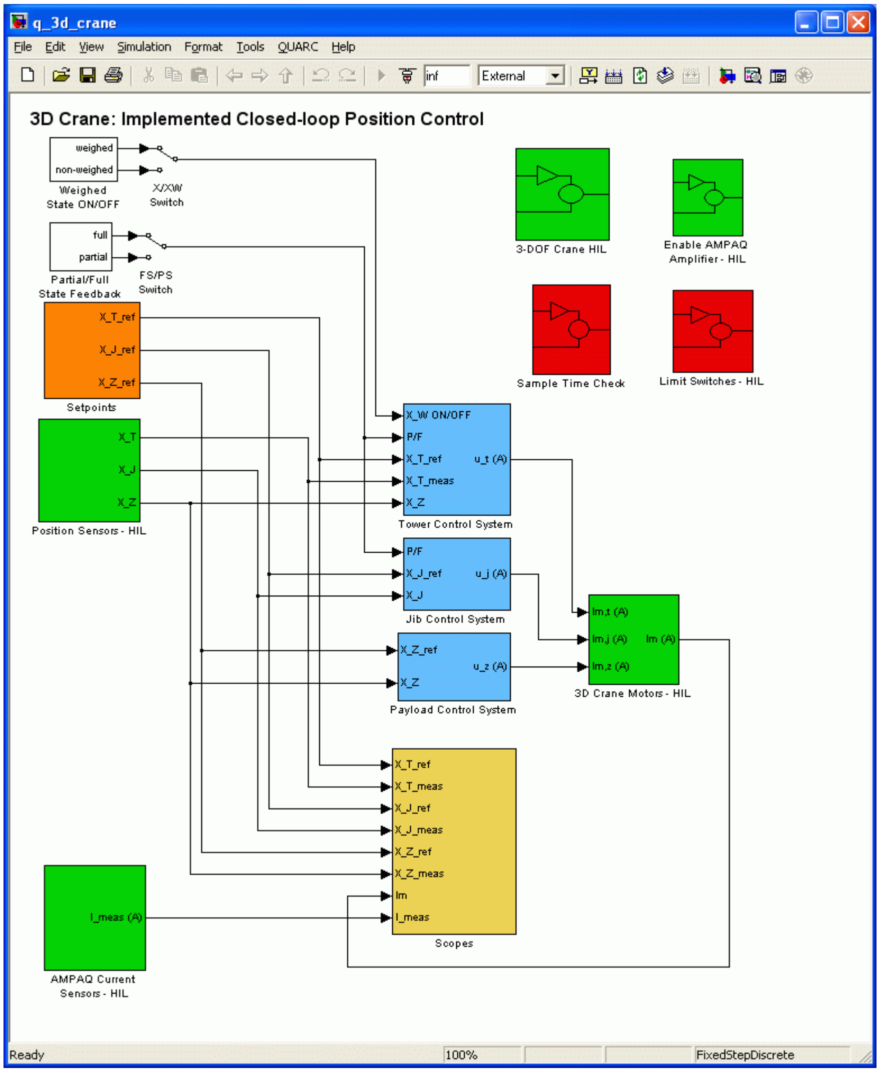


Figure 29 Simulink model that implements the full 3 DOF Crane position controller.

The *Setpoints*, *Tower Control System*, *Jib Control System*, and *Payload Control System* subsystems are very similar to the blocks included in the Simulink models that are used to simulate each 3 DOF Crane subsystem, as described section 10.1. One difference is the *Tower Control System* block that is being implemented contains a *Weighed State* subsystem, which is explained in Section 9.3.2. This was not present in the simulation version of the tower control system (would require a full model of the 3 DOF Crane system). The effect of the *Weighed State* system will be discussed further in Section 10.2.4.

The give green blocks called *3-DOF Crane HIL*, *Enable AMPAQ Amplifier - HIL*, *Position*

Sensors - HIL, *AMPAQ Current Sensors – HIL*, and *3D Crane Motors - HIL* and the red *Limit Switches - HIL* subsystem all contain QUARC blocks that interface with the hardware of the actual plant.

10.2.2.1. 3-DOF Crane HIL Subsystem

The interior of the *3-DOF Crane HIL* block is depicted in Figure 30. This contains the QUARC blocks that interfaces with the AMPAQ and the 3 DOF Crane sensors. The *HIL Read Timebase* reads the AMPAQ currents on analog input channels 0-3, the 3D Crane encoders on channels 0-4, and the limit switches on digital input channels 8-11. The *HIL Write* block is used to send current commands to the AMPAQ on analog output channels 0-2 and enable the AMPAQ on digital outputs 0, 1, 2 and 4. These input and outputs signals are all sent and received through Simulink *Goto* blocks, which are found in other subsystems.

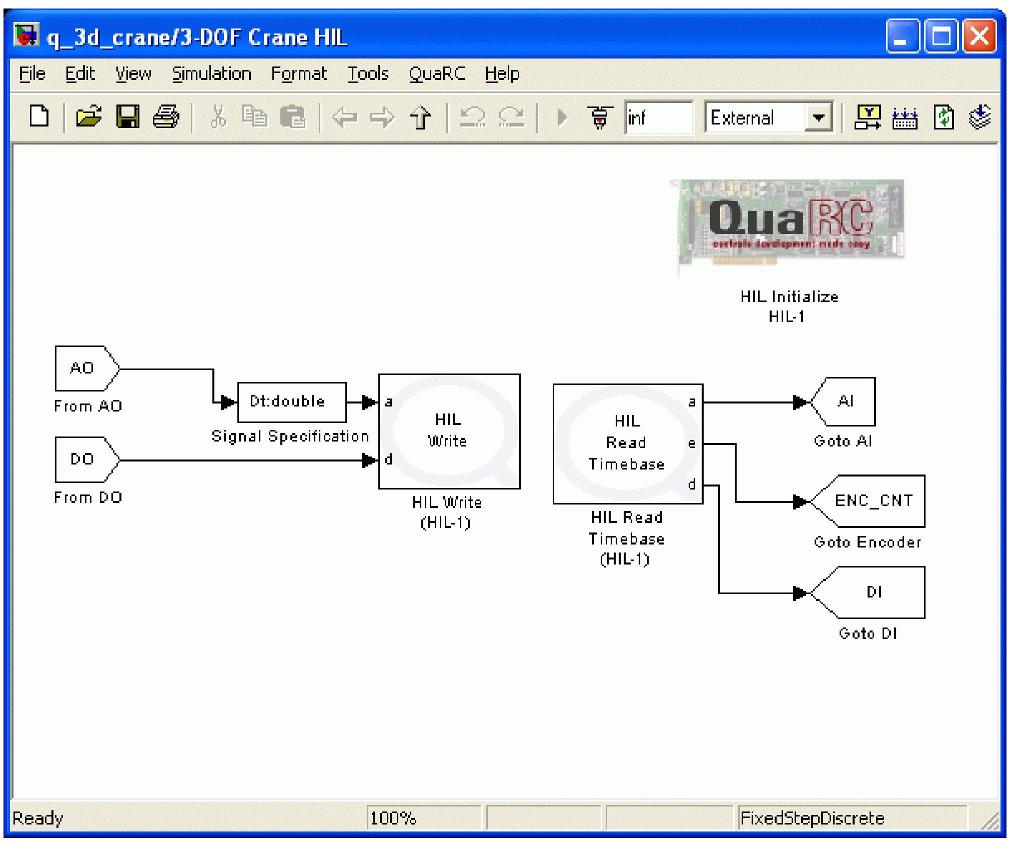


Figure 30: 3-DOF Crane HIL subsystem

10.2.2.2. Enable Amplifier Subsystem

Figure 31 depicts the interior of the *Enable AMPAQ Amplifier - HIL* block. To enable the

AMPAQ channel 0-2, the Digital Output Lines #0-2 and 4 are set to 1 for the first sampling interval when the controller is started. In the next sampling interval, DIO #0-2 and 4 are brought down to 0. DO #4 is the master enable switch on the AMPAQ. When the controller is stopped, the lines are pulled back up to 1 to disable the amplifier.

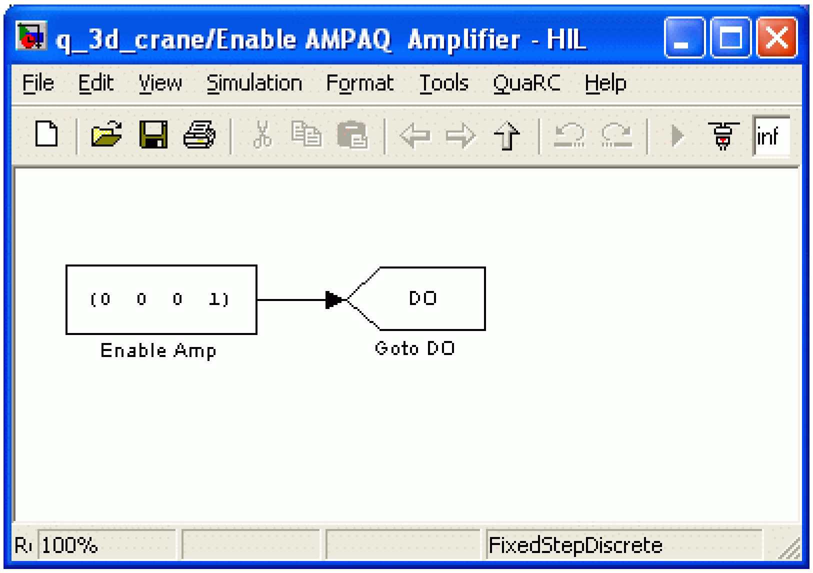


Figure 31 Enable AMPAQ Amplifier - HIL subsystem.

10.2.2.3. Position Sensors Subsystem

Figure 32 illustrates the *Position Sensors - HIL* subsystem. The *Encoder Input* outputs the measured counts from the five encoders in the 3-DOF Crane device. The *Encoder Calibration* block converts these counts to an angular or linear position measurement.

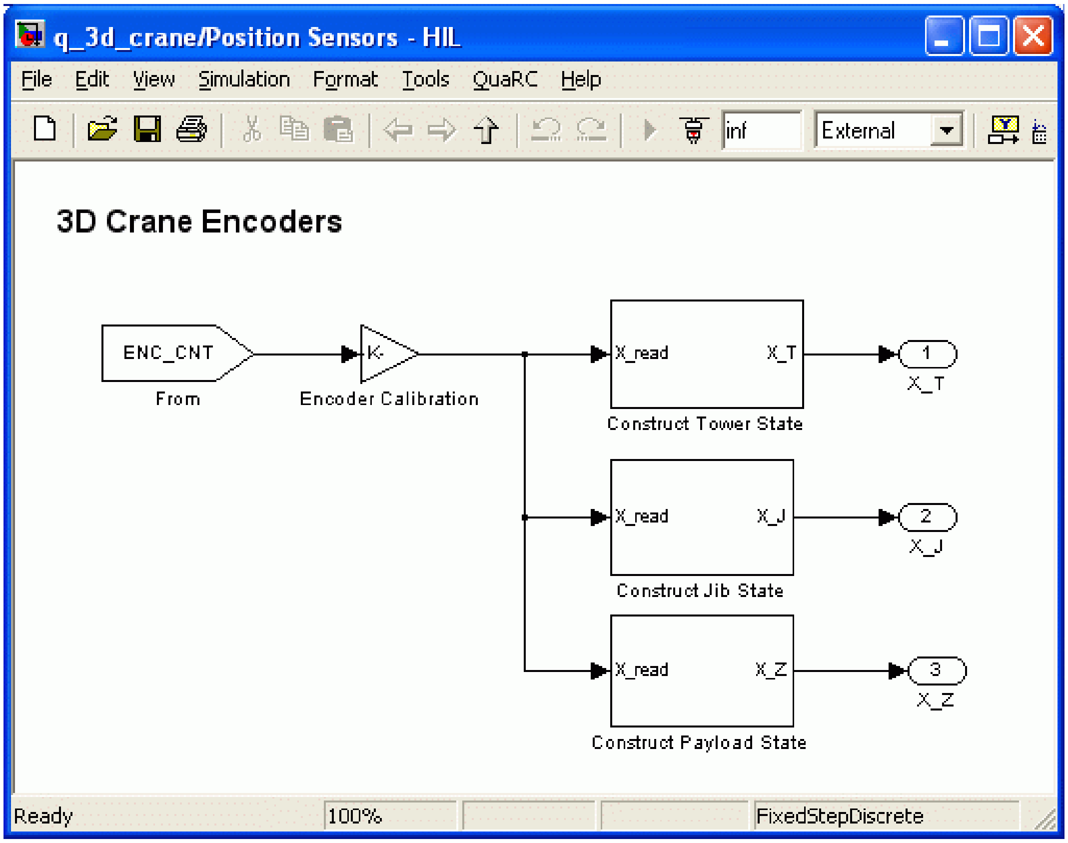


Figure 32 Position Sensors - HIL subsystem.

The tower, jib, and payload states are then constructed in the subsystems *Contruct Tower State*, *Contruct Jib State*, and *Contruct Payload State*. Similar to the observers seen in Section 10.1 and explained in sections 9.1.2, 9.2.2, and 9.3.2, these blocks include the high-pass filters to obtain smooth velocities as well as low-pass filters for the jib positions states. In addition, each of these blocks contain watchdogs that stop the real-time controller when the trolley, payload, or pendulum angles exceed a specified limit. For instance in the *Construct Tower State* subsystem, if the gimble angle α goes beyond the ALPHA_MIN and ALPHA_MAX limits specified in the *setup_3d_crane.m* file the QUARC control is stopped and the AMPAQ is disabled. This software watchdog is, however, only enabled when the ALPHA_LIM_ENABLE variable is set to 1. Similar limits are imposed on the trolley position, x_j, the payload position, z, and gimble angle γ .

10.2.2.4. Current Sensors Subsystem

The AMPAQ Current Sensors – HIL block is shown in Figure 33. The *From Analog Input* block reads the current measurements from the AMPAQ.

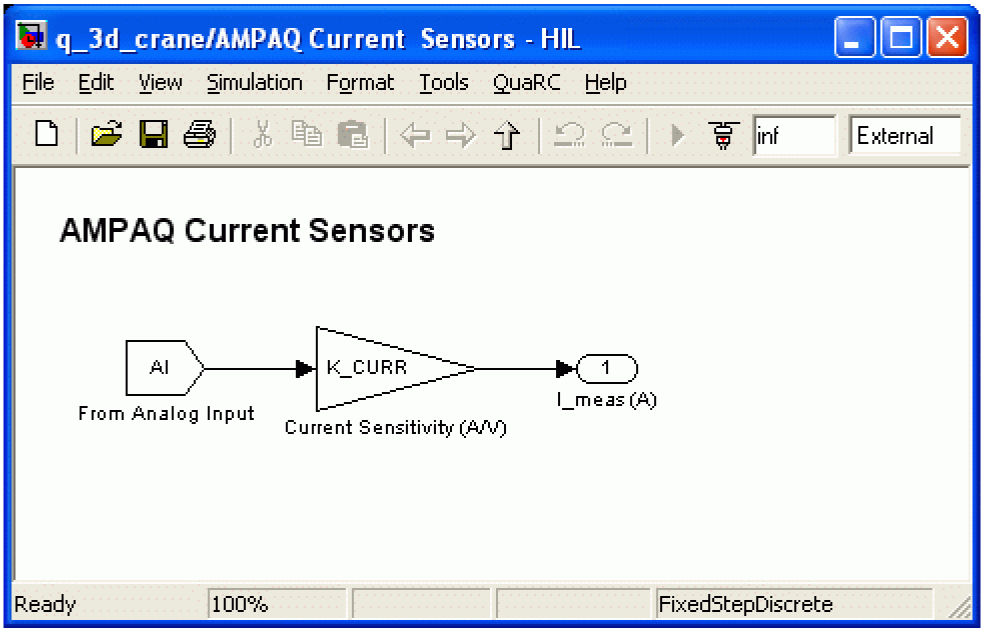


Figure 33: Current sensors subsystem.

10.2.2.5. 3D Crane Motor Subsystem

The *3D Crane Motor - HIL* subsystem is shown in Figure 34. The three reference currents computed by the payload, jib, and tower controllers are muxed together and passed through a Saturation Block to avoid over driving the AMPAQ. This signal is then converted to a voltage (since the HIL board outputs voltage) and passed through another Saturation Block that limits the control signal to the maximum D/A output voltage of HIL HIL board. The *Analog Output* block sends the voltages to the HIL board which in turn goes to the AMPAQ and drives the various 3 DOF Crane actuators.

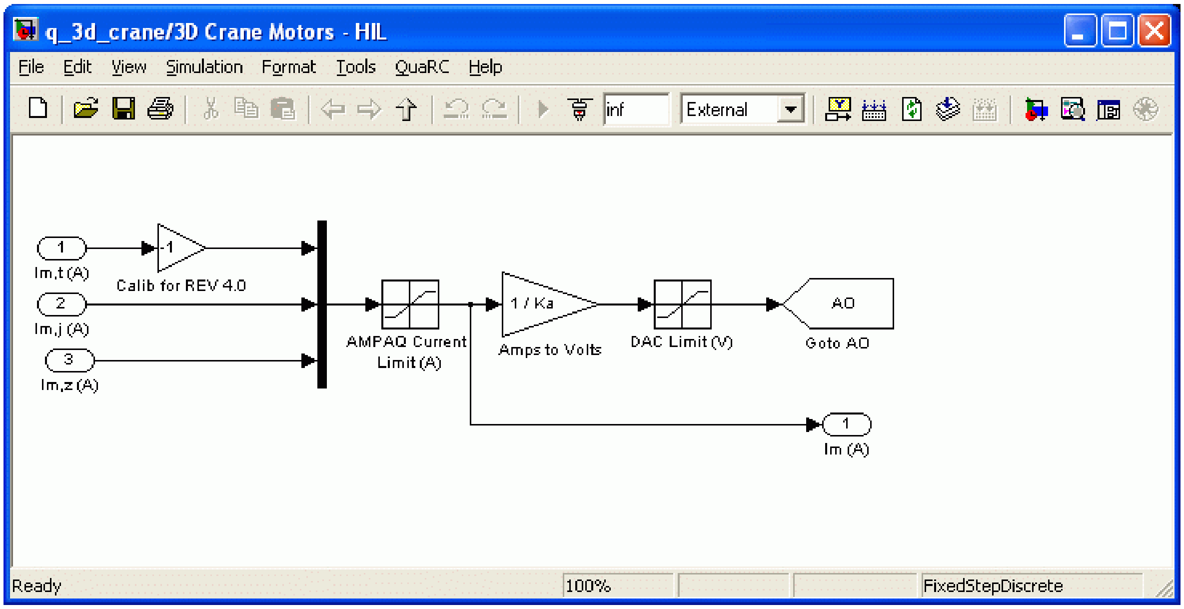


Figure 34 3D Crane Motor - HIL subsystem.

10.2.2.6. Limit Switches Subsystem

The *Limit Switches - HIL* block is pictured in Figure 35. The *Read Limit Switches* block outputs 1 when a limit switch is triggered and the *Stop with Limit Switches* block actually stops QUARC when a limit switch is triggered.

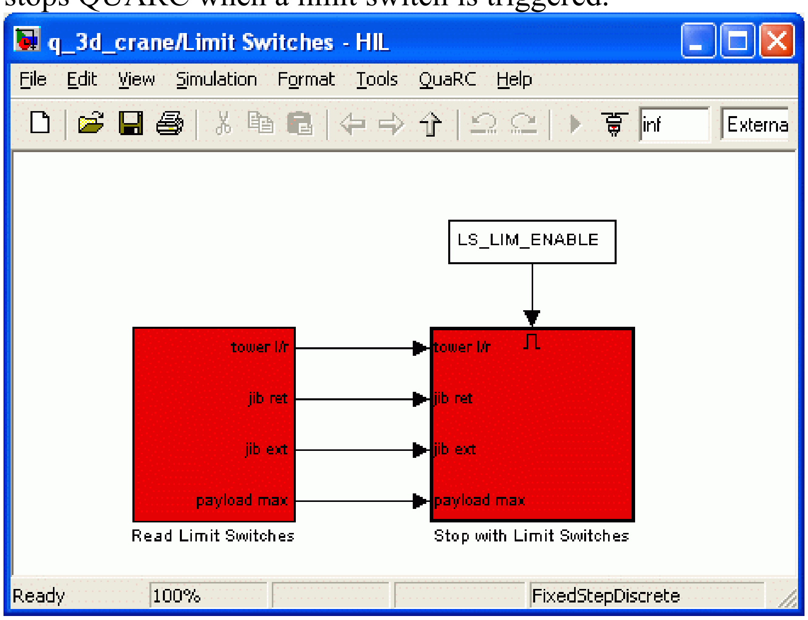


Figure 35 Limit Switches - HIL subsystem.

The interior of the *Read Limit Switches* is shown in Error: Reference source not found. The digital readouts of the *BCP-CW*, *BCP-CCW*, *CCP-Ret*, *CCP-Ext*, or *Payload* limit sensors are read using the *Quanser Digital Input* block. The actual proximity sensor outputs 1 when it is *not* triggered and gets brought down to 0 when it is triggered (i.e. when a magnet get close to the sensor). In the *Read Limit Switches* subsystem, the *tower ccw, tower cw, jib ret*, *jib ext*, or *payload max* output 1 on the event that the *BCP CCW, BCP CW, CCP-Ret*, *CCP-Ext*, or *Payload* limit switch is hit.

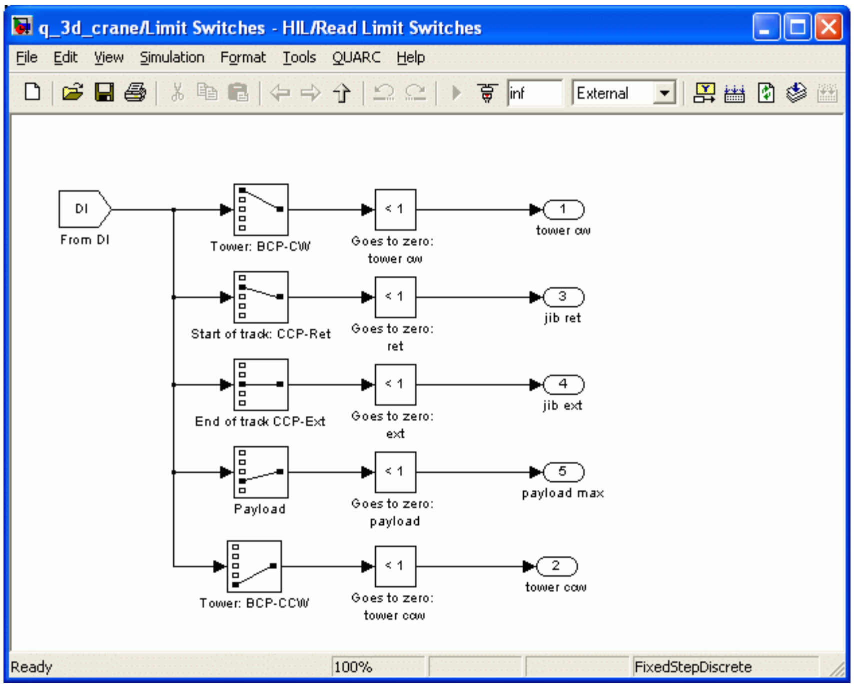


Figure 36: Read Limit Switches subsystem.

As shown in Figure 37, if the *BCP CCW, BCP CW*, *CCP-Ret*, *CCP-Ext*, or *Payload* limit switch is triggered the controller is stopped using the QUARC *Stop With Message* block. A messages will be prompted to the user describing what limit switch has been activated.

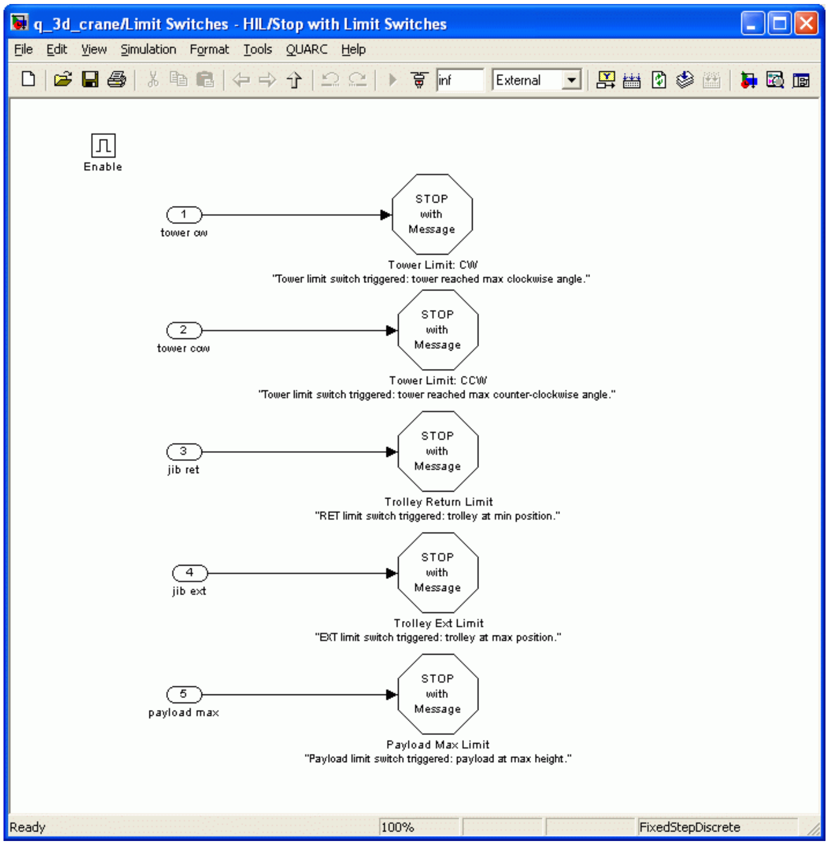


Figure 37 Stop with Limit Switches subsystem.

10.2.2.7. Sample Time Check

The *Sample Time Check* subsystem is depicted in Figure 38. This stops the QUARC controller if too many samples are lost (e.g. due to a slow PC), which can adversely effect the control performance. In particular, this can lead to jerky motions and/or vibrations when controlling the cart or payload position.

If the measured sample time is twice the desired sample time, e.g. exceeds 0.002 s for a controller supposed to be running at 0.001 s, then the counter goes up. If more than 5 samples are lost the controller is stopped. If this is the case, the CPU load must be decreased. You can also try running the controller at a lower sampling rate (e.g. 0.001 s down to 0.002 s).

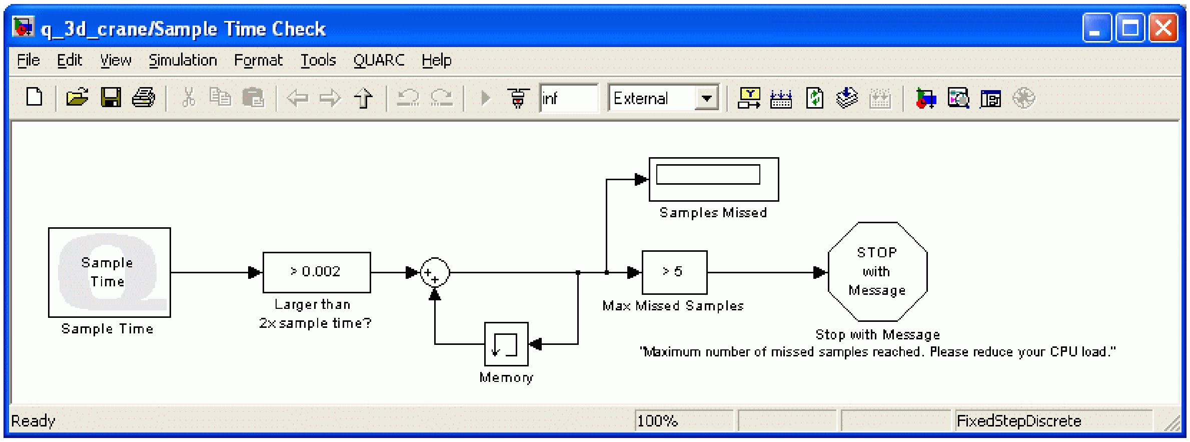


Figure 38: Sample Time Check subsystem.

10.2.3. Start up Procedure

This section outlines a procedure that is to be performed before any of the experiments given in sections 10.2.4, 10.2.5, and 10.2.6. Follow the steps described below to build and start running the designed controller in real-time:

1. **Before running the experiment:**
   (1) Ensure all the connections have been made as instructed in Section 8.
   (2) Place the 3 DOF Crane device in a clear area where the tower is free to rotate 360 degrees without any obstructions.
   (3) Run the q_3d_crane_cal controller as explained in Section 10.3.3.
   (4) Ensure the payload has settled and is not moving. The system should be similar as shown in Figure 1.
2. Load Matlab.
3. Open Simulink model *q_3d_crane.mdl* shown in Figure 29 that implements the payload, jib, and tower position controllers described in sections 9.1.2, 9.2.2, and 9.3.2.
4. As depicted in Figure 29, ensure the *X/XW Switch* is set to the *weighed* state position and the *FS/PS Switch* is set to the *full* state feedback position.
5. Execute the design file *setup_3d_crane.m* to setup the workspace. This file loads the various model parameters used in 3 DOF Crane plant and sets the state-space model of the jib and tower system. It also calculates the necessary PIV gains needed to meet the peak time and percentage overshoot specifications as in Section 9.1.2 and calculates the jib and tower feedback gain vectors *K_J* and *K_T* using the Matlab LQR command. Various other parameters such as the filter cutoff frequencies, pendulum and trolley safety limits, AMPAQ current limits, and so on are also loaded into the workspace.

6. Go to the *QUARC | Build* item in the Simulink menu bar to generate the real-time code. After successful compilation, you will be able to run your controller on your actual system time in real-time.
7. Turn the AMPAQ power on. The green Power LED on the upper-left corner of the amplifier should be lit.
8. When the payload is motionless, start the controller by clicking on the *Start* button in the Simulink diagram toolbar. The controller can be stopped at any time by clicking on the *Stop* button located in the Simulink diagram toolbar. Alternatively, the *Pause/Break* key on the keyboard can be used to stop the controller.
9. The system is now ready to run any of the sample position control experiments given in sections 10.2.4, 10.2.5, and 10.2.6.

10.2.4. Tower Position Control Procedure

Follow this procedure to control the position of the tower:

1. The system should be ready and the controller running, as dictated in the steps of Section 10.2.3.
2. Open the scopes *theta (deg)* and *alpha (deg)* to view the position of the tower along with the swings in the payload. The *theta (deg)* scope displays reference tower angle in green and the measured angle in red. Similarly, the *alpha (deg)* scope shows the measured gimble angle in red (note: the reference is in yellow but is zero).
3. In the *Setpoints* subsystem, set the Slider Gain labeled *Tower Setpoint* to -60 degrees. The horizontal member should be rotating clockwise 60 degrees.
4. Set *Tower Setpoint* to 60 degrees to give the tower a reference amplitude of 120 degrees and examine the effect on the scopes.
5. Figure 39 depicts the measured response of the tower position (top) and the pendulum angle (bottom) when in *full-state feedback* mode. The red solid line is the measured response and the blue dash-dot is the reference position. The tower tracks the commanded angle well while maintaining the swinging motions of the payload below ±5 degrees.

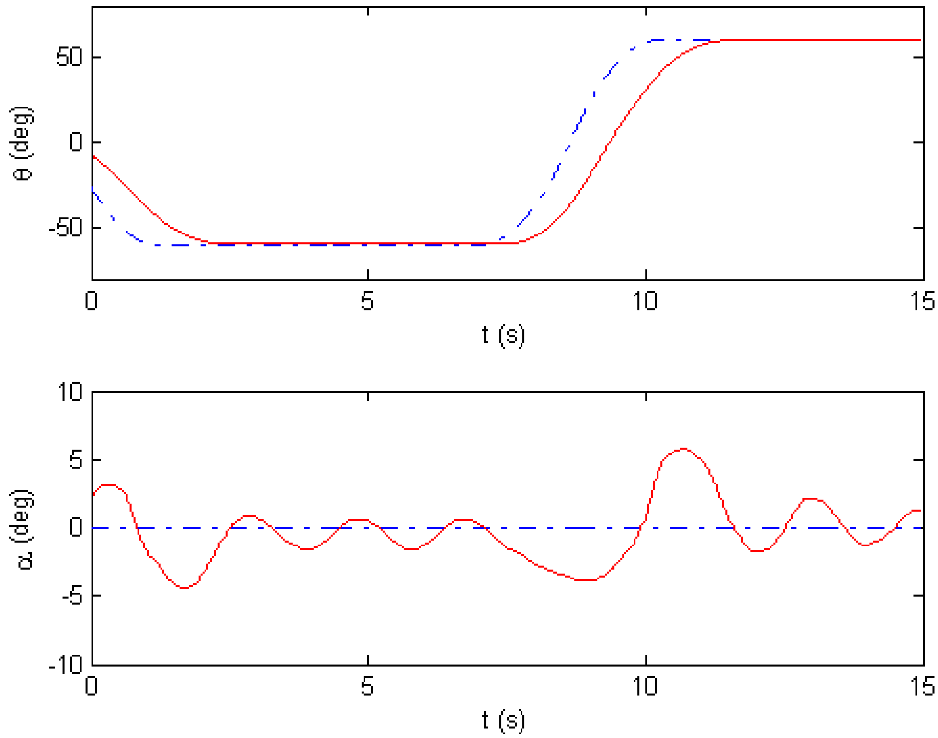


Figure 39 Full-state feedback response of tower system.

6. To investigate the effect of *not* using the gimble measurement place the *FS/PS Switch* on *partial* mode.
7. Reset the *Tower Setpoint* to -60 degrees.
8. Once the tower reaches this position and the payload settles, change the setpoint to 60 degrees and observe the response.
9. The top plot in Figure 40 shows the measured tower position and the bottom plot illustrates an obtained pendulum angle when the controller is set to *partial-state feedback* mode. As observed in the simulation, i.e. in Section 10.1, the pendulum oscillations decay very slowly and the largest peak exceeds ±5 degrees.

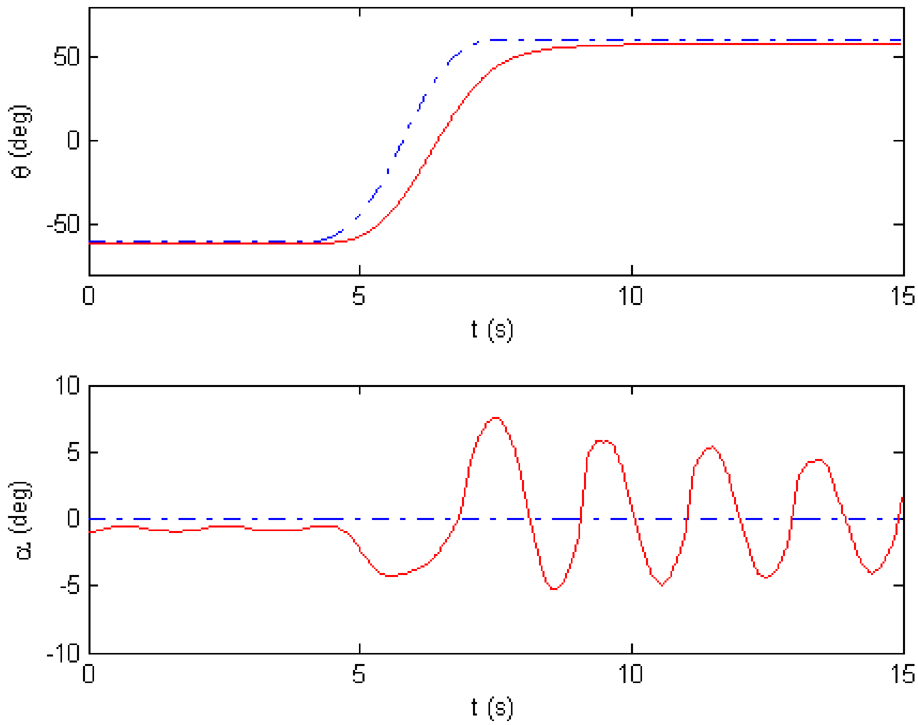


Figure 40 Partial-state feedback response of tower system.

10. Set the *FS/PS Switch* back to the *full* state feedback position to dampen the payload.
11. If finished, click on the Stop button in the Simulink diagram to stop the running the controller and turns off the AMPAQ.

10.2.5. Trolley Position Control Procedure

Go through these steps to control the position of the trolley:

1. The system should be ready and the controller running, as dictated in the steps of Section 10.2.3.
2. Open the *x (m)* and *gamma (deg)* scopes. The *x (m)* scope shows the reference trolley position in green and the measured trolley position in red. The measured γ gimble angle is shown in green in the *gamma (deg)* scope.
3. In the *Setpoints* subsystem, set the Slider Gain labelled *Trolley Setpoint* to 0.3 meters and observe the response in the opened scopes. The trolley should move away from the tower towards the end of the jib by 0.3 meters.
4. Figure 39 depicts the measured response of the tower position and the pendulum angle when in *full-state feedback* mode. The red solid line is the measured response

and the blue dash-dot is the reference position. The trolley tracks the commanded position, shown in the top plot, while maintaining trying to keep the payload motionless, illustrated in the bottom plot.

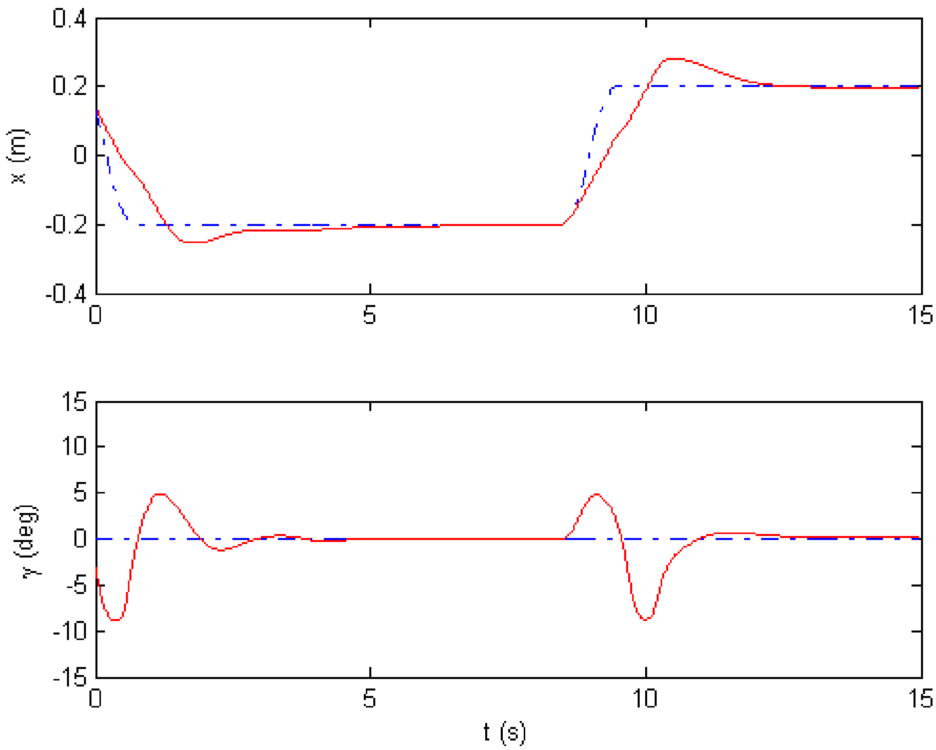


Figure 41 Full-state feedback response of jib system.

5. Reset the *Trolley* setpoint to 0 meters.
6. Once the payload motions settle, set the *FS/PS Switch* to the *partial* state feedback position.
7. Change the setpoint to 0.3 meters and examine the measured trajectory in the scopes.
8. As shown in the top plot of Figure 42, the trolley still tracks the setpoint. However, the bottom plot illustrates how the payload motions do not decay rapidly when using *partial*-state feedback.

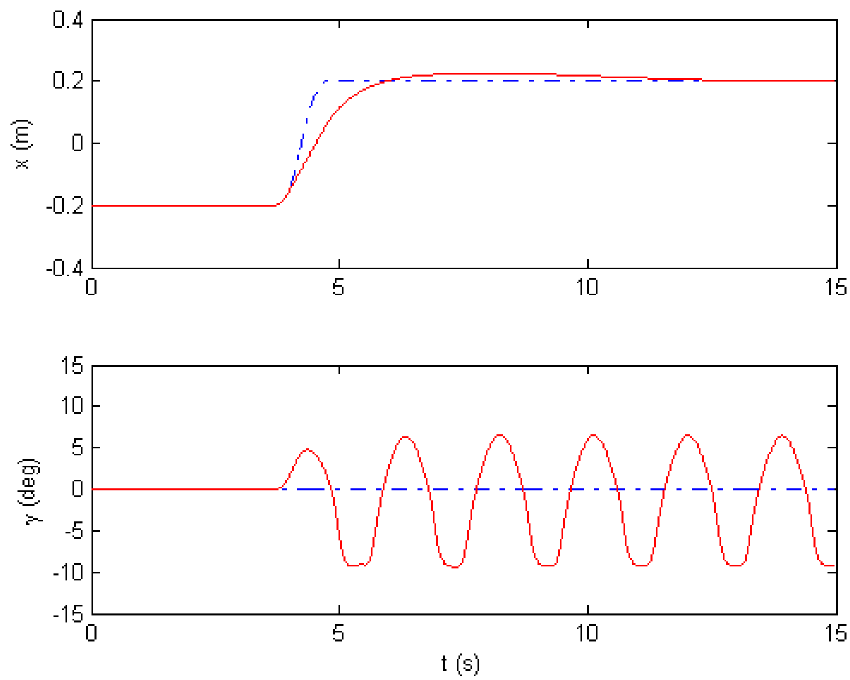


Figure 42 Partial-state response of jib system.

9. Set the *FS/PS Switch* back to the *full* state feedback position to dampen the payload.
10. If finished, click on the *Stop* button in the Simulink diagram to stop the running the controller and turns off the AMPAQ.

10.2.6. Payload Position Procedure

Go through these steps to control the vertical position of the payload:

1. The system should be ready and the controller running, as dictated in the steps of Section 10.2.3.
2. Open the z *(m), theta (deg),* and *x (m)* scopes. In all the scopes, the reference is in green and the measured position is in red. Recall that 0 meters is when trolley spool is fully reeled out and the payload is closest to the ground.
3. In the *Setpoints* subsystem, set the Slider Gain labelled *Payload Setpoint* to 0.6 meters and observe the response in the opened scopes. The reel on the trolley should begin spinning and the payload should lift 0.6 meters from its original location.
4. The top plot in Figure 43 depicts the response of the payload position when in *full-state feedback* mode and *weighed-state* mode. The red solid line is the measured response and the blue dash-dot is the reference position. As shown, the payload tracks the commanded position well. The bottom-left plot in Figure 43 is the

measured tower response and the bottom-right plot is the response of the trolley position. Since full-state feedback is used, the tower and the trolley have some small displacement to compensate for the payload motions.

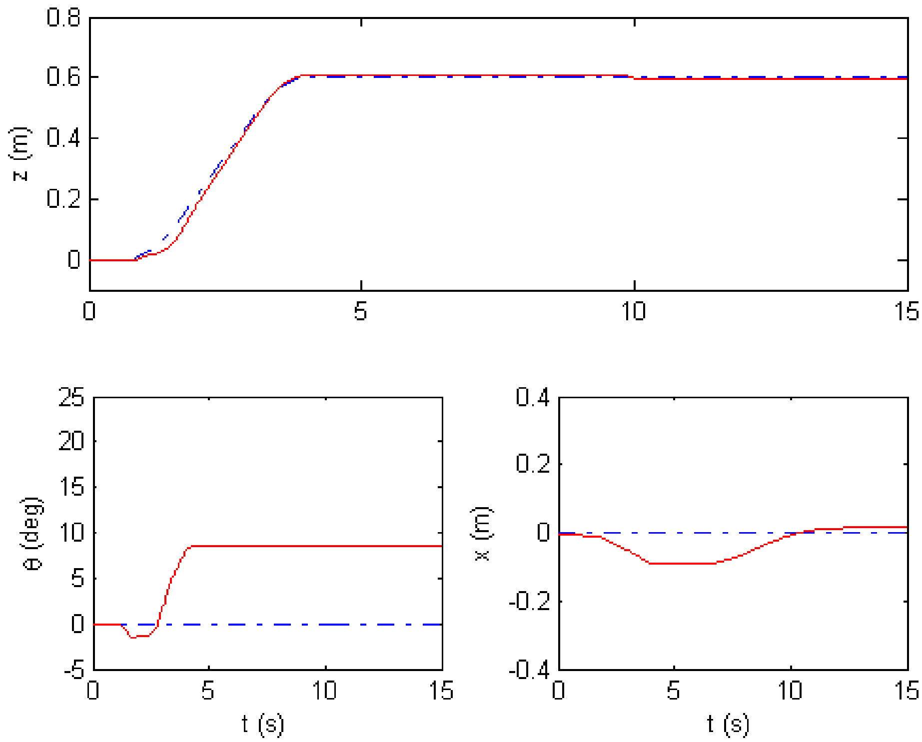


Figure 43 Full-state and weighed-state payload response.

5. Reset the *Payload* setpoint to 0 meters.
6. Set the *X/XW Switch* to the *non-weighed* state feedback position. The overcompensating effects of *not* using the *Weighed State* system, as discussed in Section 9.3.2, will now illustrated.
7. Once the payload motions settle, change the setpoint to 0.6 and examine the measured trajectory in the scopes.
   Get ready to set the *X/XW Switch* back to the *weighed* state position when the tower being oscillating rapidly!
8. As shown by the *non-weighed* state response in Figure 44, the tower begins to chatter uncontrollably when trying to compensate for the swinging payload.

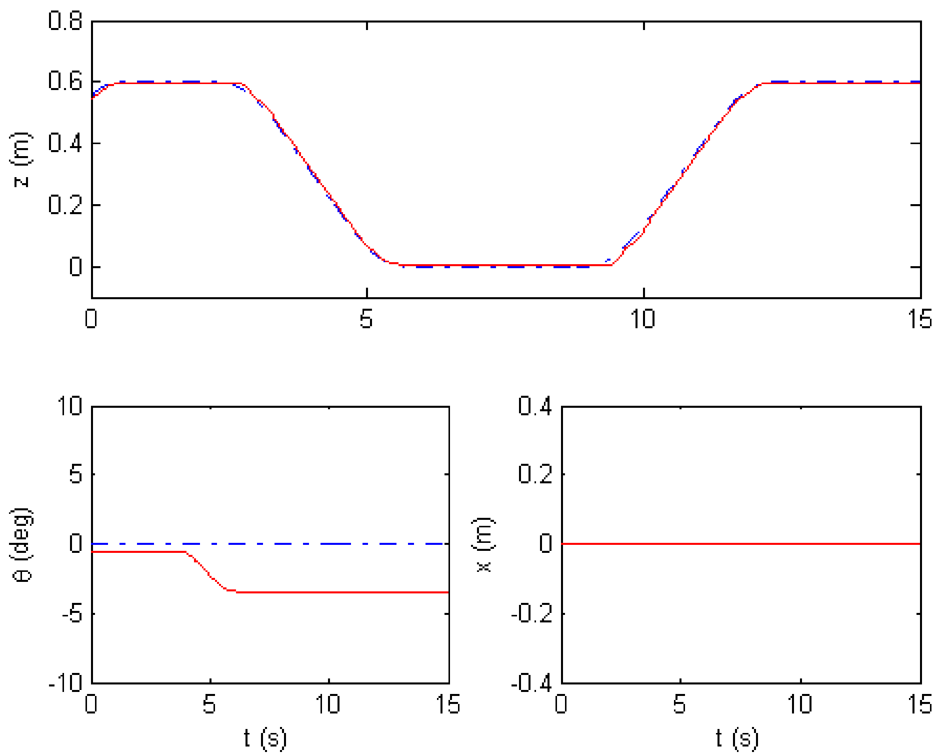


Figure 44 Non-weighed state payload position response.

9. If not already done so, set the *X/XW Switch* back to the *weighed* state position to dampen the payload properly.
10. Bring the payload back down by setting the *Payload* setpoint to 0 meters.
11. If finished, click on the Stop button in the Simulink diagram to stop the running the controller and turns off the AMPAQ.

10.3. Crane Calibration

The calibrated 3 DOF Crane system is depicted in Figure 1. This is when the tower BCP L/R sensor is between the left and right magnets, the trolley is in the mid-stroke position along the jib, and the payload is about 0.7 meters down from the jib.

10.3.1. Objectives

Calibrate the 3 DOF Crane system such that the tower, trolley, and payload are at their home positions.

10.3.2. 3-DOF Crane Calibration Simulink Model Description

The *q_3d_crane_cal.mdl* Simulink model used to calibrate the 3 DOF Crane system is shown in Figure 45. The calibration controller is a position controller with setpoints that move the tower, trolley, and payload to their specified home positions. Many of the subsystems used the position controller in Section 10.2.2 are used in *q_3d_crane_cal*. The two new subsystems are *Setpoints for Calibration* and *Calibration Complete* are discussed in Section 10.3.2.1 and Section 10.3.2.2, respectively.

The default calibration procedure is as follows (all performed simultaneously):

1. Rotate the tower CCW until the left tower limit switch, BCP L/R, is triggered. At that point, reset the encoder and move the tower CW 155 degrees to its home position. The home position is the when the jib is in the middle of the two BCP L/R magnets.
2. Move the trolley back towards the tower until the *CCP-Ret* limit switch is activated. Then, move the trolley 0.3 meters to the mid-stroke position on the jib, as shown in Figure 1.
3. Lift the payload until the *Payload* limit switch is triggered. At that point, reset the payload encoder and drop the payload 0.7 meters.

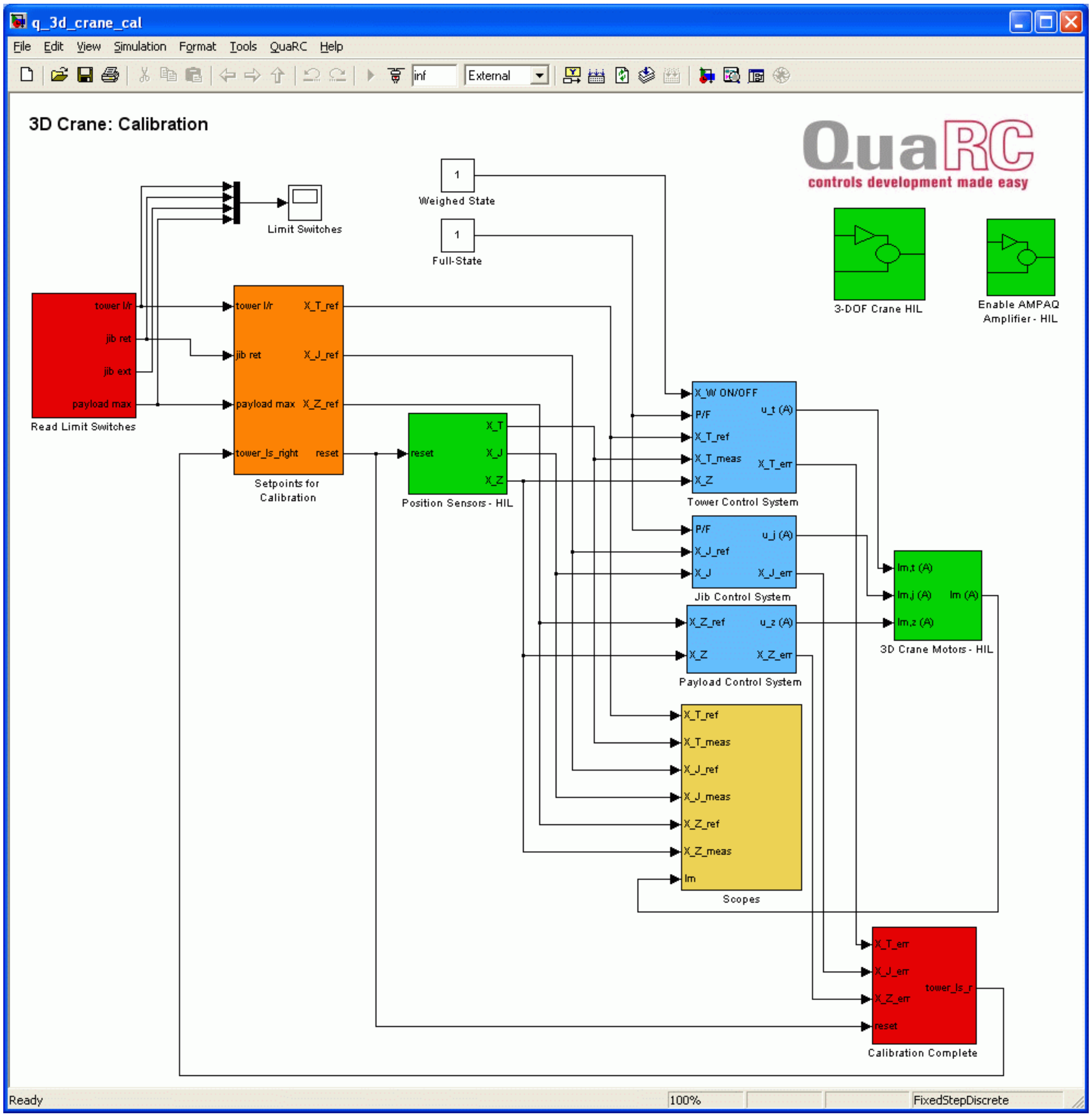


Figure 45 Simulink model used with QUARC to calibration 3 DOF Crane.

10.3.2.1. Calibration Setpoints Subsystem

The *Setpoint for Calibration* subsystem shown in Figure 46 generates desired tower, trolley, and payload positions according to the limit switches triggered in order to move the systems to their home positions.

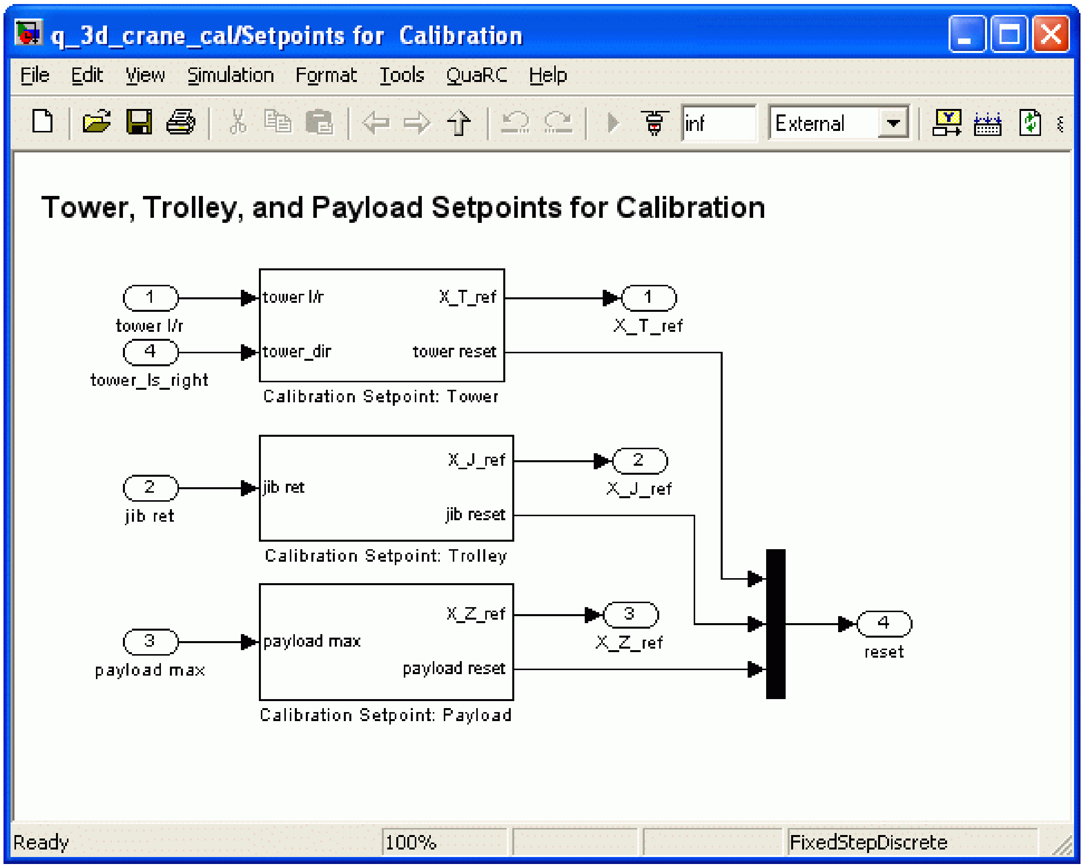


Figure 46 Setpoint for Calibration subsystem.

The *Calibration Setpoint: Tower* subsystem, shown in Figure 47, initially rotates the tower counter-clockwise. When the *BCP CCW* limit switch is hit, the encoder is reset to zero and the tower is rotated clockwise 155 degrees to its home position. The tower home position can be changed (instead of 155 degrees) by setting a different value for the *sp_home_tower variable* found in *setup_3d_crane.m*. Note that the *Triggered Sigmoid* block is used to re-initialize the setpoint trajectory.

If the tower *BCP CCW* limit switch is already being triggered, the the tower moves directly to home. Similarly, if the *BCP CW* switch is already depressed, then the tower moves counter-clockwise to its home position.

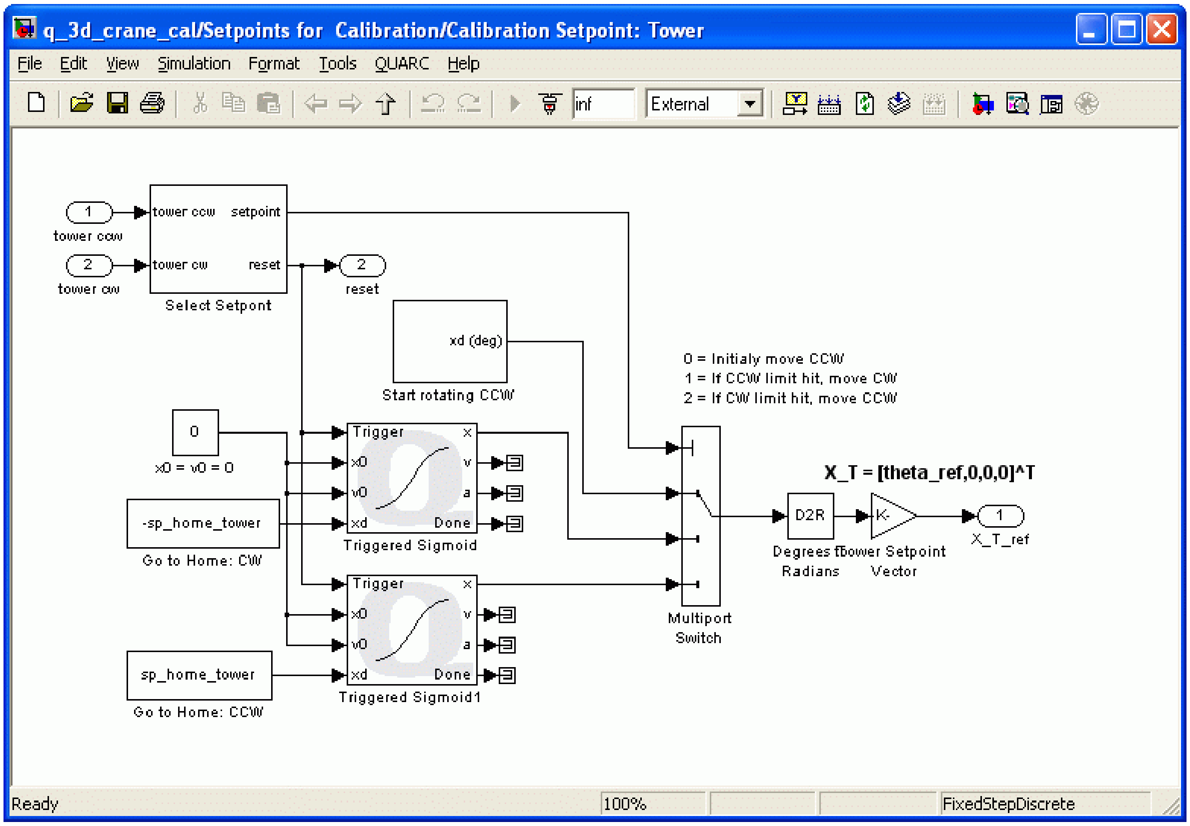


Figure 47 Tower Calibration Setpoint subsystem.

The *Calibration Setpoint: Trolley* subsystem, shown in Figure 48, begins to move the trolley back towards the tower until the *CCP-Ret* limit switch is triggered. Once the limit is hit, the jib encoder is reset and the trolley is commanded to move the middle position of the jib. By default, this is approximately 0.30 meters but the desired home position can be changed by setting a different value for the *sp_home_trolley variable* in *setup_3d_crane.m*.

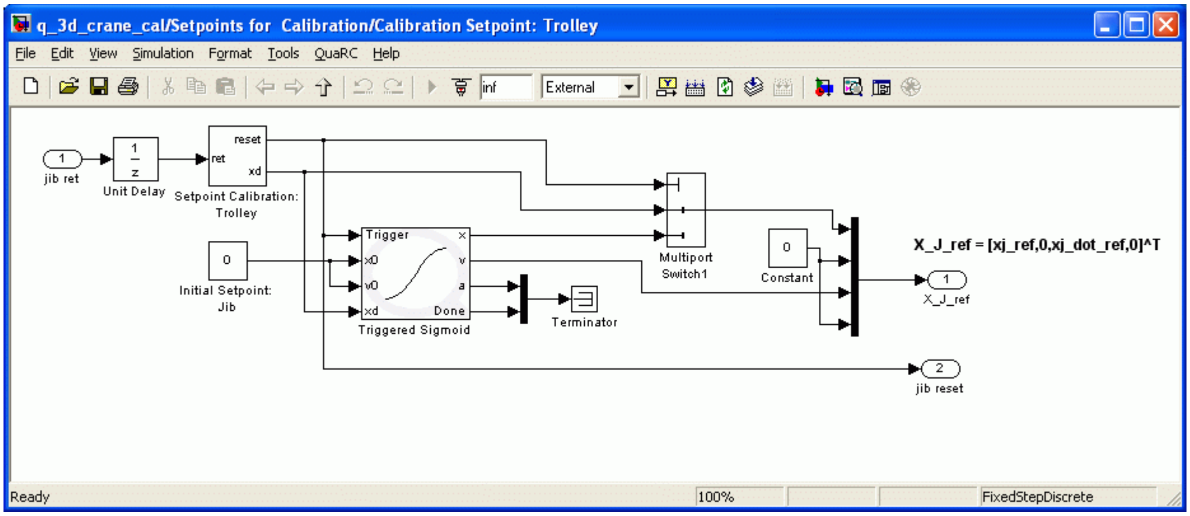


Figure 48 Trolley Calibration Setpoint subsystem.

The *Calibration Setpoint: Payload* subsystem that is pictured in Figure 49 lifts the payload until the *Payload* proximity sensor detects the payload magnet. At that point, the payload encoder is reset and the payload is dropped 0.7 meters from the jib, or to whatever value the *sp_home_payload variable* in *setup_3d_crane.m* is set too.

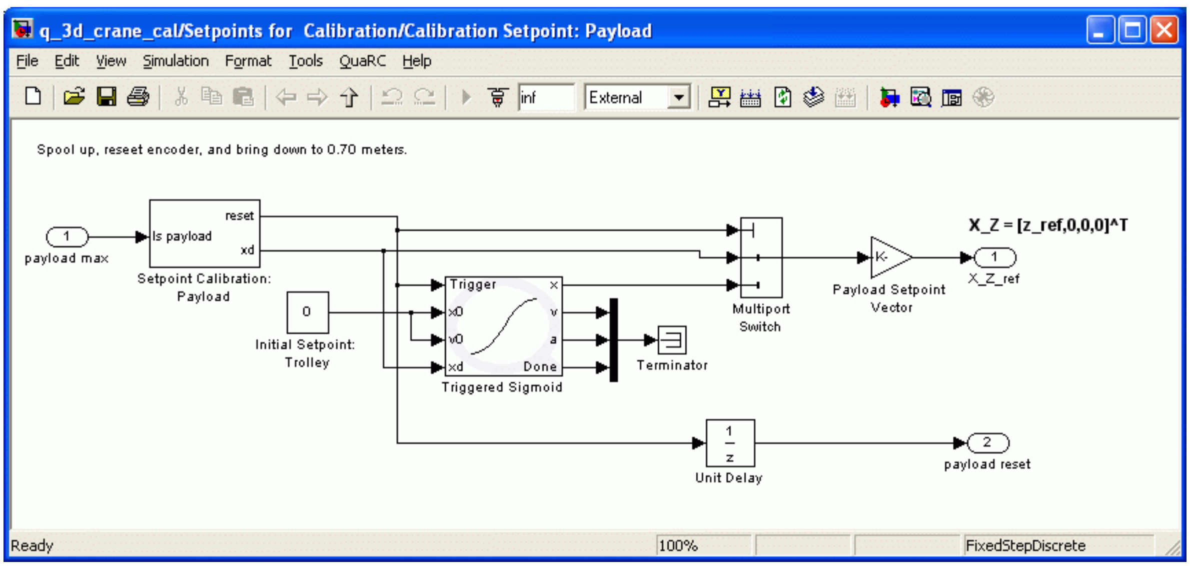


Figure 49 Payload Calibration Setpoint subsystem.

10.3.2.2. Calibration Complete Subsystem

The interior of the *Calibration Complete* block is shown in Figure 50. It determines when the calibration is complete. When the tower, trolley, and payload encoders have all been reset, the error between the desired and measured positions and velocities are examined. The tower is calibrated when the following condition applies

$$|-\theta_d + \theta| - calib\_theta \leq 0 \textbf{ and } \left|\frac{d}{dt}\theta(t)\right| - calib\_theta\_dot \leq 0, \quad [53]$$

where *calib_theta* is the tower position error threshold and *calib_theta_dot* is the tower velocity error threshold. Both of these variables are can be set in the *setup_3d_crane.m* script. Thus if the position is equal or below to *calib_theta* (default is set 3.5 degrees) and its velocity is below *calib_theta_dot* (default is 0.001 rad/s) then the tower is calibrated. Similarly, the trolley is calibrated when

$$|-x_d + x| - calib\_x \leq 0 \textbf{ and } \left|\frac{d}{dt}x(t)\right| - calib\_x\_dot \leq 0 \quad [64]$$

and the payload is calibrated when

$$|-z_d + z| - calib\_z \leq 0 \textbf{ and } \left|\frac{d}{dt}z(t)\right| - calib\_z\_dot \leq 0. \quad [65]$$

The *calib_x* and *calib_x_dot* are the trolley position and velocity error thresholds and the *calib_z* and *calib_z_dot* are the position and velocity calibration thresholds for the payload. Once everything is satisfied, the calibration controller is stopped using the *Stop With Message* block and the "Calibration complete" message is prompted.

If the message is not prompted, it may be that the thresholds are set too low. They may have to be fine tuned according to the particular 3 DOF Crane device.

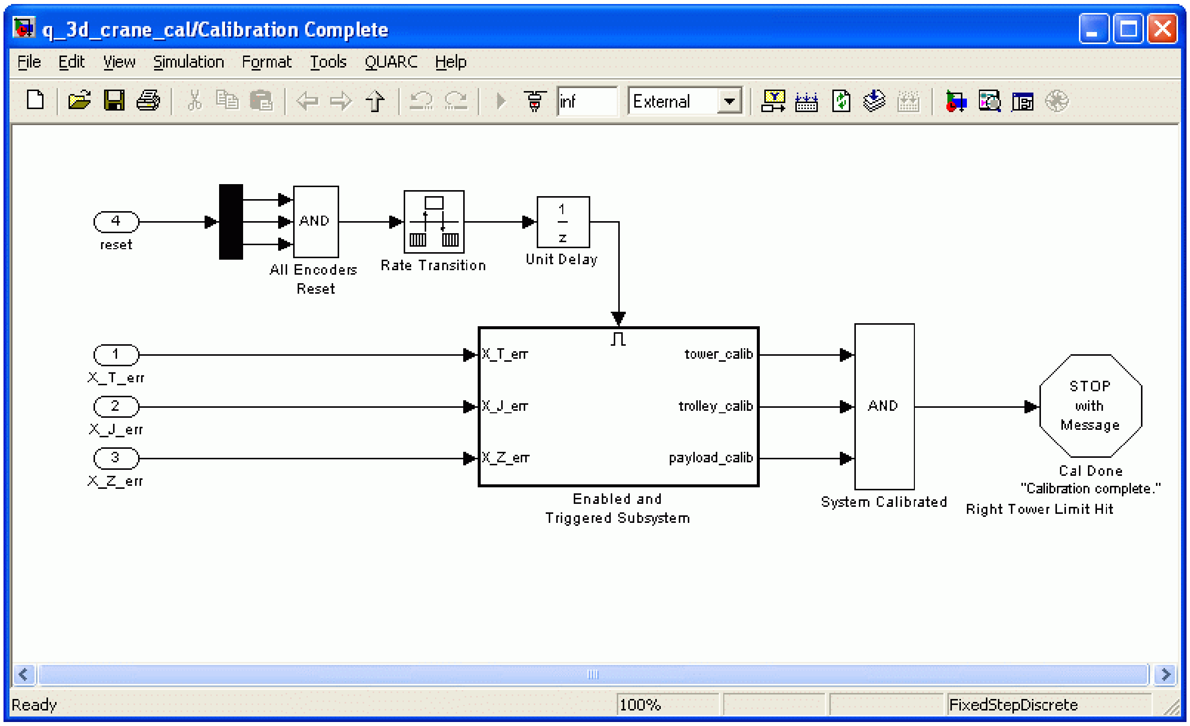


Figure 50 Calibration Complete subsystem.

10.3.3. Running Procedure

Follow the steps described below to build and run the controller that calibrates the 3 DOF Crane system:

1. **Before running the experiment:**
   (1) Ensure all the connections have been made as instructed in Section 8.
   (2) Place the 3 DOF Crane device in a clear area where the tower is free to rotate 360 degrees without any obstructions.
   (3) Make sure a payload is attached and let the payload suspend and settle down, as illustrated in Figure 1.
2. Load Matlab.
3. Open Simulink model *q_3d_crane_cal.mdl* shown in Figure 45.
4. Execute the design file *setup_3d_crane.m* to setup the workspace.
5. Click on the *QUARC | Build* item located in the Simulink menu bar to generate the real-time code.
6. Turn the AMPAQ power on. The green Power LED on the upper-left corner of the amplifier should be lit.
7. When the payload is motionless, start the controller by clicking on the *Start* button in the toolbar of the Simulink model. The real-time controller can be stopped at any time

by clicking on the *Stop* button found on the toolbar of the Simulink model. Alternatively, the *Pause/Break* key on the keyboard can be used to stop the controller.

8. The tower should begin calibrating: typically the tower is moved counter-clockwise, the trolley begins to move towards the tower and the payload is lifted up in increments. Once all the limit switches are hit and the systems have been moved to their home positions, the controller is stopped and the "Calibration complete" message is displayed.

11. Obtaining Support

Note that a support contract may be required to obtain technical support. To obtain support from Quanser, go to http://www.quanser.com and click on the *Tech Support* link. Fill in the form with all requested software version and hardware information and a description of the problem encountered. Be sure to include your email address and a telephone number where you can be reached. A qualified technical support person will contact you.