Voice-Coil-Driven Flexible Positioner

VCFP Demo

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dSPACE

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Important Notice

Contents

About This Document

Content

This documentation describes the hardware and software provided by the VCFP demo equipment. The demo equipment can be used to simulate a hard disk's access arm that is a 7th-order mechanical actuator (Voice-Coil-driven Flexible Positioner, VCFP). You can run the demo as Simulink simulation or as a real-time simulation on a DS1104 R&D Controller Board.

Symbols

dSPACE user documentation uses the following symbols:

Symbol	Description
⚠ DANGER	Indicates a hazardous situation that, if not avoided, will result in death or serious injury.
⚠ WARNING	Indicates a hazardous situation that, if not avoided, could result in death or serious injury.
⚠ CAUTION	Indicates a hazardous situation that, if not avoided, could result in minor or moderate injury.
NOTICE	Indicates a hazard that, if not avoided, could result in property damage.
Note	Indicates important information that you should take into account to avoid malfunctions.
Tip	Indicates tips that can make your work easier.
⍰	Indicates a link that refers to a definition in the glossary, which you can find at the end of the document unless stated otherwise.
📖	Precedes the document title in a link that refers to another document.

Naming conventions

dSPACE user documentation uses the following naming conventions:

%name% Names enclosed in percent signs refer to environment variables for file and path names.

< >   Angle brackets contain wildcard characters or placeholders for variable file and path names, etc.

The VCFP Simulator

Introduction

The principles of the VCFP simulator are explained in the following sections.

Where to go from here

Information in this section

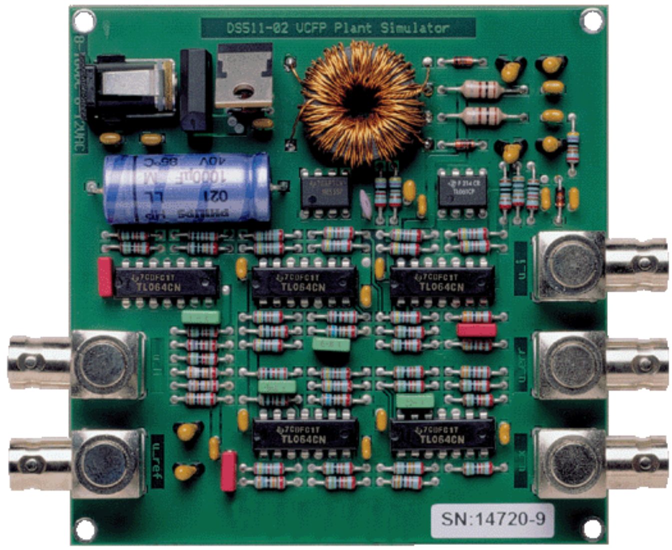
The VCFP Simulator Board

Introduction

The VCFP Simulator Board (DS511 VCFP Plant Simulator is printed on the circuit board) is a completely analog circuit that simulates a 7th-order electromechanical system, a voice coil-driven flexible positioner. This system is typical of the fast actuators and positioning mechanisms found in computer disk drives.

When connected to a dSPACE controller board, the VCFP Simulator Board can be used to demonstrate control design and implementation. PID control with or without hand-tuning, high-order state-space control based on LQG or H∞ design methods, and self-tuning control experiments are just a few examples of what can be demonstrated with the VCFP Simulator Board.

To connect the VCFP Simulator Board, a standard power adapter can be used for the power supply, and BNC connectors make it easy to hook up to a function generator, scope, and dSPACE controller board.



The VCFP Simulator Board is 'impossible-to-break' if designs go wrong, which is ideal for university labs. Since the bandwidth of the control loops can be up to about 1 kHz, standard oscilloscopes can be used to observe step responses, which gives students in the lab very quick visual feedback.

Related topics

Basics

Electromechanical Model.. 8

References

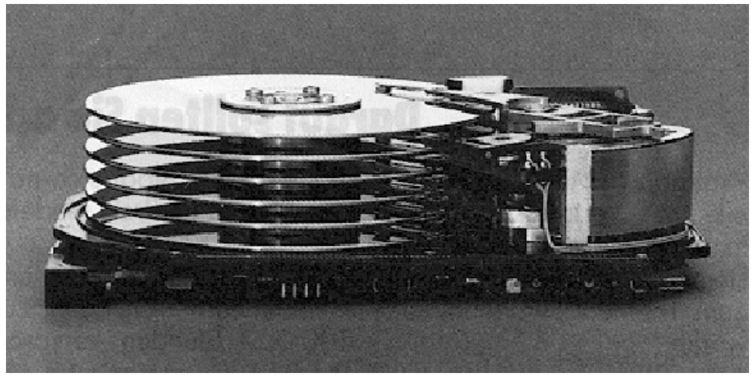
Connecting the VCFP Simulator Board.. 17

Electromechanical Model

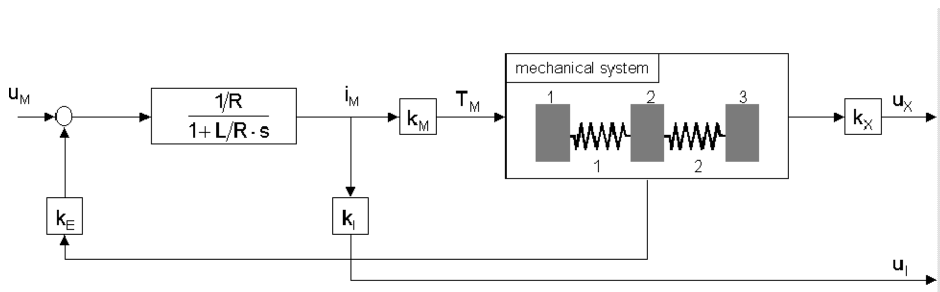
Basics

A common high-bandwidth positioning method is to have a coil moving in a magnetic field with a moving arm attached to the coil and electrical current flowing through the coil. The magnetic field is normally provided by permanent magnets.

This same principle is found in loudspeakers, where the term voice coil originates. In a loudspeaker the motion is linear, whereas in other applications such as computer disk drives the motion may be rotational. An example of a disk drive is shown in the illustration below.



When the coil moves, a voltage is induced. The amplifier feeding the coil may be either a voltage or a current amplifier. If it is a voltage amplifier, the only difference between the applied voltage and the induced voltage is the generated current. If it is a current amplifier, it ideally forces the required current to flow regardless of the induced voltage. This is assumed in the model below.



The mechanical arm is normally designed to be rigid. However, at a high control bandwidth it is not unusual for resonances to appear, even with seemingly stiff structures. In such cases the measured frequency response plots often have a 'zigzag' pattern, with many low-damped resonances and very deep notches.

Sometimes there are some lower-frequency flexible modes that can reasonably be modeled by just a few resonances. In such cases it is possible to create a lumped parameter model, even if the true effects are more structural and complicated finite element models would be more natural.

For the VCFP simulator model, a lumped parameter model is set up with three masses of inertia connected by two springs with dampers. Although the real arm might not look like a series connection of lumped masses with springs and dampers, the I/O behavior is very similar.

Parameters

The parameters chosen for the lumped parameter model of the VCFP simulator model generate a frequency response typical of a real arm construction. The variables, electrical parameters, and mechanical parameters of the VCFP simulator are listed in the following three tables:

Variables	Description	Range	Unit
u_M	Input voltage, control signal	±10	[V]
u_X	Voltage representing the position	±10	[V]
u_I	Voltage representing the voice-coil current	±10	[V]
i_M	Voice-coil current	—	[A]
T_M	Torque driving the mechanical system	—	[Nm]

Electrical Parameters	Description	Value	Unit
R	Voice-coil armature resistance	1	[W]
L	Voice-coil armature inductance	0.1	[mH]
k_E	Electromotive force constant	1	[Vs/rad]
k_I	Current sensor gain	10	[V/A]
k_M	Torque constant	0.1	[Nm/A]
k_X	Position sensor gain	100	[V/mm]

Mechanical Parameters	Description	Value	Unit
J_1	Inertia 1	0.11	[g/m2]
J_2	Inertia 2	0.26	[g/m2]
J_3	Inertia 3	0.11	[g/m2]
d_1	Damping constant (at inertia 1)	0.08	[Nms/rad]
d_2	Damping constant (at inertia 2)	0.08	[Nms/rad]
d_3	Damping constant (at inertia 3)	0.03	[Nms/rad]
C_{12}	Spring constant (of spring 1)	1000	[Nm/rad]
C_{23}	Spring constant (of spring 2)	1000	[Nm/rad]
d_{12}	Damping constant (internal damping of spring 1)	0.08	[Nms/rad]
d_{23}	Damping constant (internal damping of spring 2)	0.08	[Nms/rad]
k_r	Rotational to linear constant	0.08	[Nms/rad]

Related topics

Basics

Dynamics

Time constants and frequencies

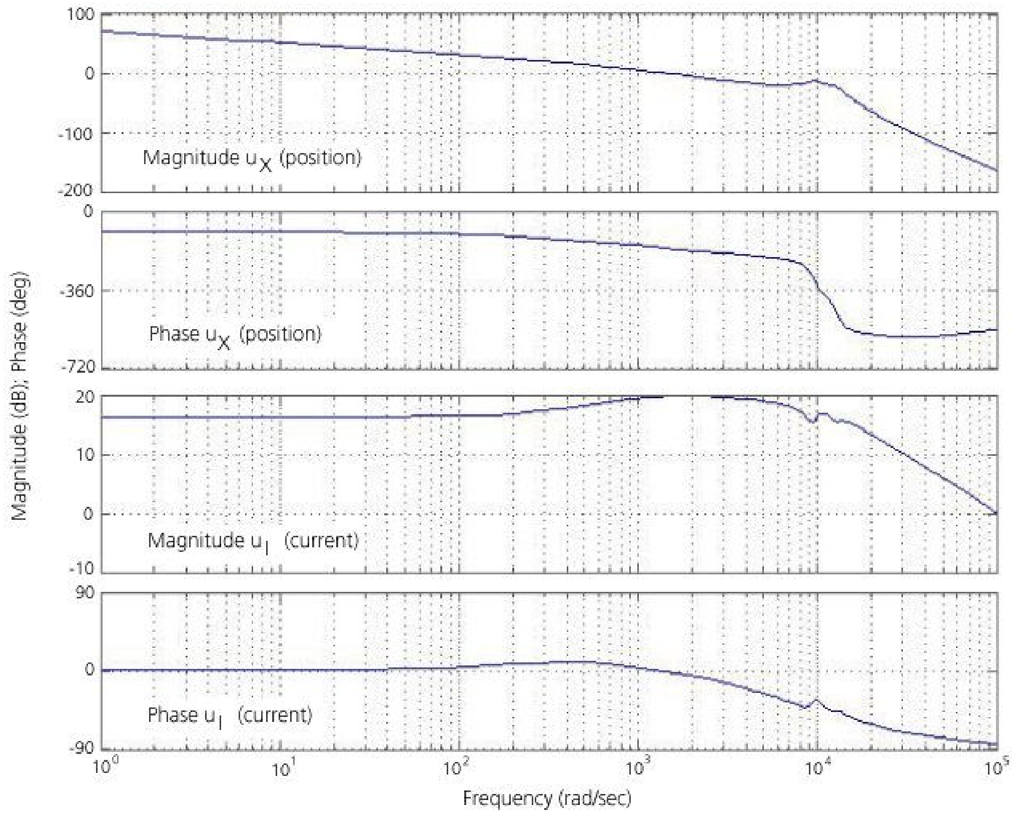
The time constants and frequencies in the next two tables can be computed from the mathematical model derived in State-Space Equations on page 12.

Time Constant	Time Constant [ms]
1	0.106
2	Infinity
3	1613

Time constant 1 of the aperiodic modes is determined primarily by the resistance and inductance of the coil. Infinity time constant 2 represents the integrator from velocity to position, and time constant 3 is associated with the induced voltage feedback.

Frequency [kHz]	Damping Factor	Decay Time Constant [ms]
2071	0.072	1068
1538	0.076	1353

The damping of the oscillatory modes is relatively high. In actual mechanical systems, damping could be much lower if the resonances are real structural resonances, which would make the control more difficult than in this example. The frequency response is given in the following Bode plot:



Related topics

Basics

State-Space Equations

Basics

The mathematical model is based on the following state-space equations.

$$\dot{x} = Ax + Bu$$

$$y = Cx$$

State variables

The following state variables are used in the derivation:

Vector	Equation	Description	Unit
x1	Ω1	Angular velocity mass 1	rad/s

Vector	Equation	Description	Unit
x2	Φ1	Rotation angle mass 1	rad
x3	Ω2	Angular velocity mass 2	rad/s
x4	Φ2	Rotation angle mass 2	rad
x5	Ω3	Angular velocity mass 3	rad/s
x6	Φ3	Rotation angle mass 3	rad
x7	iM	Electrical current	A

Basic equation

The basic equation required is

$$\dot{\Omega} = \frac{1}{J_i}\left(T_a - T_d - d_i\Omega_i\right)$$

where T_a means 'accelerating' torque (accelerating when positive) and T_d means 'decelerating' torque at a mass number i.

This yields

$$\dot{\Omega}_1 = \frac{1}{J_1}\left(T_M - T_{12} - d_1\Omega_1\right)$$

$$\dot{\Omega}_2 = \frac{1}{J_2}\left(T_{12} - T_{23} - d_2\Omega_2\right)$$

$$\dot{\Omega}_3 = \frac{1}{J_3}\left(T_{23} - d_3\Omega_3\right)$$

Torques

The torques used above are

$$T_M = k_M i_M$$
$$T_{12} = d_{12}\left(\Omega_1 - \Omega_2\right) + c_{12}\left(\Phi_1 - \Phi_2\right)$$
$$T_{23} = d_{23}\left(\Omega_2 - \Omega_3\right) + c_{23}\left(\Phi_2 - \Phi_3\right)$$

where

$$\dot{\Phi} = \Omega_i$$

Matrices

This results in matrices A and B with coefficients whose calculations can be seen clearly in the MATLAB M file in the following section (see Numerical Input in MATLAB on page 14).

The output vector has two components: the current voltage and the position voltage. The single non-zero element of matrix C for the current is $c_{17} = k_I$ because the output is in volts. Correspondingly, the single element in C for the position is c26 = k_X k_r for the conversion from rotary to linear to voltage.

The numerical values of the matrices A, B and C are:

$$A = \begin{pmatrix} -1.4545e+3 & -9.0909e+7 & 7.2727e+2 & 9.0909e+7 & 0 & 0 & 9.0909e+2 \\ 1.0000e+0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3.0769e+2 & 3.8462e+7 & -9.2308e+2 & -7.6923e+7 & 3.0769e+2 & 3.8462e+7 & 0 \\ 0 & 0 & 1.0000e+0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 7.2727e+2 & 9.0909e+7 & -1.0000e+3 & -9.0909e+7 & 0 \\ 0 & 0 & 0 & 0 & 1.0000e+0 & 0 & 0 \\ -1.0000e+4 & 0 & 0 & 0 & 0 & 0 & -1.0000e+4 \end{pmatrix}$$

$$B = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1.0000e+4 \end{pmatrix}$$

$$C = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1.0000e+4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.0000e+1 \end{pmatrix}$$

Related topics

Basics

Dynamics.......... 11
Nonlinear Effects.......... 16
Numerical Input in MATLAB.......... 14

Numerical Input in MATLAB

Basics

You can parameterize matrices A, B and C by creating an M file containing the numerical input values.

Example M file

The following M file generates A, B and C:

```
% set VCFP Simulator parameters
```

```
R   = 1;
L   = 1e-4;
kE  = 1;
kI  = 10;
kM  = 0.1;
kx  = 1e5;
J1  = 1.1e-4;
J2  = 2.6e-4;
J3  = 1.1e-4;
d1  = 0.08;
d2  = 0.08;
d3  = 0.03;
c12 = 1e4;
c23 = 1e4;
d12 = 0.08;
d23 = 0.08;
kr  = 0.1;
```

```
% VCFP Simulator linear state-space model
```

```
a_p      = zeros(7,7);
a_p(1,7) = kM/J1;
a_p(1,1) = (-d1-d12)/J1;
a_p(1,3) = d12/J1;
a_p(1,2) = -c12/J1;
a_p(1,4) = c12/J1;
a_p(2,1) = 1.0;
a_p(3,1) = d12/J2;
a_p(3,3) = (-d12-d23-d2)/J2;
a_p(3,5) = d23/J2;
a_p(3,2) = c12/J2;
a_p(3,4) = (-c12-c23)/J2;
a_p(3,6) = c23/J2;
a_p(4,3) = 1;
a_p(5,3) = d23/J3;
a_p(5,5) = (-d23-d3)/J3;
a_p(5,4) = c23/J3;
a_p(5,6) = -c23/J3;
a_p(6,5) = 1.0;
a_p(7,7) = -R/L;
a_p(7,1) = -kE/L;
```

```
b_p      = zeros(7,1);
b_p(7,1) = 1/L;
```

```
c_p      = zeros(2,7);
c_p(1,6) = kr*kx;
c_p(2,7) = kI;
```

```
d_p(1,1) = 0.0;
d_p(2,1) = 0.0;
```

Related topics

Basics

Nonlinear Effects

Basics

The model derived in the previous section is valid for the linear operation range. When using it for control at or beyond the limits of linear operation, be aware of the following issues and limitations.

- Position Range and Control Saturation
- Current Sensor Saturation
- Internal Operational Amplifier Saturation

Position Range and Control Saturation

The position range is ± 10 V. As is usually the case with position control, full-stroke or even large-stroke steps can never be followed closely by the control system. Extremely high torque and, in this case, input voltage would be required. With a large enough amplifier, this might be available, but the coil would probably melt instantly. When you use the VCFP Simulator Board, the input voltage should be limited to ± 10 V and only small steps can be carried out in the commanded position.

A good practical position command system in an industrial application would also not let any large position command step go through unmodified. With very aggressive controllers, square wave position commands of ± 0.1 V bring the control signal to the limits. In this case, nonlinear rate limiters in the command path of a digital controller are a good solution. They also help avoid the current sensor saturation described below.

Note

In an open loop, the position will saturate at a positive or negative limit because the plant is unstable due to the integrator in the dynamics.

Current Sensor Saturation

With aggressive controllers, the current sensor output (± 10 V range) may saturate much earlier than the control signal. This is harmful if the current sensor signal is used in the controller (for instance, to assist in state estimation) and no countermeasures are taken.

Internal Operational Amplifier Saturation

The operational amplifiers used to implement the transfer functions can also saturate. It is important to know this when nonlinear effects show up differently in an offline simulation compared to the VCFP Simulator Board.

For example, one aggressive demo controller available at dSPACE still performs reasonably well without a command/reference rate limiter when the current control signal exceeds ± 10 V and the AD converter to the digital controller clips that signal. However, if the same system is simulated offline, modeling the linear system plus the entire AD converter and DA converter saturation, the system shows basically unstable behavior. Large full-swing limit cycles are the result. The reason for the difference between the real and the simulated behavior is the internal saturation of the VCFP simulator circuit, which prevents huge modeled currents from developing. In offline simulation, however, the current is not limited, only the sensor signal is.

Related topics

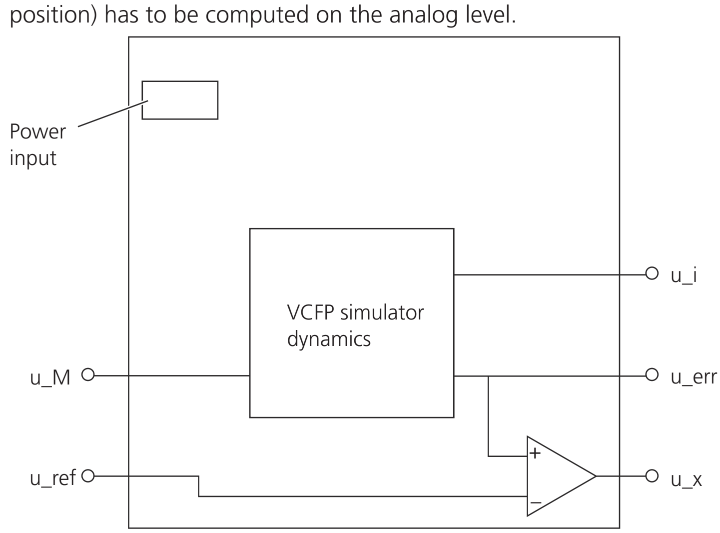
Basics

Numerical Input in MATLAB.. 14
State-Space Equations.. 12

Connecting the VCFP Simulator Board

Basics

The VCFP Simulator Board has BNC connectors for u_M, u_X and u_I. There are two other BNC connectors available, which are useful if the position error (reference position) has to be computed on the analog level.



The VCFP Simulator Board is ready to be used once power is applied to the power input shown in the upper left corner. A switched power supply is on-board to generate the ± 15 V for the operational amplifiers from any voltage input between 8 … 16 V DC, regardless of polarity, or between 6 … 12 V AC.

The power consumption is 2 W.

NOTICE

Risk of hardware damage

If you use an AC power supply, the voltage must not exceed 12 V AC, independently of the loads.

DS1104 connector cables

For information on connecting the VCFP Simulator Board, refer to the following table:

BNC connector for DS1104 [1)]	Port
ADC 1	u_ref (external reference source, optional)
ADC 3	u_x
DAC 1	u_M

[1)] Connector P1A of the DS1104 adapter cable

The VCFP Control Demo

Introduction

This is a short guide to running the VCFP Control Demo with a dSPACE controller board and the VCFP Simulator Board. The demo software is designed to be used by Simulink and ControlDesk.

Where to go from here

Information in this section

Information in other sections

VCFP Control Demo for Simulink

Introduction

The first step in implementing an application with Real-Time Interface (RTI) is Simulink simulation. Both the controller and the VCFP simulator are designed within the MATLAB/Simulink development environment. You can therefore check the physical model of the VCFP simulator combined with the controller.

Where to go from here

Information in this section

Information in other sections

How to Run the Simulink Simulation From Within MATLAB

Objective

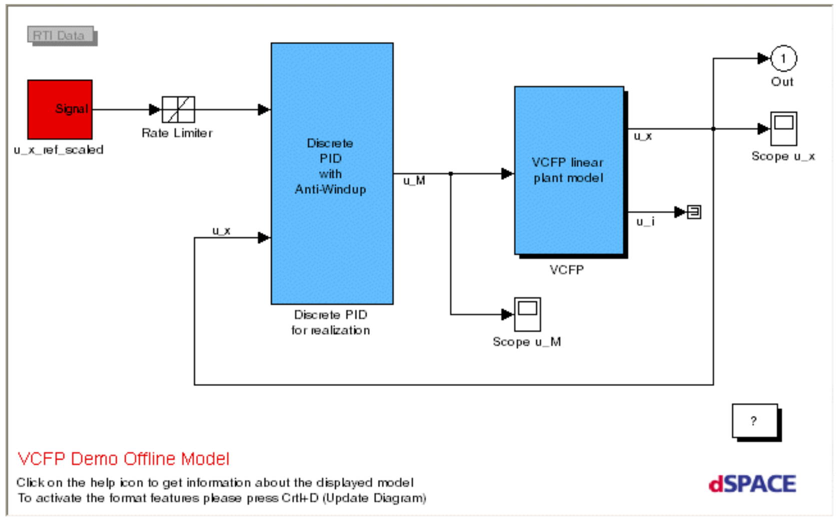
You can run the VCFP control demo directly with the VCFP Simulator Board without building a real-time application first, or start an offline simulation with Simulink.

Method

To run the Simulink simulation from within MATLAB

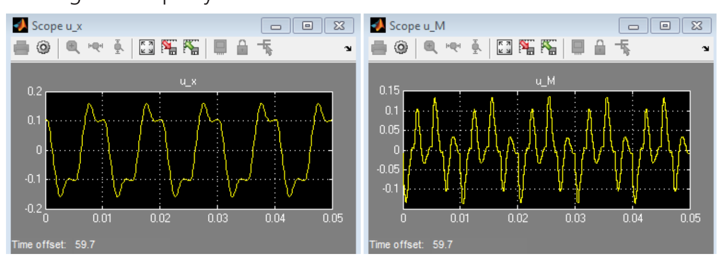
1. Start MATLAB.
2. Make sure that the current folder agrees with `<RCP_HIL_InstallationPath>\Demos\DS1104\Vcfp`.

3 To open the VCFP demo model, type **go PC** at the MATLAB prompt.



4 To start the simulation, click the **Start simulation** button.

To observe the behavior of the model, you can open the scopes by double-clicking the scope symbols in the model.



VCFP Control Demo for Real-Time Hardware

Introduction

The real-time simulation lets you implement an application on the real-time hardware. This lets you tune up the controller for the VCFP Simulator Board with the help of ControlDesk.

Where to go from here

Information in this section

Information in other sections

How to Open the Simulink Model for Real-Time Simulation

Objective

To show the Simulink model, from which the simulation application has been built.

Basics

The real-time simulation is based on the same discrete PID controller that is used in VCFP Control Demo for Simulink on page 20. The controller is connected to the VCPF simulator by an ADC and a DAC. A further ADC is necessary for external generation of the reference signal (optional).

The channels that are used depend on the real-time hardware. This is the reason why a specific model for a DS1104 is necessary.

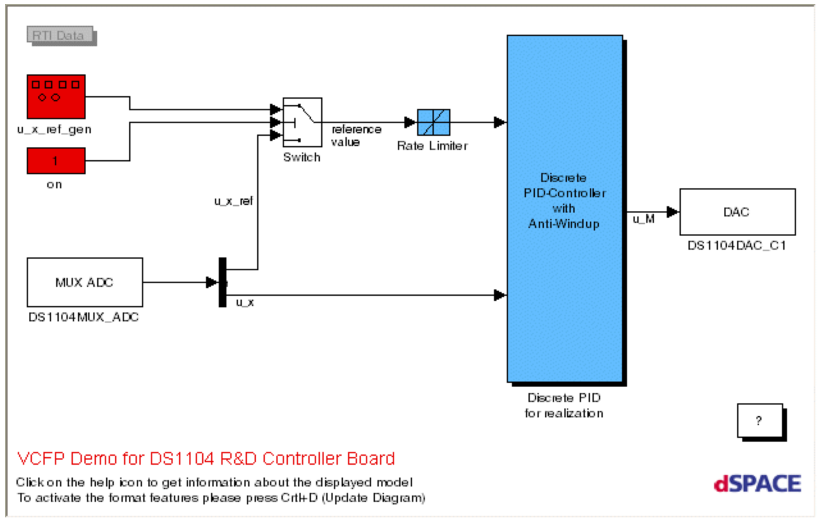
Method

To open the Simulink model for real-time simulation

1. Start MATLAB.
2. Make sure that the current folder agrees with `<RCP_HIL_InstallationPath>\Demos\DS1104\Vcfp`.
3. Type **go DSPACE** at the MATLAB prompt.

Result

The following model appears for the DS1104 R&D Controller Board:



Related topics

HowTos

How to Run the Real-Time Simulation

Objective

To run the simulation application that implements the PID controller on real-time hardware.

Precondition

The real-time hardware is connected with the VCFP Simulator Board like specified in Connecting the VCFP Simulator Board on page 17.

Tip

The VCFP Control Demo folder includes a prepared Simulink model and a ready-to-use object code, so it is not necessary to perform code generation beforehand.

Method

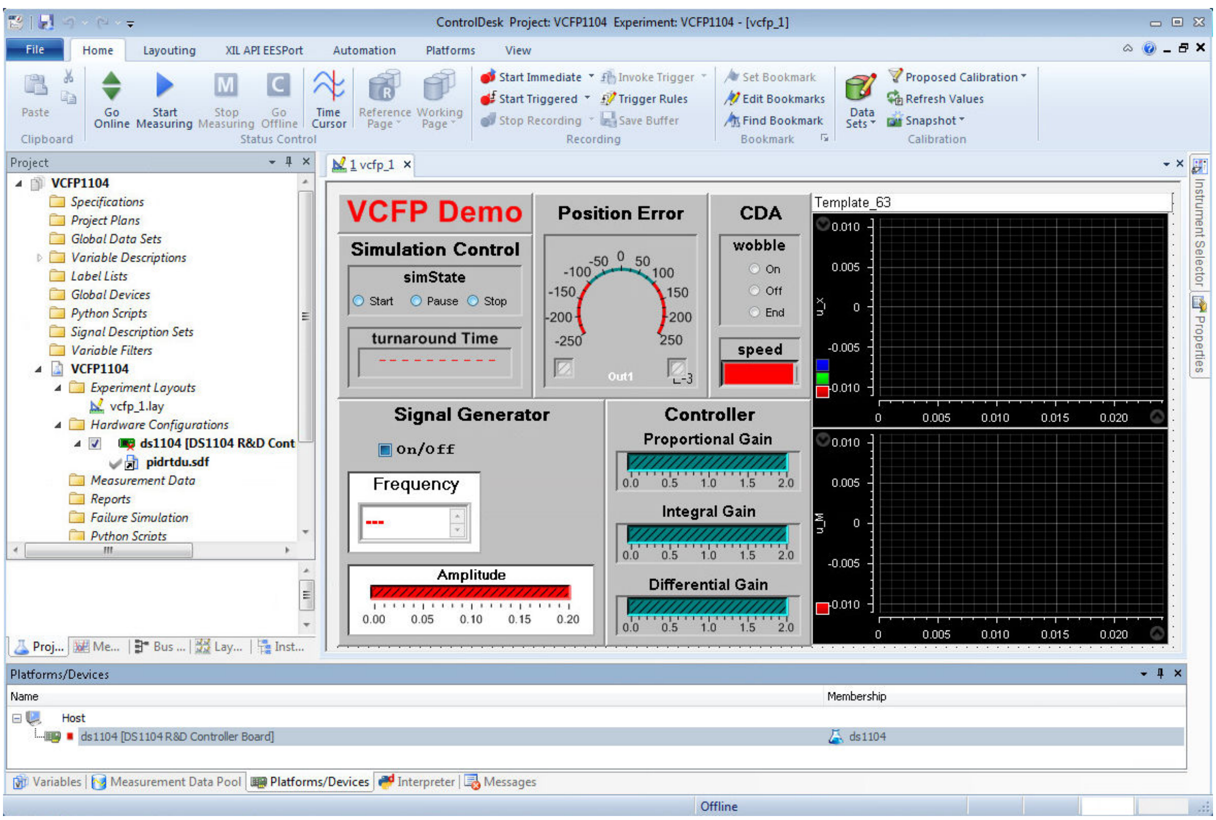
To run the real-time simulation

1 Start ControlDesk.

2 If your real-time controller board is not displayed in the Platform/Device Manager, register it. For details, refer to How to Register a Platform (ControlDesk Platform Management 📖).

3 On the File ribbon, click Open - Project + Experiment from Backup to open the backup ZIP file that contains the ControlDesk project for the VCFP Control demo. Choose the following backup file:<RCP_HIL_InstallationPath>\Demos\DS1104\Vcfp\VCFP1104.zip

The VCFP demo project is copied to your current ControlDesk root directory. Then this copy is opened. The controller board is assigned automatically to the activated experiment. The simulation application is specified via the PIDrtdu.sdf active variable description and the vcfp_1 experiment layout is displayed.

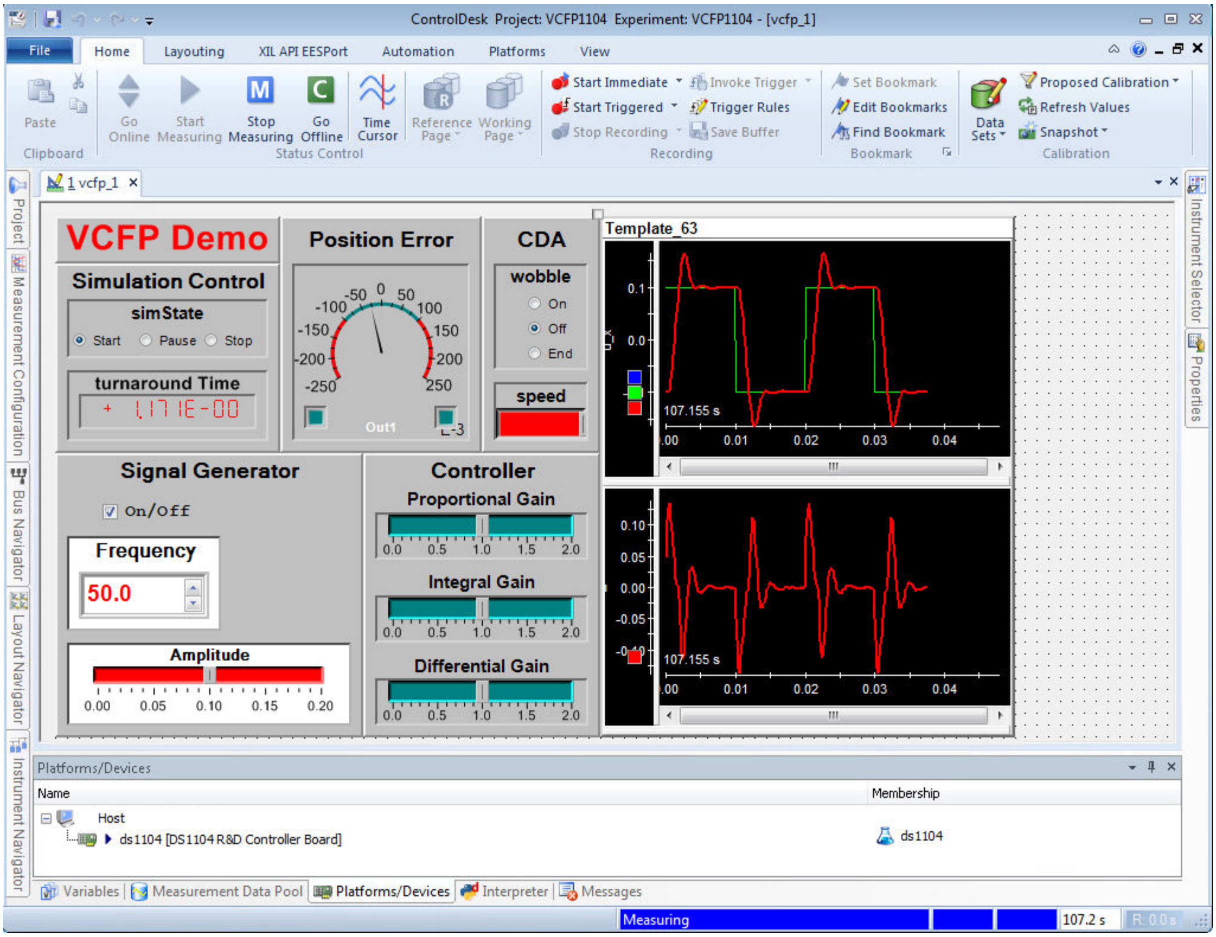


4 On the Home ribbon, click Start Measuring to download and start the simulation application on the real-time hardware.

The captured values of the running simulation application are displayed on the experiment layout.

Result

The VCFP Demo Control simulation application is running on the controller board and interacting with the connected VCFP Simulator Board. Using the instruments of the experiment's layout, you can change parameters and observe the simulation's behavior.



Note

The wobble and the speed instrument provide an obsolete automated testing feature and do not have an effect in the current experiment.

Related topics

HowTos