CH. 3: Control Practice of Planar Robots

[1] Introduction to xPC Target and speedgoat Controller

(1) xPC Target

(2) speedgoat controller

[2] Development of Robot Manipulators and Controllers

(1) Controller design

(2) Design of planar robots

[3] Control Practice

(1) Hardware Test

(2) PID control of DC motors

(3) Line move

(4) Trajectory move

(5) Gravity compensation

[1] Introduction to xPC Target and speedgoat Controller

(1) xPC Target

1) Basics

- Sequence: Simulink program on the Host PC → C-code Generation using Simulink Coder (previously, called Real-time Workshop) → C compiler → Making execution file with dlm extension → Downloading the dlm execution file to Target PC through TCP/IP (or RS-232).

2) Network setting

- TCP/IP setting of the Target PC:

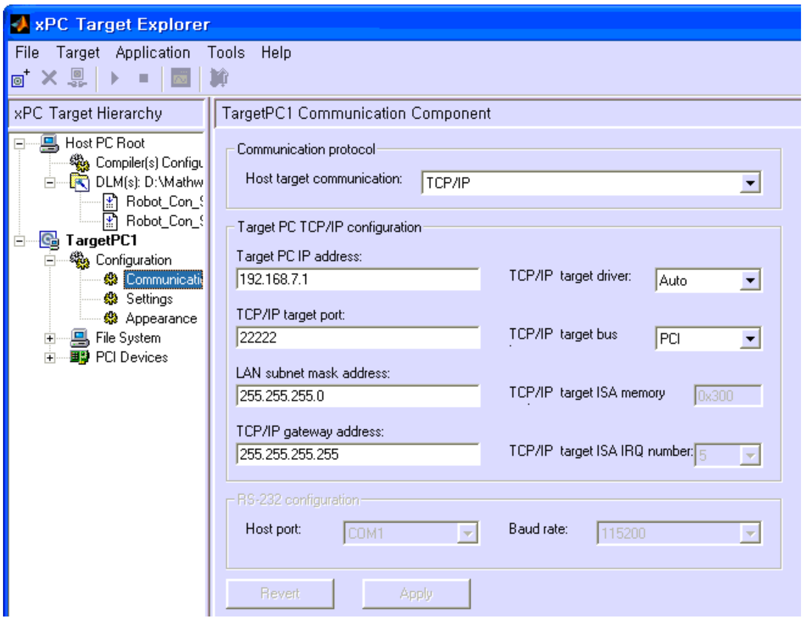
    (IP address) 192.168.7.1

    (Subnet mask address) 255.255.255.0

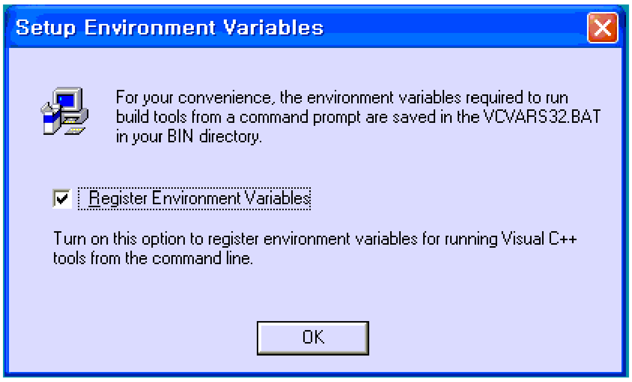
- TCP/IP setting of the Host PC:

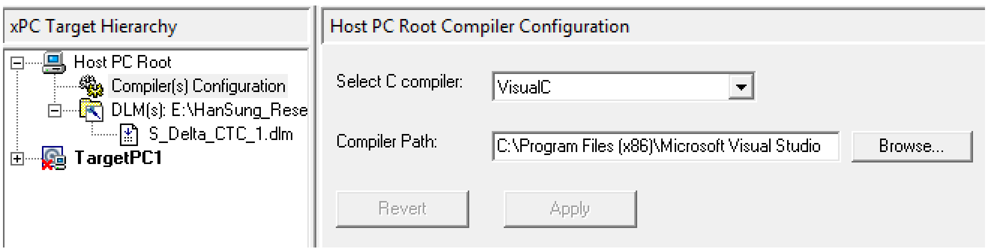
    (IP address) 192.168.7.2

    (Subnet mask address) 255.255.255.0



- Visual Studio Setting: Visual C++ 6.0 and higher version is required. Please, check “Register Environment Variables” options and set the compiler path of xPC explorer (xpcexplr) as follows.
- In the latest version, type xpcsetCC(‘setup’) in the command window.





(2) speedgoat Controller

1) Basics

- xPC Target Turnkey
- Education real-time target machine

Chassis	
Enclosure	Sheet chassis with EMI protection
Color	Zinc coated, black with blue label
Dimensions (*h* x *d* x *w*)	270 x 241.1 x 111.9 mm
Weight	4.5 kg
Power supply	24 V VDC input power rating, external power supply included
Mounting	Including rear brackets for wall or machine cabinet mounting

Mainboard and CPU	
Processor	Intel Celeron M 1 GHz
Chipset	Intel 82855GME (GMCH) with ICH4, 400 MHz front side bus
Bus	PCI, 32-bit/33 MHz
Graphics	Intel Extreme Graphics 2, DVI/SDL, on board
Memory	256 MB DDR RAM standard (1024 MB DDR RAM optional)
BIOS	Phoenix
Ethernet	1 x Intel 82562 10/100 Mb/s, 1 x Intel 82551ER 10/100 Mb/s
Available I/O slots	2

Drives	
Main drive	1024 MB IDE flash device
USB drive	1 x USB memory device, 4 GB

Accessible Components	
I/O module slots	2 PCI slots: one slot occupied by the included I/O module, one available
Power inlet	24 V DC (+/- 25%), external AC 110/240 V, 50/60 Hz power adaptor included
Power switch	none
Power LED	At front
Drive activity LED	At front
DVI-I connector	DVI-I to VGA connector included
Ethernet	2 x 10/100 Mb/s; for host-target communication and real-time Ethernet I/O
Serial ports	2 x RS232; for general-purpose I/O connectivity
USB	2 x USB 2.0; for xPC Target kernel and file transfer between host and target using the provided USB memory device (recommended) or the external USB 3.5 in. 1.44 MB floppy drive (classic method)
Keyboard and mouse	1 x PS/2, at front

Environment	
Temperature	0 to +55 °C, operating
Humidity	10–90%, non-condensing
Shock/vibration	15 g, 11 ms/2–9 Hz: 3.5 mm amplitude/9–200 Hz: 1 g

Software	
OS/RTOS	FreeDOS and xPC Target kernel, preinstalled on flash device or hard disk
Host PC	xPC Target driver blocks and Simulink test models for installed I/O module and USB kernel transfer utility

Accessories (Included)	
VGA	DVI-I to VGA adapter
Power supply	External 50 W power adapter (universal AC input range)
Terminal board	68 terminals arranged in two rows, spring loaded, and SCSI3 female connector with 68 pins DIN rail mounting support Dimensions (*h* x *w* x *d*): 50 x 182 x 90 mm
Cable	6 ft/1.8 m round black cable with SCSI3 male connectors with 68 pins at both ends
Drivers	Driver software for xPC Target and Simulink test models

<DAQ Package: IO101>

I/O Module (Included)	
Form factor	PCI I/O module installed in one of the two available I/O slots
PCI bus	32-bit/33 MHz
Power requirements	2.6 W typical, 3.4 W maximal
Operating temperature	0 to +70 °C
Relative humidity	5–95%, non-condensing
Analog channels	32 single-ended or 16 differential analog inputs, 8 analog outputs, 16-bit
Digital channels	8 digital TTL inputs and 8 digital TTL outputs
A/D sampling and conversion time	15 µs per channel
D/A conversion time	12.375 µs per channel
A/D voltage ranges	-3.3 to +3.3, -5 to +5, -10 to +10, 0 to +5, and 0 to +10 V (selectable)
D/A voltage ranges	-10 to +10 V

<Motion Control FPGA package: IO311 (64 TTL I/O, 24k logic cells)>

I/O Module (Included)	
I/O module	32-bit 33 MHz I/O module with 64 digital TTL lines
Pulse train functionality	Fixed set of PWM, capture, quadrature decoding, and generic digital I/O channels (two selectable implementations)
Drivers and test models	Speedgoat tools and drivers for xPC Target and Simulink test models

Accessories (Included)	
Terminal board	68 terminals arranged in two rows, spring loaded, and SCSI3 female connector with 68 pins DIN rail mounting support Dimensions (*h* x *w* x *d*): 50 x 182 x 90 mm
Cable	6 ft/1.8 m round black cable with SCSI3 male connectors with 68 pins at both ends
Documentation	Description of I/O module and pulse train driver functionality for PWM, capture (CAP), quadrature decoding (QAD), and generic digital I/O (DIO)

2) How to use

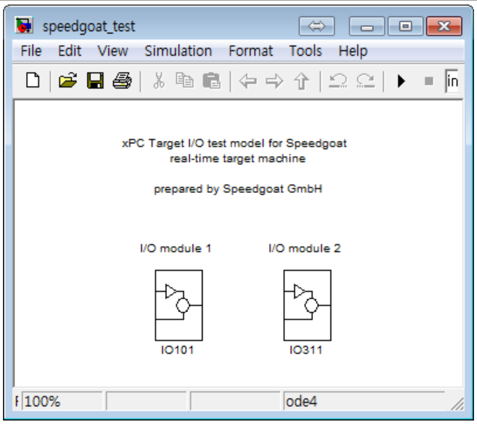
- Install the device driver provided by speedgoat. For Windows 7, the installation should be with the administration mode (ex) speedgoat_R2012a.exe)
- Installation folder (For MATLAB 2012a and Windows 7):
  C:\Program Files (x86)\MATLAB\R2012a
- To solve the error message,

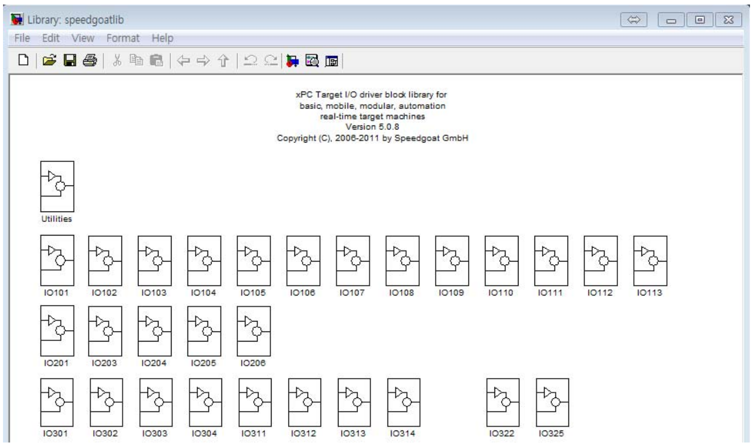
xPC Target: Error 'Undefined function or variable 'speedgoat_xpcblocks'.' while adding third party library from speedgoat_xpcblocks

  If the function wasn't found, did you remember to 'rehash toolbox'?

  ⇨ Type ‘rehash toolbox’ in the command window.

- Type the follows to check library and examples.
  >> speedgoatlib
  >> speedgoat_test





- If FPGA module (IO311) is used in the program, the following error occurs.

```
### Compiling
C:\PROGRA~1\MATLAB\R2011a\toolbox\rtw\targets\xpc\target\build\xpcblocks\thirdpartydrivers\setup_
acromag_fpga.c
    cl -DWIN32  -D_WIN32 -D_MT -MT /Op  /W3 /c /nologo /O2 /Oy- -DMODEL=DAQ_DA1 -DRT -
DNUMST=2  -DTID01EQ=0 -DNCSTATES=0  -DMT=0 -DHAVESTDIO -DXPCMSVISUALC  -
DXPCCALLCONV=__cdecl  -DUSE_RTMODEL -DERT_CORE
C:\PROGRA~1\MATLAB\R2011a\toolbox\rtw\targets\xpc\target\build\xpcblocks\thirdpartydrivers\setup_
acromag_fpga.c
setup_acromag_fpga.c
C:\PROGRA~1\MATLAB\R2011a\toolbox\rtw\targets\xpc\target\build\xpcblocks\include\IO311_3PWM_
3CAP_3QAD_INT.fpga(10245) : fatal error C1076: compiler limit : internal heap limit reached; use /Zm to
specify a higher limit
NMAKE : fatal error U1077: 'cl' : return code '0x2'
Stop.
The make command returned an error of 2
'An_error_occurred_during_the_call_to_make' is not batch file.
```

- IO311 fpga file compilation problem: use /Zm to specify a higher limit
- Method1: Find xpc_vc.tmf in the folder, C:\Program Files\MATLAB\R2012a\toolbox\rtw\targets\xpc\xpc , then add OPTS="-Zm300", and copy the tmf file in current folder.
- Method2: Use the following option in compile:

  make_rtw OPTS="-Zm300"

- IO101

  16-bit analog module with 32 single-ended or 16 differential analog input

  8 analog output, 8 digital input, 8 digital output

Pin on Terminal Board	Signal
1	Counter
2	Digital In 01
3	Digital In 02
4	Digital In 03
5	Digital In 04
6	Digital In 05
7	Digital In 06
8	Digital In 07
9	Digital In 08
10	Ground
11	Ground
12	Analog Out 01
13	Analog Out 02
14	Analog Out 03
15	Analog Out 04
16	Ground
17	Ground
18	Ground
19	Analog In SE: 16, DIFF: 16 (+)
20	Analog In SE: 15, DIFF: 15 (+)
21	Analog In SE: 14, DIFF: 14 (+)
22	Analog In SE: 13, DIFF: 13 (+)
23	Analog In SE: 12, DIFF: 12 (+)
24	Analog In SE: 11, DIFF: 11 (+)
25	Analog In SE: 10, DIFF: 10 (+)
26	Analog In SE: 09, DIFF: 09 (+)
27	Analog In SE: 08, DIFF: 08 (+)
28	Analog In SE: 07, DIFF: 07 (+)
29	Analog In SE: 06, DIFF: 06 (+)
30	Analog In SE: 05, DIFF: 05 (+)
31	Analog In SE: 04, DIFF: 04 (+)
32	Analog In SE: 03, DIFF: 03 (+)
33	Analog In SE: 02, DIFF: 02 (+)
34	Analog In SE: 01, DIFF: 01 (+)

Pin on Terminal Board	Signal
35	Ground
36	Digital Out 01
37	Digital Out 02
38	Digital Out 03
39	Digital Out 04
40	Digital Out 05
41	Digital Out 06
42	Digital Out 07
43	Digital Out 07
44	Analog Out 05
45	Analog Out 06
46	Ground
47	Ground
48	Ground
49	Ground
50	Analog Out 07
51	Analog Out 08
52	Sense
53	Analog In SE: 32, DIFF: 16 (-)
54	Analog In SE: 31, DIFF: 15 (-)
55	Analog In SE: 30, DIFF: 14 (-)
56	Analog In SE: 29, DIFF: 13 (-)
57	Analog In SE: 28, DIFF: 12 (-)
58	Analog In SE: 27, DIFF: 11 (-)
59	Analog In SE: 26, DIFF: 10 (-)
60	Analog In SE: 25, DIFF: 09 (-)
61	Analog In SE: 24, DIFF: 08 (-)
62	Analog In SE: 23, DIFF: 07 (-)
63	Analog In SE: 22, DIFF: 06 (-)
64	Analog In SE: 21, DIFF: 05 (-)
65	Analog In SE: 20, DIFF: 04 (-)
66	Analog In SE: 19, DIFF: 03 (-)
67	Analog In SE: 18, DIFF: 02 (-)
68	Analog In SE: 17, DIFF: 01 (-)

- IO311:

  Reconfigurable FPGA-based I/O module with 64 TTL I/O lines and Xilinx Virtex-II chip with 24 logic cells.

- Default FPGA setting:

FPGA Code Module	No. of FPGA Code Modules	Tranceiver type	No. of I/O lines per code module	Total I/O lines
PWM	3	TTL	3	9 + 1 (res.)
CAP	3	TTL	1	3
Negation	1	TTL	2	2
Interrupt	1	TTL	2	2
QAD	3	TTL	3	9
DIO	38	TTL	1	38
Total				**64**

<Lower channel group setup>

I/O line number	Pin on Terminal Board	Vector Value • 1 = Output • 0 = Input	Functionality implemented on FPGA bitstream	Transceiver type
1	1	1	PWM1 – A	TTL
2	2		PWM1 – B	TTL
3	3	1	PWM1 – Trigger	TTL
4	4		PWM2 – A	TTL
5	5	1	PWM2 – B	TTL
6	6		PWM2 – Trigger	TTL
7	7	1	PWM3 – A	TTL
8	8		PWM3 – B	TTL
9	9	1	PWM3 – Trigger	TTL
10	10		Reserved	TTL
11	11	0	CAP1	TTL
12	12		CAP2	TTL
13	13	0	CAP3	TTL
14	14		QAD1 – A	TTL
15	15	0	QAD1 – B	TTL
16	16		QAD1 – C/Index	TTL
-	17	no value	Ground	
-	18		Ground	
17	19	0	QAD2 – A	TTL
18	20		QAD2 – B	TTL
19	21	0	QAD2 – C/Index	TTL
20	22		QAD3 – A	TTL
21	23	0	QAD3 – B	TTL
22	24		QAD3 – C/Index	TTL
23	25	0	Interrupt Input	TTL
24	26		Negation Input	TTL
25	27	1	Negation Output	TTL
26	28		Reserved	TTL
27	29	0/1	DIO01	TTL
28	30		DIO02	TTL
29	31	0/1	DIO03	TTL
30	32		DIO04	TTL
31	33	0/1	DIO05	TTL
32	34		DIO06	TTL

<Upper channel group setup>

I/O line number	Pin on Terminal Board	Vector Value • 1 = Output • 0 = Input	Functionality implemented on FPGA bitstream	Transceiver type
-	35	no value	Ground	
-	36		Ground	
33	37	0/1	DIO07	TTL
34	38		DIO08	TTL
35	39	0/1	DIO09	TTL
36	40		DIO10	TTL
37	41	0/1	DIO11	TTL
38	42		DIO12	TTL
39	43	0/1	DIO13	TTL
40	44		DIO14	TTL
41	45	0/1	DIO15	TTL
42	46		DIO16	TTL
43	47	0/1	DIO17	TTL
44	48		DIO18	TTL
45	49	0/1	DIO19	TTL
46	50		DIO20	TTL
47	51	0/1	DIO21	TTL
48	52		DIO22	TTL
49	53	0/1	DIO23	TTL
50	54		DIO24	TTL
51	55	0/1	DIO25	TTL
52	56		DIO26	TTL
53	57	0/1	DIO27	TTL
54	58		DIO28	TTL
55	59	0/1	DIO29	TTL
56	60		DIO30	TTL
57	61	0/1	DIO31	TTL
58	62		DIO32	TTL
59	63	0/1	DIO33	TTL
60	64		DIO34	TTL
61	65	0/1	DIO35	TTL
62	66		DIO36	TTL
63	67	0/1	DIO37	TTL
64	68		DIO38	TTL

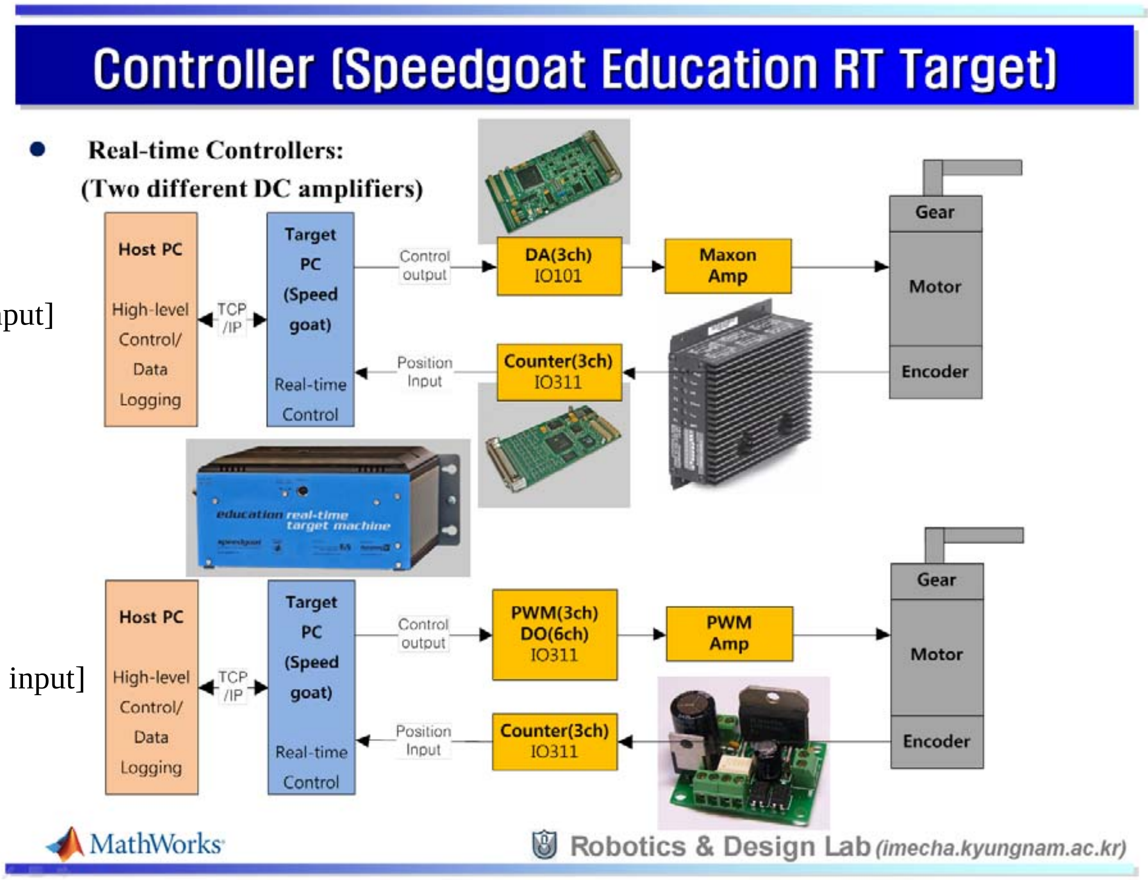
[2] Development of Robot Manipulators and Controllers

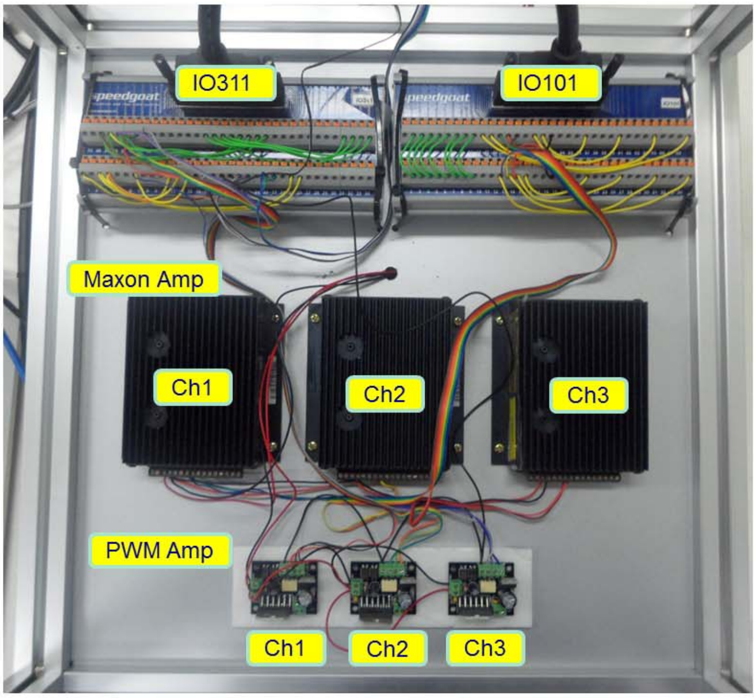
(1) Controller design

- speedgoat Controller: Two kinds of motor amplifiers with voltage and PWM inputs are considered.
- DA Type: IO101 module – DA output, IO311 module – Counter input
- PWM Type: IO311 module – PWM output, IO311 module – Counter input

[DA input]

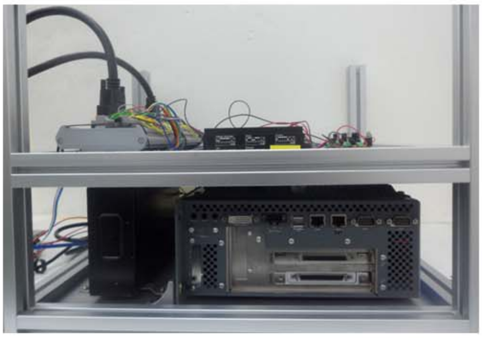
[PWM input]





[Top view]

[Front view]



[Side view]

- IO101 (Analog I/O module with 8-ch DA, 16-ch AD, 8-ch DI, 8-ch DO):

- DA output connection:

PIN	Signal	Amplifier	PIN	Signal	Amplifier
12	AO01	+set (ch1)	46	GND	-set (ch1)
13	AO02	+set (ch2)	47	GND	-set (ch2)
14	AO03	+set (ch3)	48	GND	-set (ch3)

- Keypad connection:

PIN	Signal	4x4 Keypad
2	DI01	S1
3	DI02	S2
4	DI03	S3
5	DI04	S4
6	DI05	S5
7	DI06	S6
8	DI07	S7
9	DI08	S8

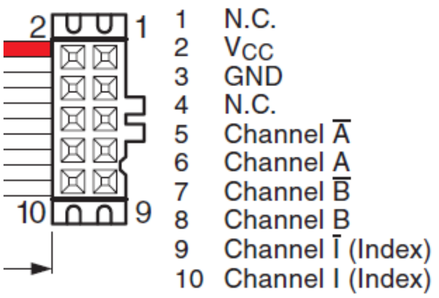
- IO311 (Configurable FPGA I/O modules, Xilinx Virtex-II 24k):

- PWM output & Quadrature Encoder connections:

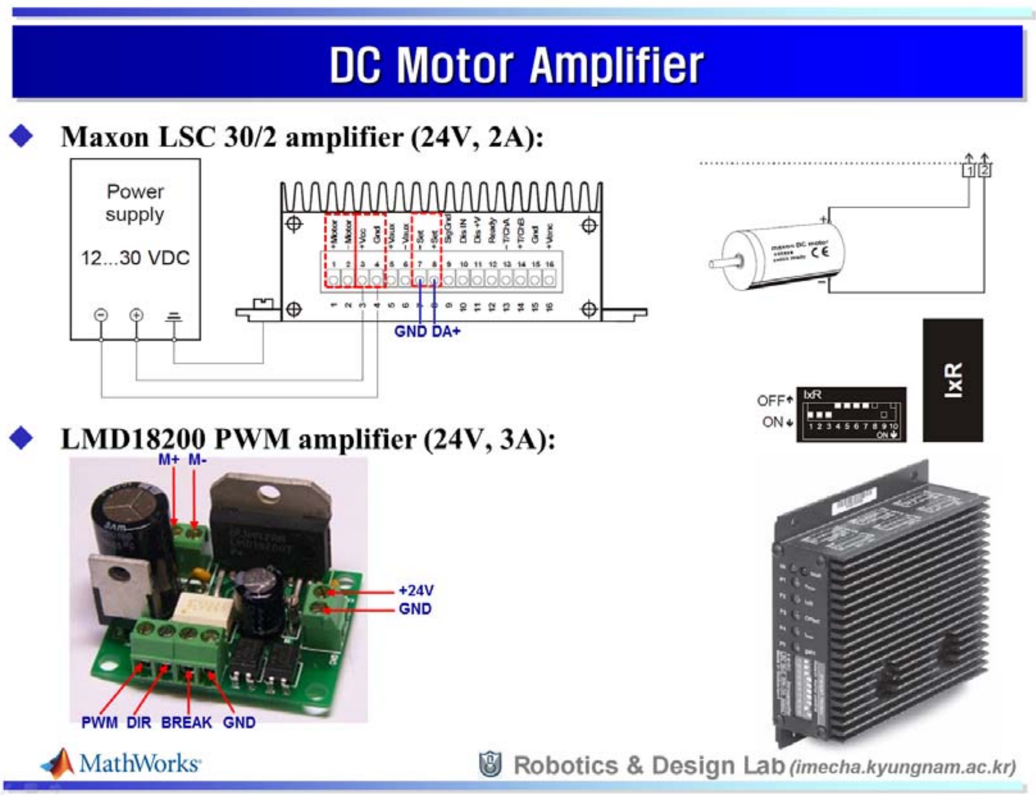
PIN	Signal	Amp	PIN	Signal	Encoder
1	PWM1-A	PWM (ch1)	14	QAD1-A	A+ (ch1)
4	PWM2-A	PWM (ch2)	15	QAD1-B	B+ (ch1)
7	PWM3-A	PWM (ch3)	19	QAD2-A	A+ (ch2)
17	GND	GND (AMP)	20	QAD2-B	B+ (ch2)
18	GND	GND (ENC)	22	QAD3-A	A+ (ch3)
			23	QAD3-B	B+ (ch3)

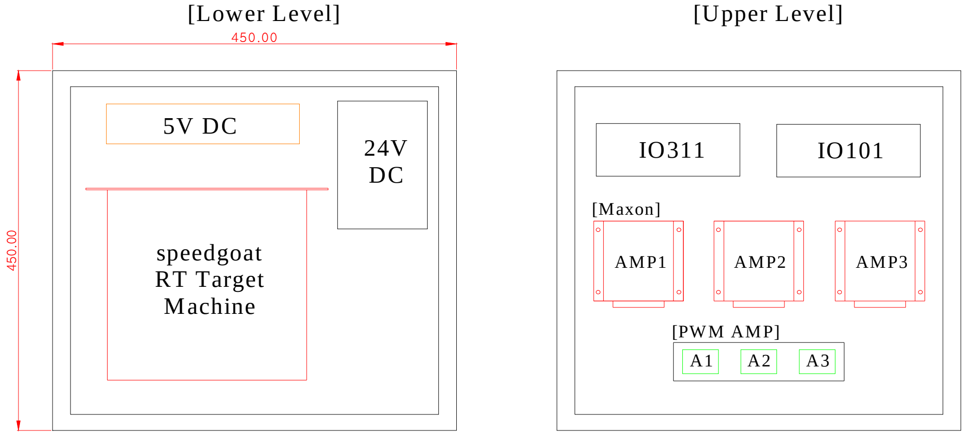
- DO of the PWM output:

PIN	Signal	Amp
37	DIO07	DIR (ch1)
38	DIO08	DIR (ch2)
39	DIO09	DIR (ch3)
40	DIO10	BRK (ch1)
41	DIO11	BRK (ch2)
42	DIO12	BRK (ch3)

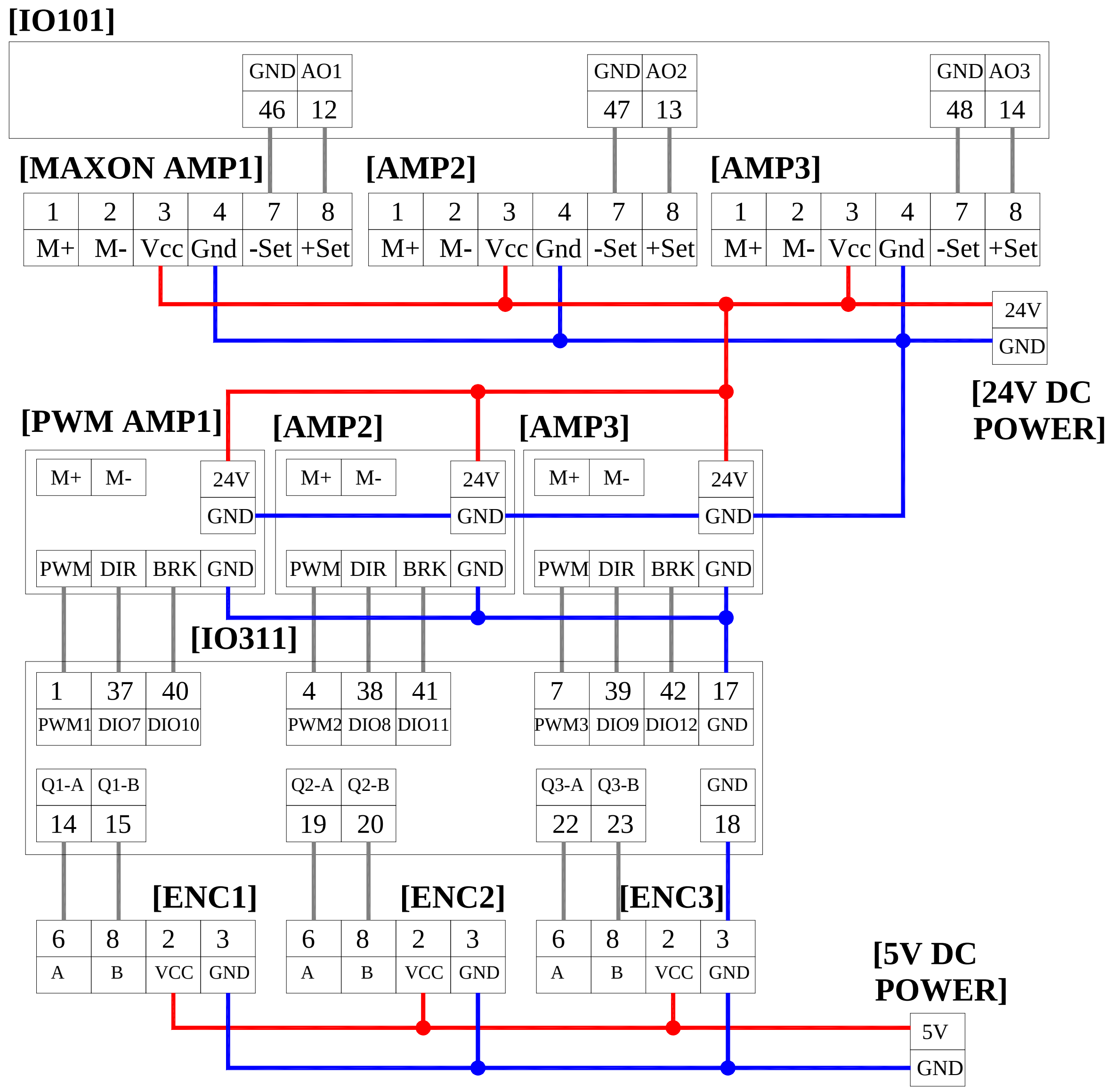


- DC Motor Amplifier:





[Controller Layout]



[Controller connection]

(2) Design of planar robots

1) DC servo motor

- Maxon motor (Diameter 25mm, 20Watt), Part No.: 118752

  $T_R = 26.7$ mNm, $\omega_R = 8,360$ rpm, $I_R = 1.17$ A

  $T_{\max} = 257$ mNm, $\omega_{\max} = 9,550$ rpm, $I_{\max} = 11.0$ A

  $K_T = 23.4$ mNm/A

- DC Motor Amplifier:

  LMD18200 (3A, 55V)

  Maxon LSC 30/2 (30V, 2A)

- Max. Torque for 2A continuous current:

  $T_m = K_T \times 2$ A=46.8 mNm

  23:1 geared motor: $T_{out,1} = 1.1$ Nm

  66:1 geared motor: $T_{out,2} = 3.1$ Nm

	according to dimensional drawing		118752
	shaft length 15.7 shortened to 4 mm		302005
Motor Data			
	Values at nominal voltage		
1	Nominal voltage	V	24.0
2	No load speed	rpm	9550
3	No load current	mA	36.9
4	Nominal speed	rpm	8360
5	Nominal torque (max. continuous torque)	mNm	26.7
6	Nominal current (max. continuous current)	A	1.17
7	Stall torque	mNm	257
8	Starting current	A	11.0
9	Max. efficiency	%	86
	Characteristics		
10	Terminal resistance	Ω	2.19
11	Terminal inductance	mH	0.238
12	Torque constant	mNm / A	23.4
13	Speed constant	rpm / V	407
14	Speed / torque gradient	rpm / mNm	38.1
15	Mechanical time constant	ms	4.28
16	Rotor inertia	gcm^2	10.7

- MR Encoder (500 line/rev), Part No.: 225778

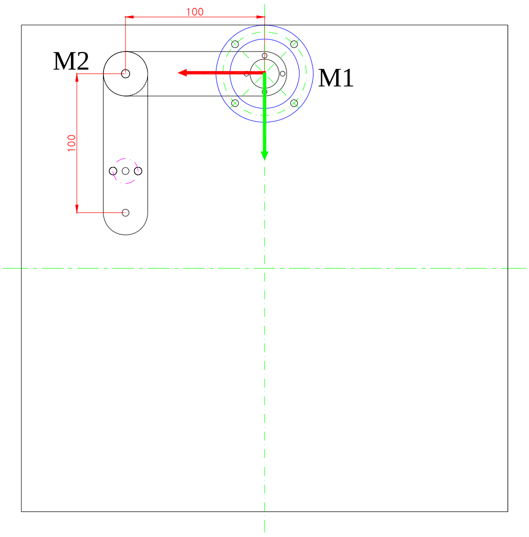
	225778
Type	
Counts per turn	500
Number of channels	3
Max. operating frequency (kHz)	200

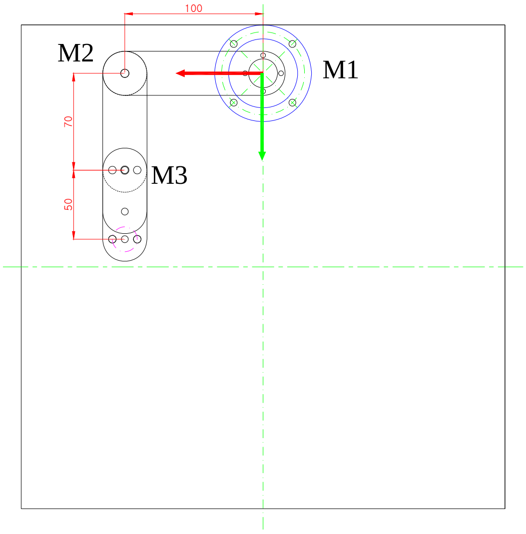
- Planetary Gearhead (GP 32 A, Diameter 32mm, 0.75 – 4.5 Nm)

  Part No.: 166161 (23:1), 166165 (66:1)

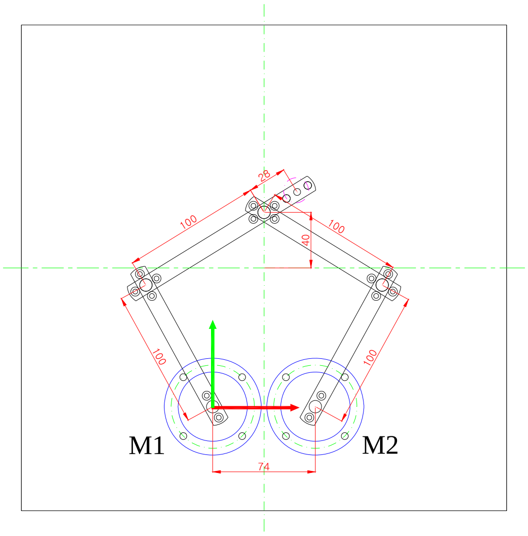
	Gearhead Data				
1	Reduction		14 : 1	33 : 1	51 : 1
2	Reduction absolute		676/49	529/16	17576/343
3	Max. motor shaft diameter	mm	6	3	6
	Order Number		**166159**		**166165**
1	Reduction		18 : 1		66 : 1
2	Reduction absolute		624/35		16224/245
3	Max. motor shaft diameter	mm	4		4
	Order Number		166160		166166
1	Reduction		21 : 1		79 : 1
2	Reduction absolute		299/14		3887/49
3	Max. motor shaft diameter	mm	3		3
	Order Number		**166161**		**166167**
1	Reduction		23 : 1		86 : 1
2	Reduction absolute		576/25		14976/175
3	Max. motor shaft diameter	mm	4		4
	Order Number		166162		166168
1	Reduction		28 : 1		103 : 1
2	Reduction absolute		138/5		3588/35
3	Max. motor shaft diameter	mm	3		3
4	Number of stages		2	2	3
5	Max. continuous torque	Nm	2.25	2.25	4.50
6	Intermittently permissible torque at gear output	Nm	3.4	3.4	6.5
7	Max. efficiency	%	75	75	70
8	Weight	g	162	162	194
9	Average backlash no load	°	0.8	0.8	1.0
10	Mass inertia	gcm²	0.8	0.8	0.7
11	Gearhead length L1	mm	36.4	36.4	43.1

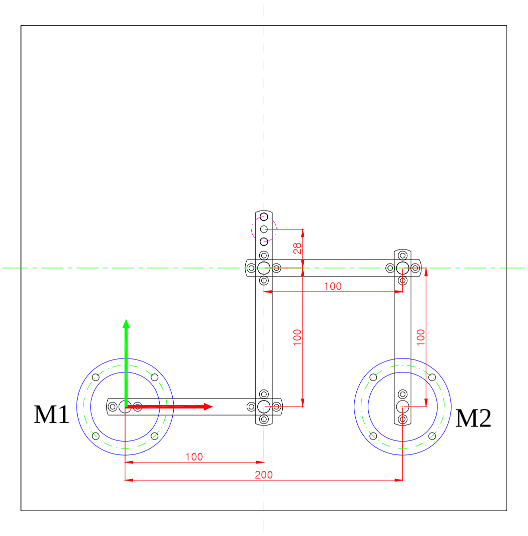
2) Kinematic dimension of planar robots



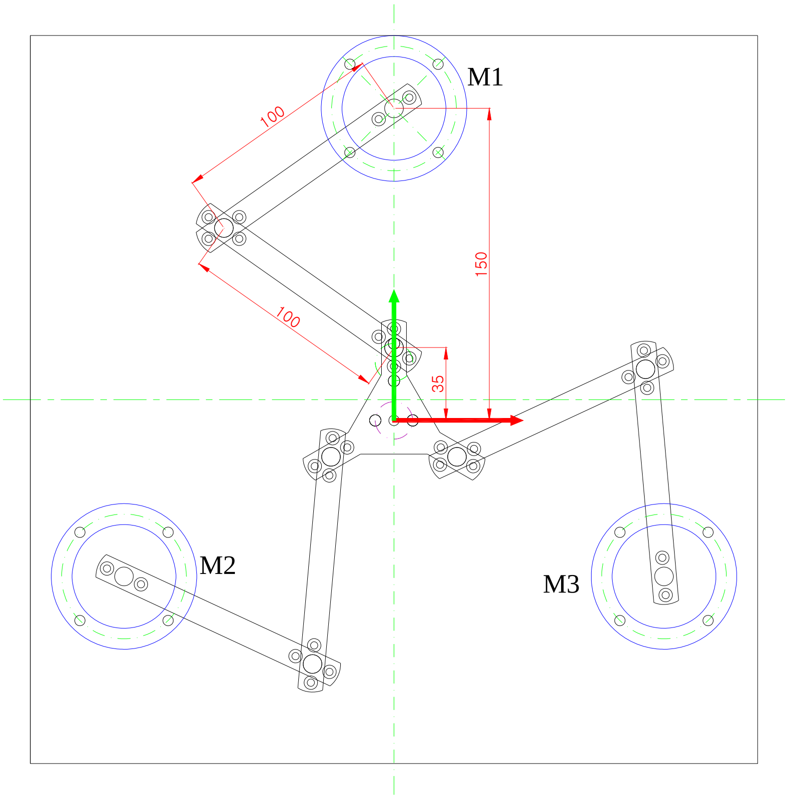


[2-DOF Serial Robot]	[3-DOF Serial Robot]
- Motor1: 66:1, Motor2: 23:1	- Motor1: 66:1, Motor2,3: 23:1
- $a_1 = 100$, $a_2 = 100$ mm	- $a_1 = 100$, $a_2 = 70$, $a_3 = 50$ mm
- $\theta_1 = 0^\circ, \theta_2 = 90^\circ$	- $\theta_1 = 0^\circ, \theta_2 = 90^\circ, \theta_3 = 0^\circ$
- $p_x = 100$, $p_y = 100$ mm	- $p_x = 100$, $p_y = 120$ mm, ϕ=90°





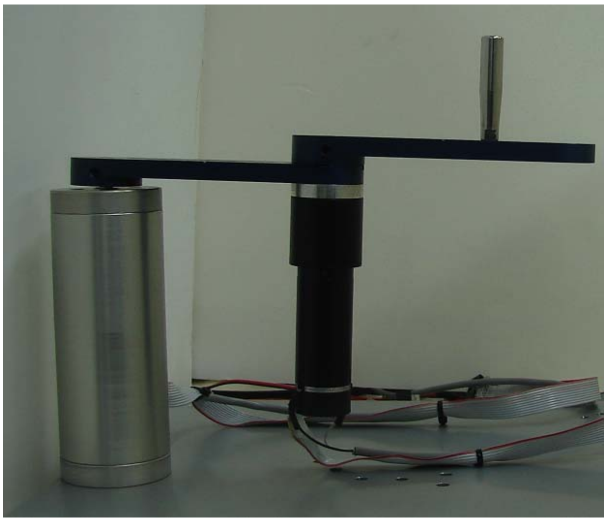
[5-bar Type I]	[5-bar Type II]
- Motor1,2: 23:1	- Motor1,2: 23:1
- $l_1 = 74$, $l_3 = 128$, $l_2 = l_4 = l_5 = 100$	- $l_1 = 200$, $l_3 = 128$, $l_2 = l_4 = l_5 = 100$
- $\theta_2 = 118.81^\circ, \theta_5 = 61.19^\circ$	- $\theta_2 = 0^\circ, \theta_5 = 90^\circ$
- $p_x = 60.8523$, $p_y = 154.6652$ mm	- $p_x = 100$, $p_y = 128$ mm



[3-DOF parallel robot]
- Motor1,2,3: 23:1
- $a=150$, $b=35$, $l_1=l_2=100$ [mm]
- $\theta_1=-144.90^\circ, \theta_2=-24.90^\circ, \theta_3=95.10^\circ$
- $p_x=0$, $p_y=0$ mm, ϕ=0°
- Red arrow: x-axis, Green arrow: y-axis

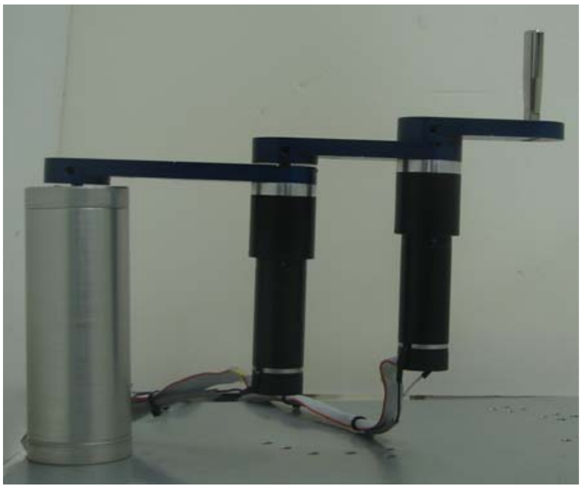
3) Planar Robot Prototypes

- 2-DOF serial robot:

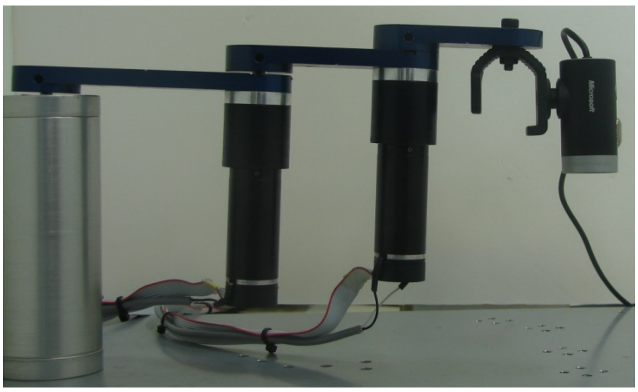


[Horizontal configuration] [Vertical configuration]

- 3-DOF serial robot:

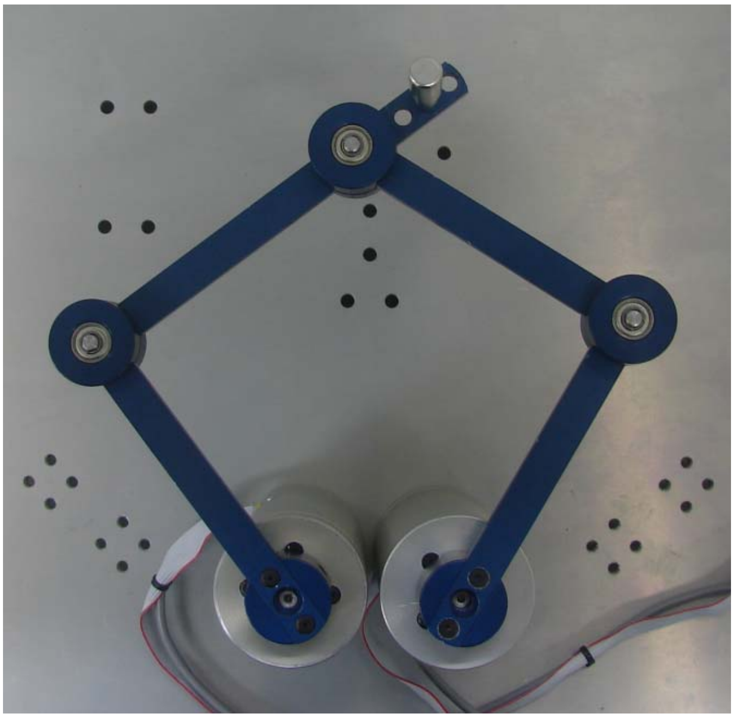


[Horizontal configuration] [Vertical configuration]

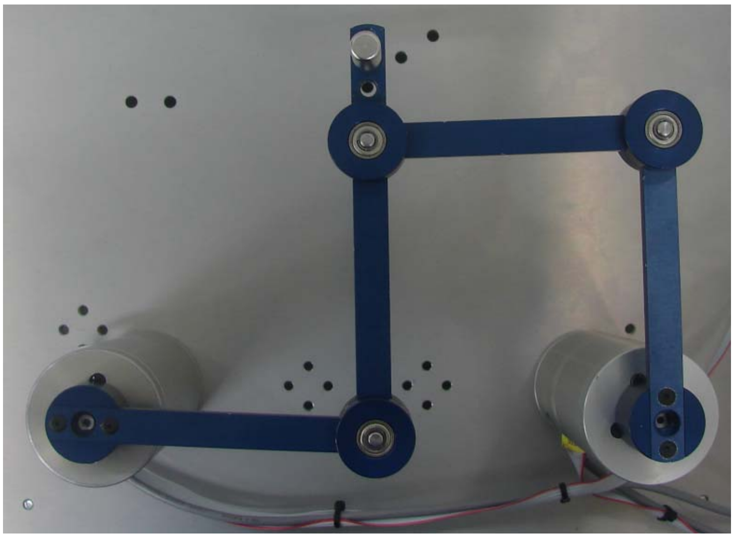


[with PC camera]

- 5-bar robot:

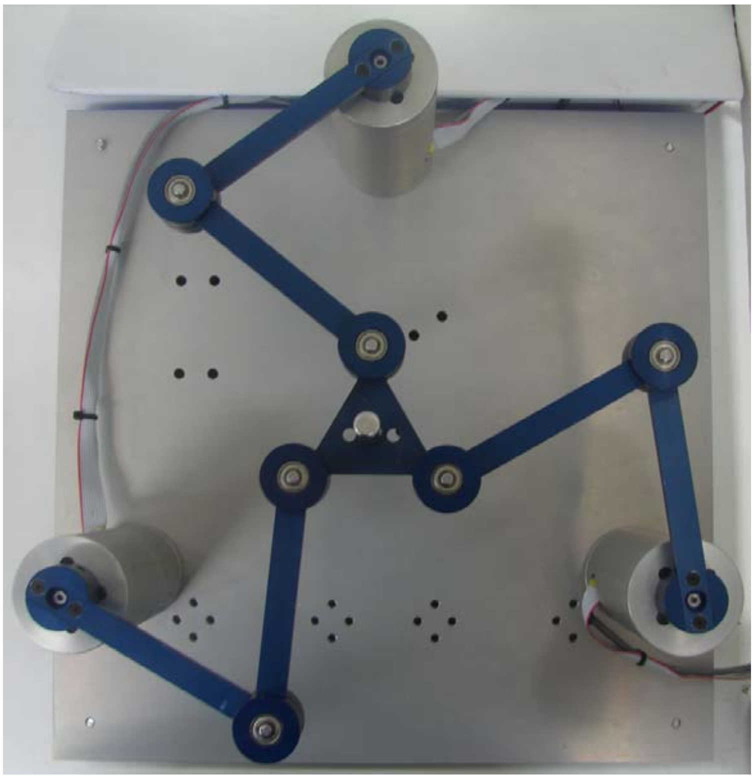


[Type I]



[Type II]

- 3-DOF parallel robot:



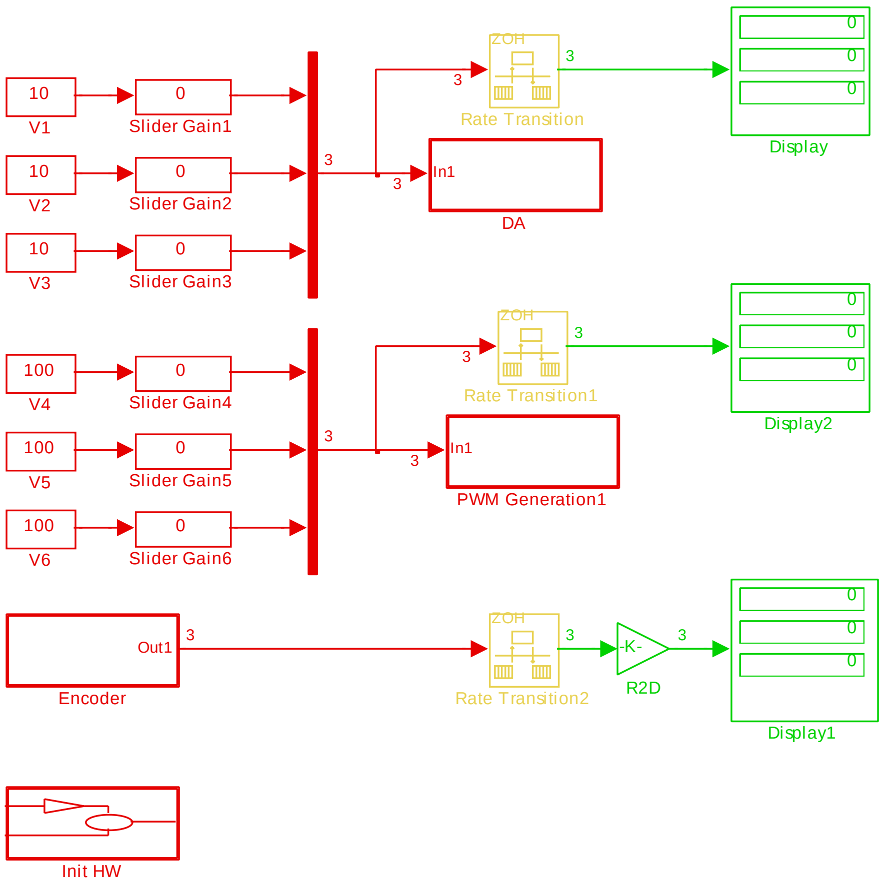
[3] Control Practice

(1) Hardware Test

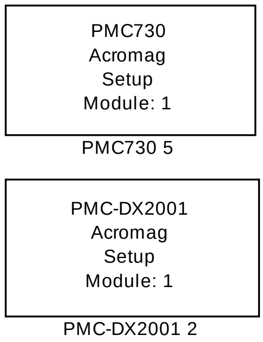
File name: daq_test1.mdl:

Functions: 3-ch DA output, 3-ch PWM output, 6-ch Digital output, 3-ch Encoder input

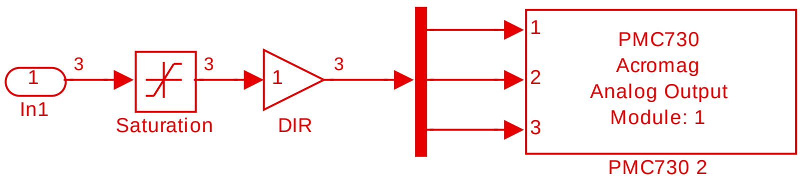
- Main program:



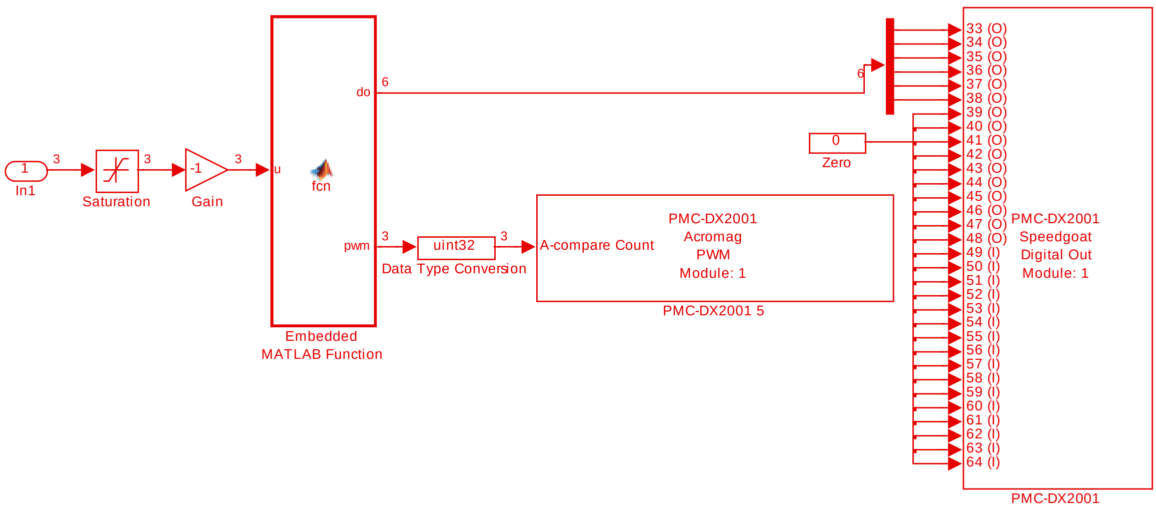
- Init HW substem:



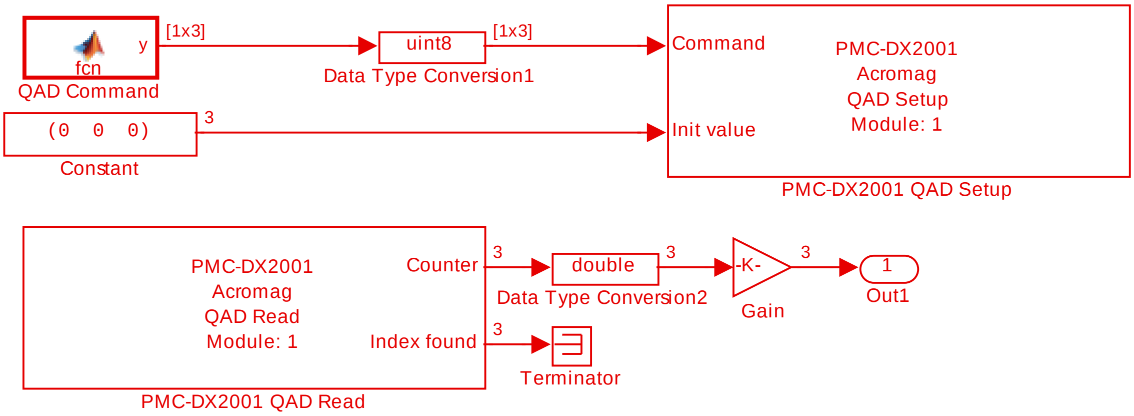
- DA subsystem:



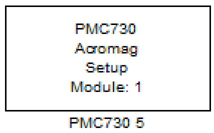
- PWM Generation subsystem:

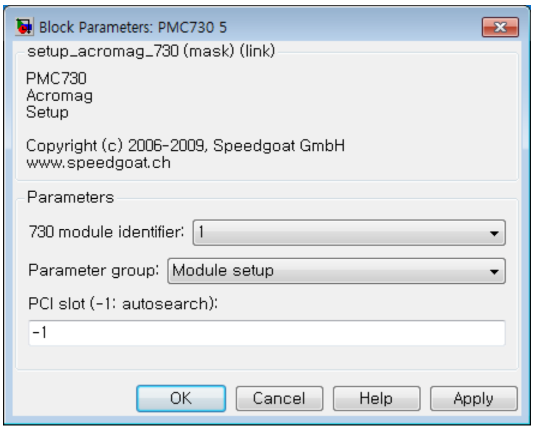


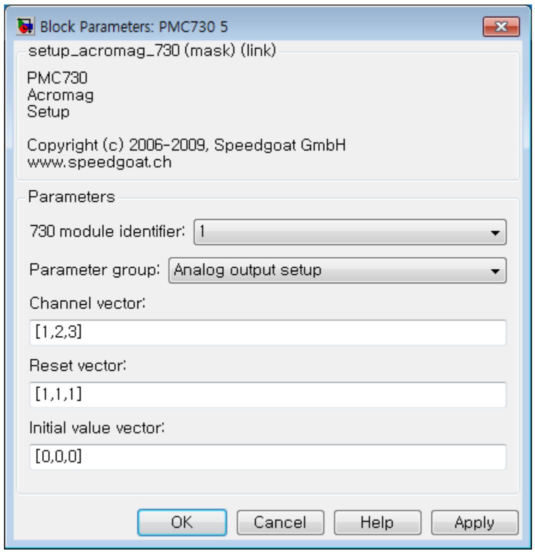
- Encoder subsystem:



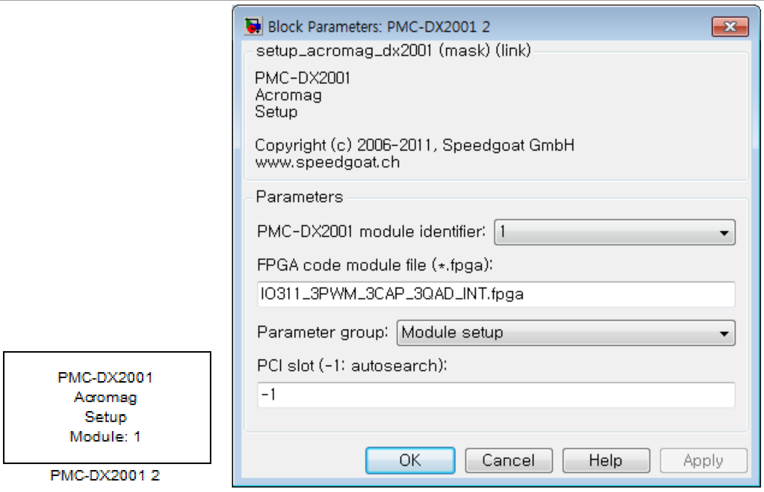
- IO101 (Setup driver block):

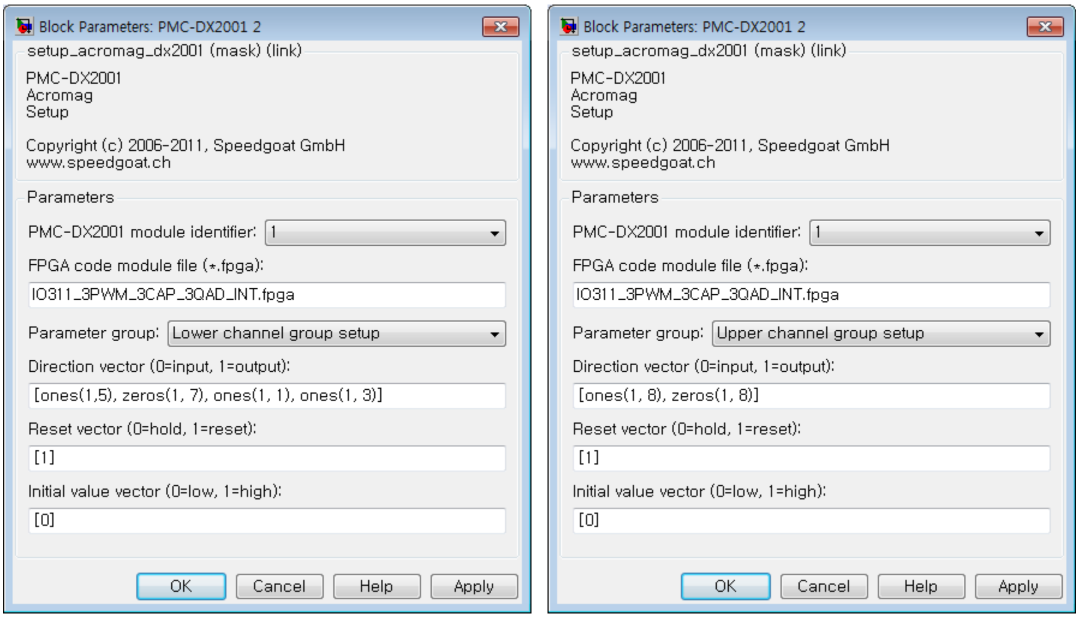






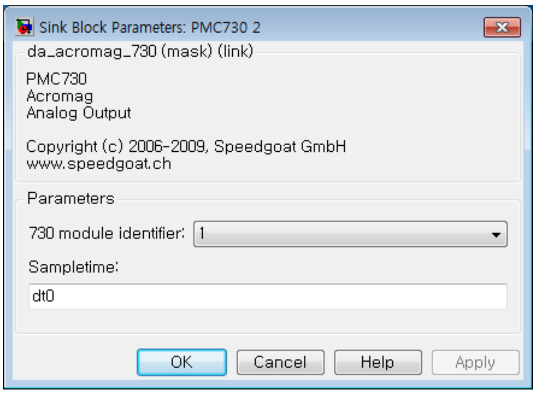
- IO311 (Setup driver block):





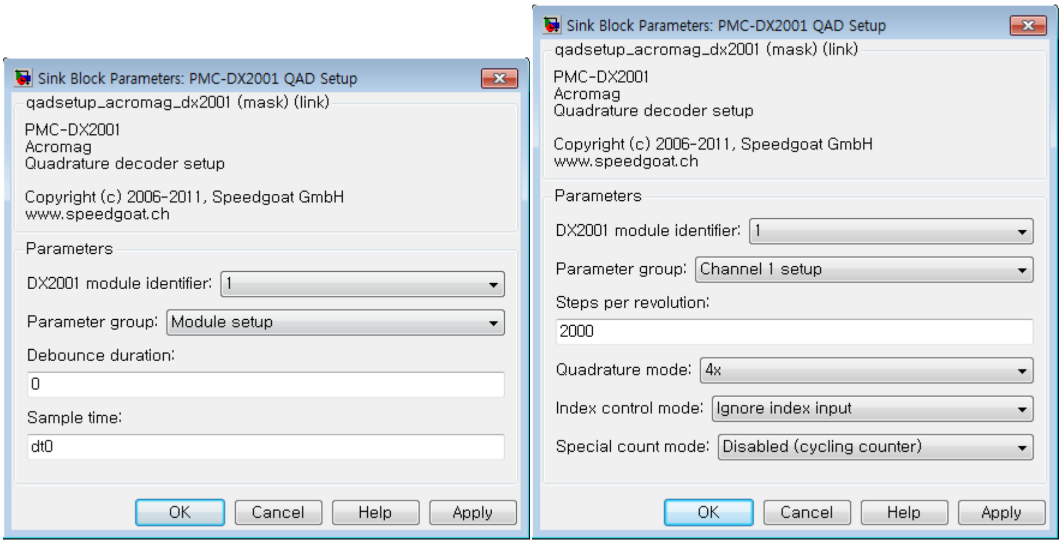
- DA output:

  <Analog Output >

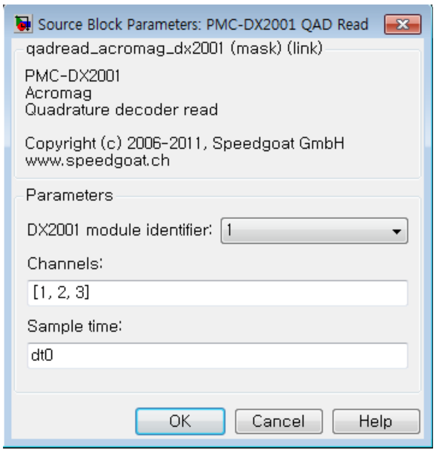


- Encoder:

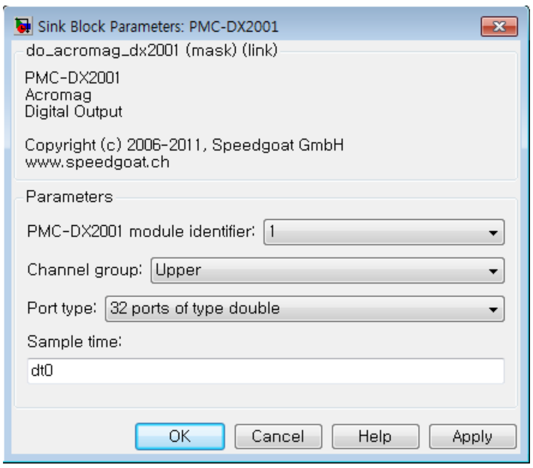
<QAD Setup>



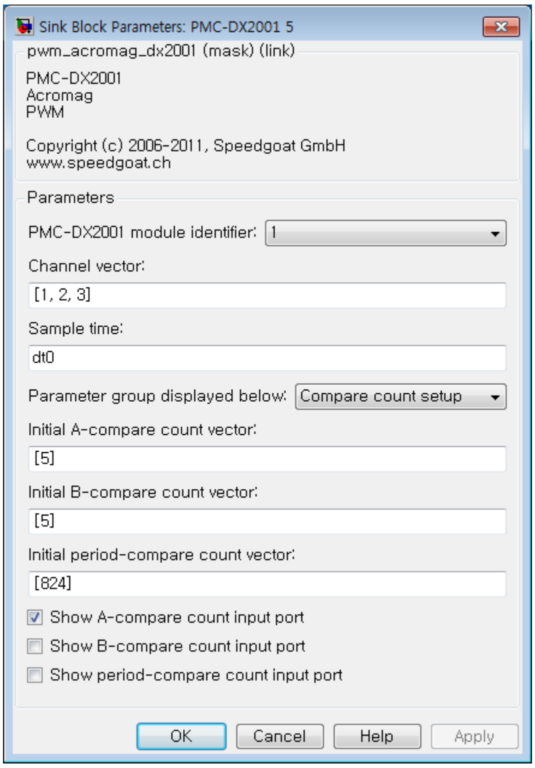
<QAD Read>



- Digital Output:



- PWM Output:

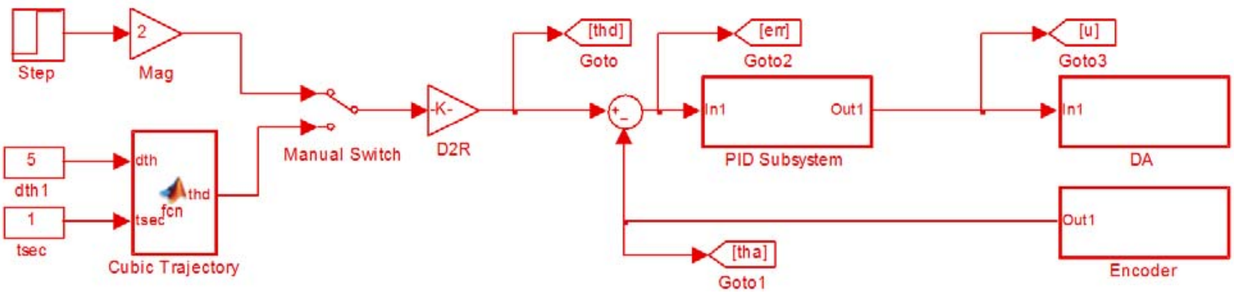

Sink Block Parameters: PMC-DX2001 5
pwm_acromag_dx2001 (mask) (link)
PMC-DX2001
Acromag
PWM
Copyright (c) 2006-2011, Speedgoat GmbH
www.speedgoat.ch
Parameters
PMC-DX2001 module identifier: 1
Channel vector:
[1, 2, 3]
Sample time:
dt0
Parameter group displayed below: Compare count setup
Initial A-compare count vector:
[5]
Initial B-compare count vector:
[5]
Initial period-compare count vector:
[824]
Show A-compare count input port
Show B-compare count input port
Show period-compare count input port
OK
Cancel
Help
Apply

(2) PID control of DC motors

- Joint-space Control:

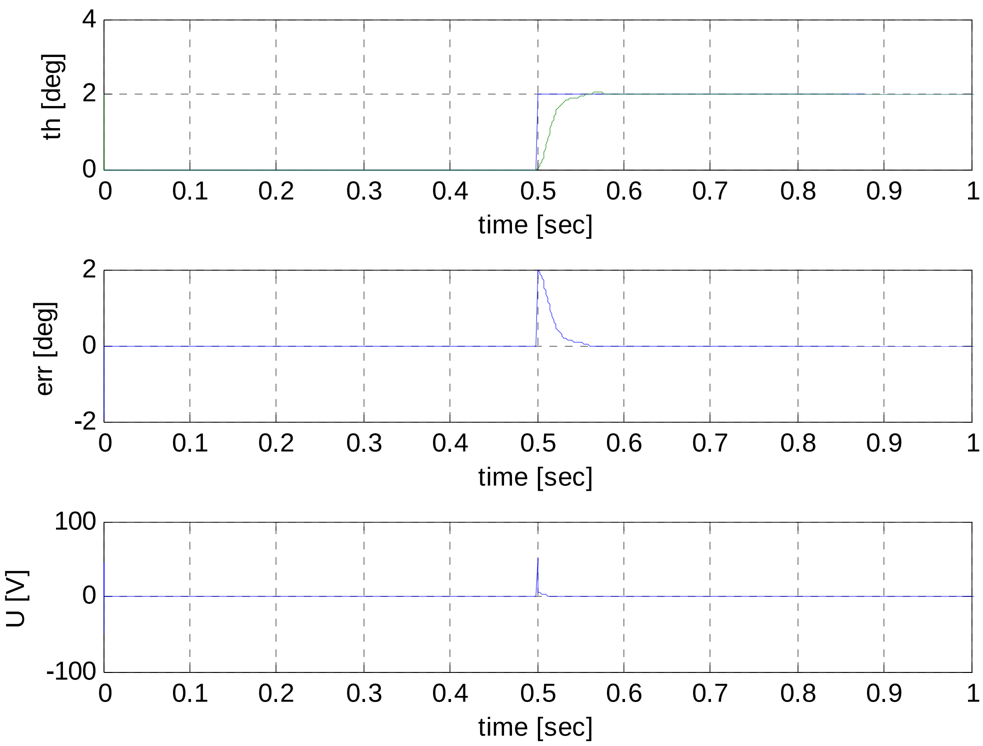
  File name: Joint_Control_ch1.mdl, Joint_Control_ch1.md2, Joint_Control_ch3.mdl

  Function: PID control experiment for Step and Cubic Trajectory inputs

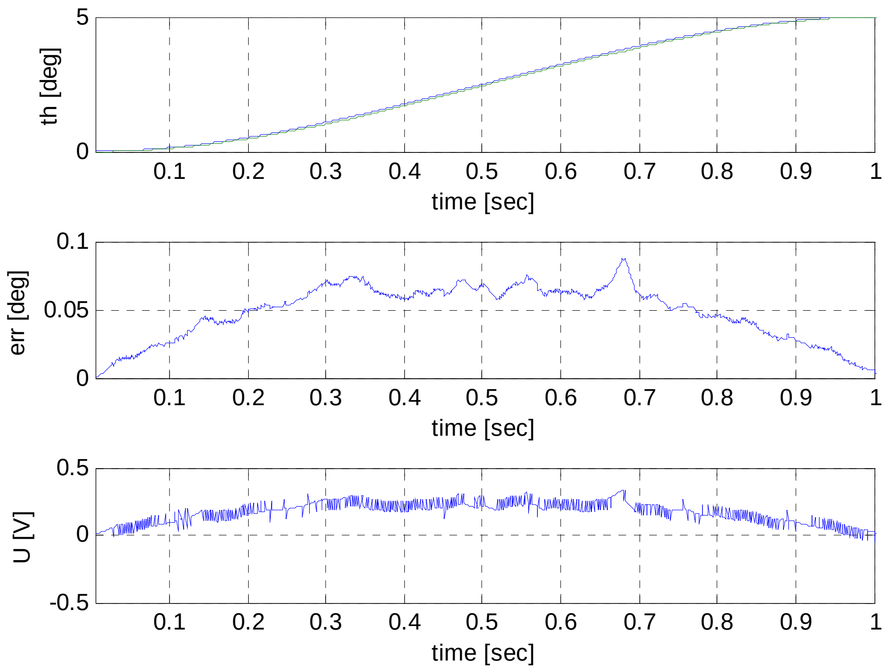


- Control result for motor1 (with 66:1 gear) (Kp=150, Kd=1):

  <Step Input>

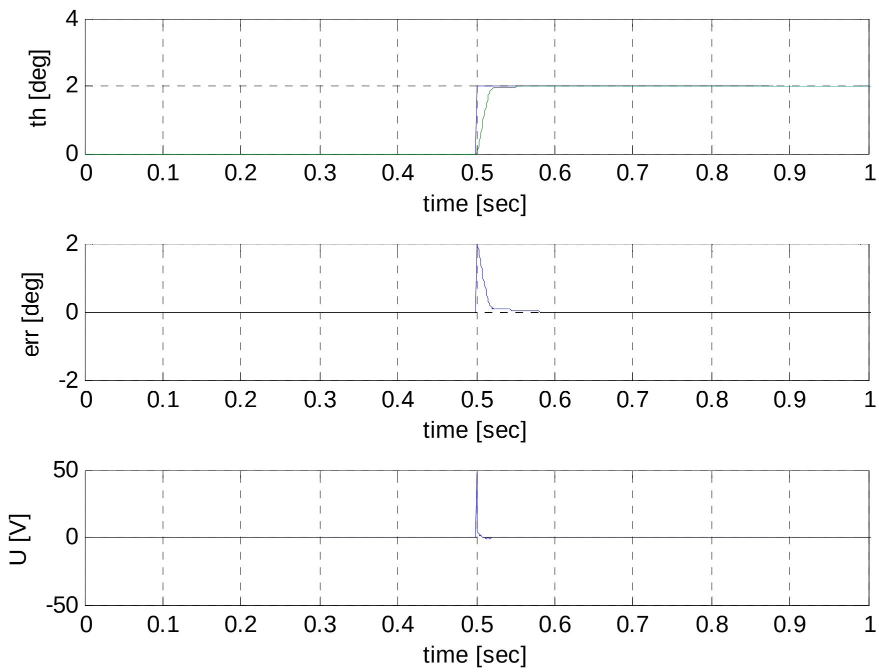


<Trajectory Input>

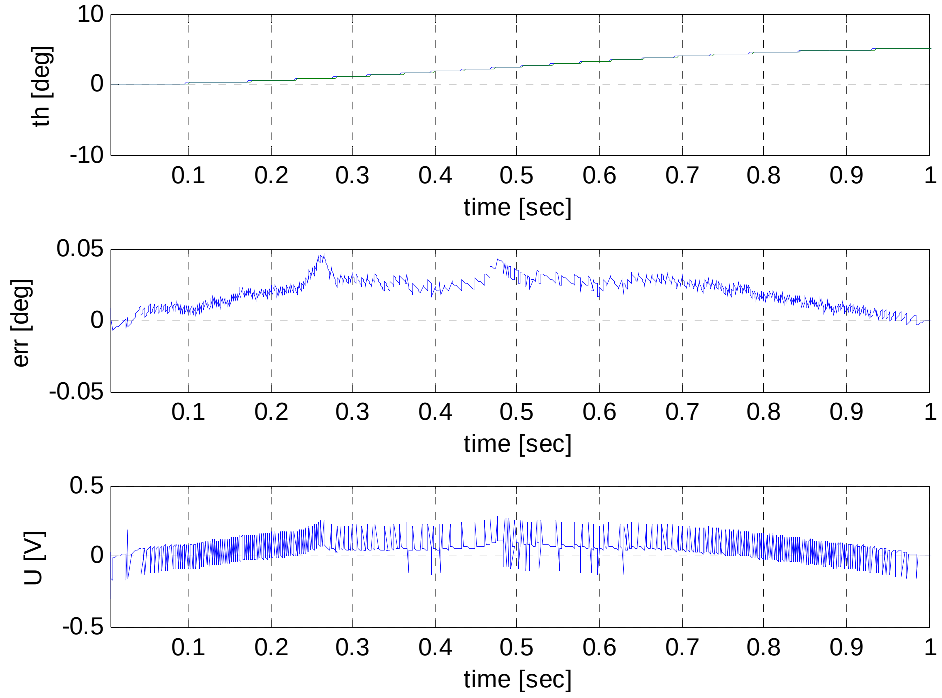


- Control result for motor2 (with 23:1 gear (Kp=100, Kd=1):

  <Step Input>



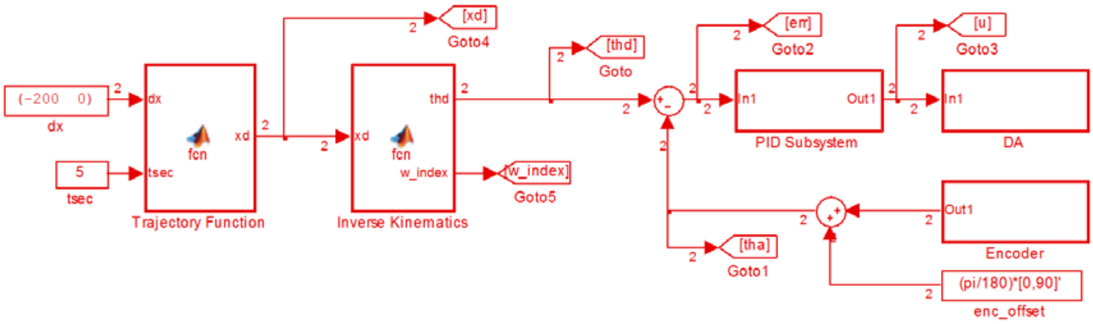
<Trajectory Input>

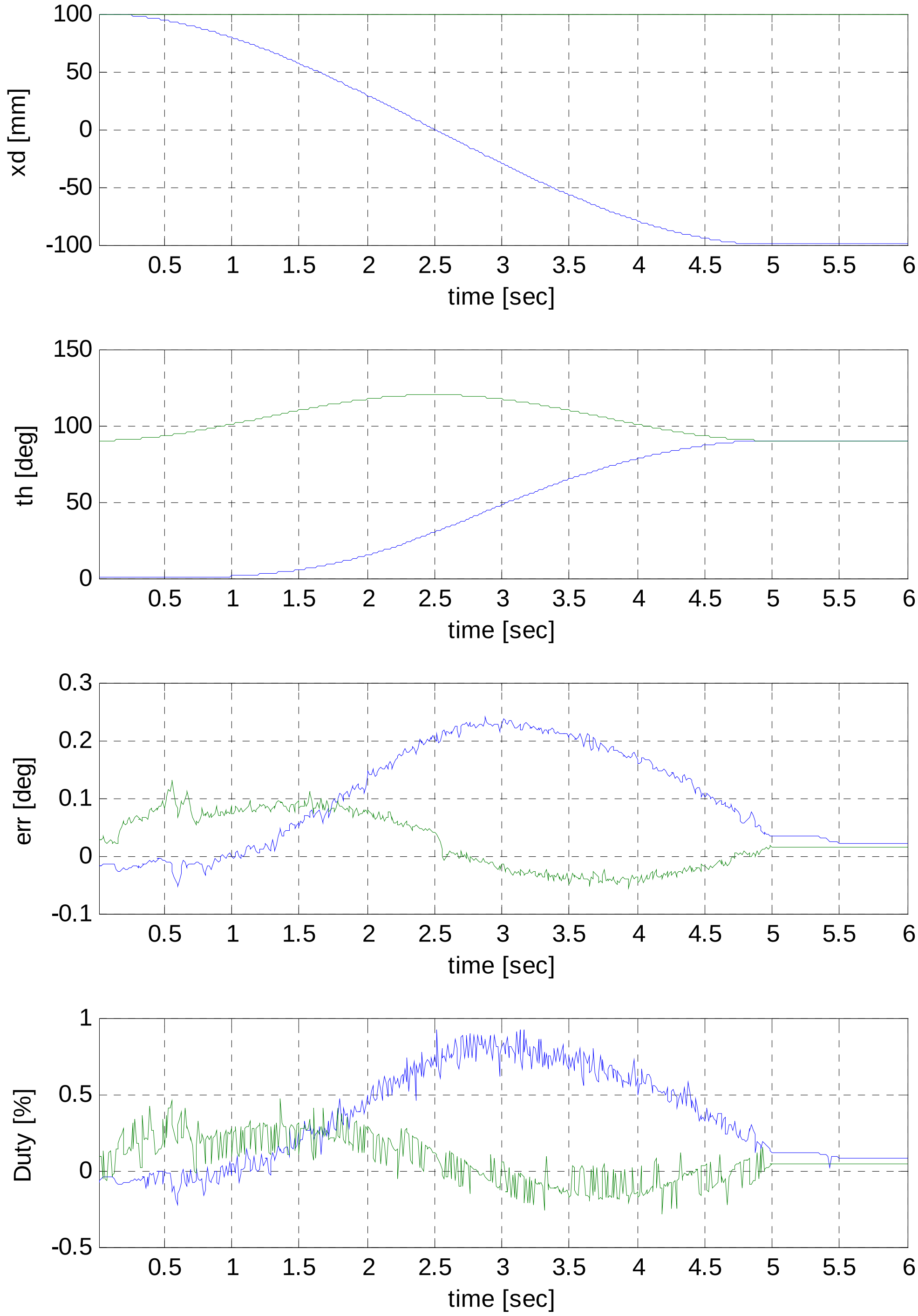

10
0
-10
th [deg]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
time [sec]
0.05
0
-0.05
err [deg]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
time [sec]
0.5
0
-0.5
U [V]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
time [sec]

(3) Line move

1) 2-DOF serial robot

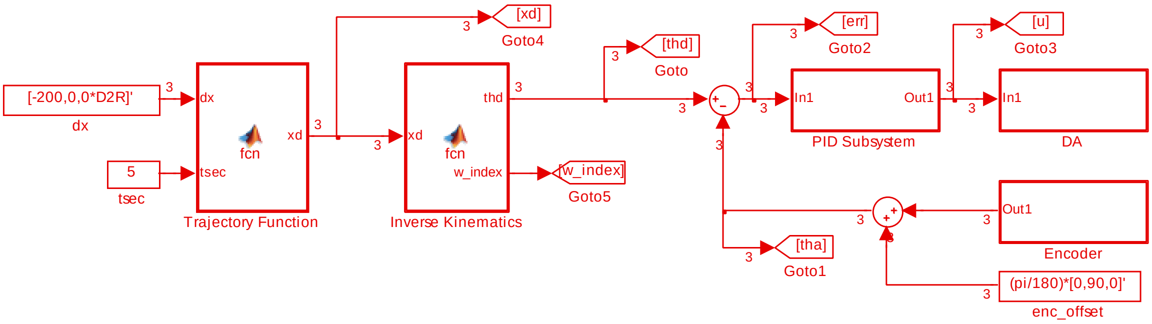
- Cartesian-space Control ((Motor1)Kp=200, Kd=1.5, (Motor2) Kp=160, Kd=1.2)
- File name: Cart_Control_SKM_2R1.mdl
- Function: Move along –X axis by 200mm ([100,100] → [-100,100])

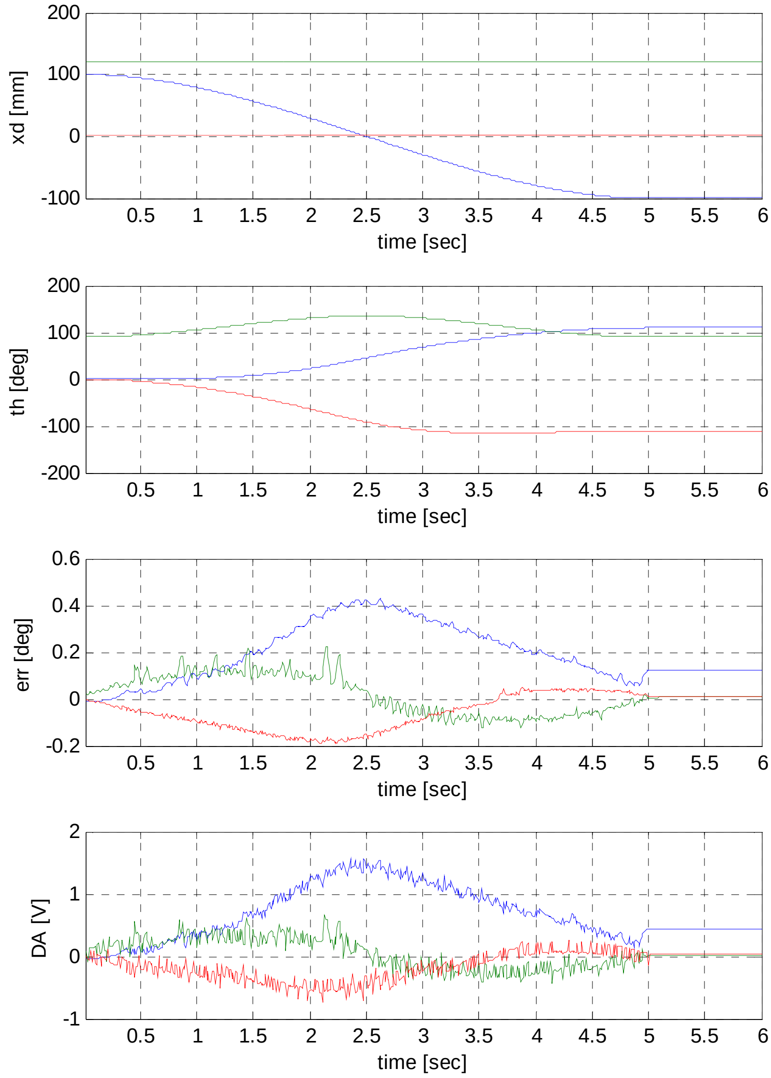



100
50
0
-50
-100
xd [mm]
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
time [sec]
150
100
50
0
th [deg]
time [sec]
0.3
0.2
0.1
0
-0.1
err [deg]
time [sec]
1
0.5
0
-0.5
Duty [%]
time [sec]

2) 3-DOF serial robot

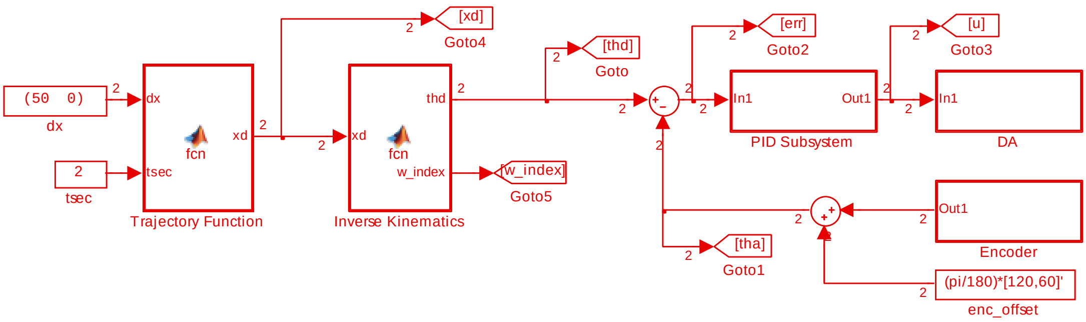
- Cartesian-space Control ((Motor1)Kp=200, Kd=1.5, (Motor2, 3) Kp=160, Kd=1.2)
- File name: Cart_Control_SKM_3R1.mdl
- Function: Move along –X axis by 200mm ([100,120], 90 deg → [-100,120], 90 deg)



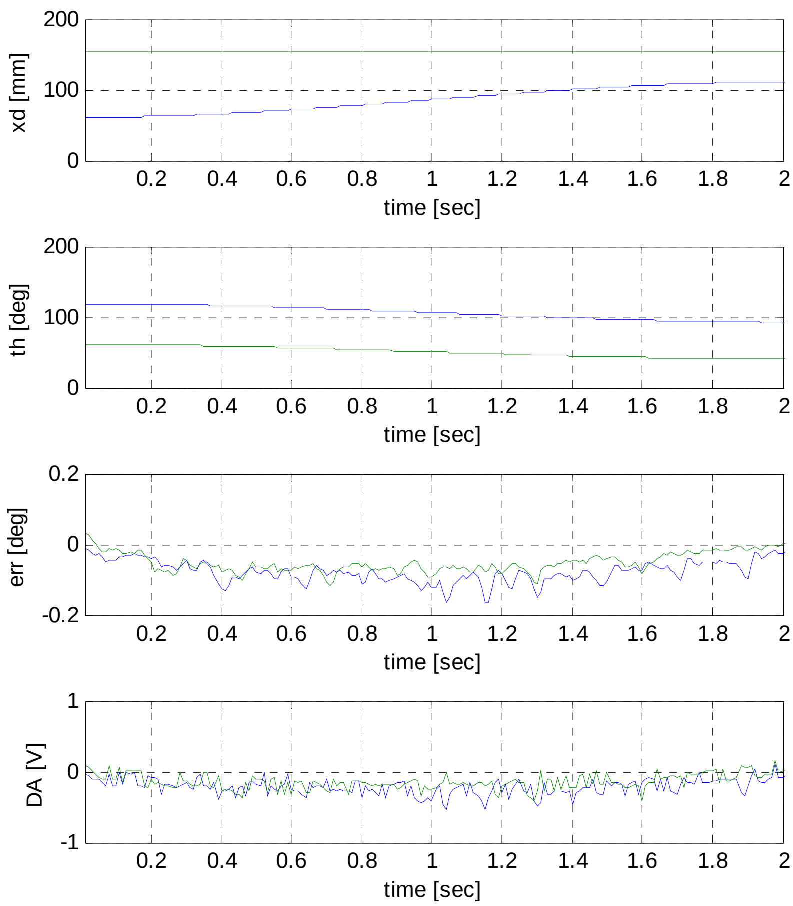

200
100
0
-100
xd [mm]
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
time [sec]
200
100
0
-100
-200
th [deg]
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
time [sec]
0.6
0.4
0.2
0
-0.2
err [deg]
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
time [sec]
2
1
0
-1
DA [V]
0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6
time [sec]

3) 5-bar (Type I) robot

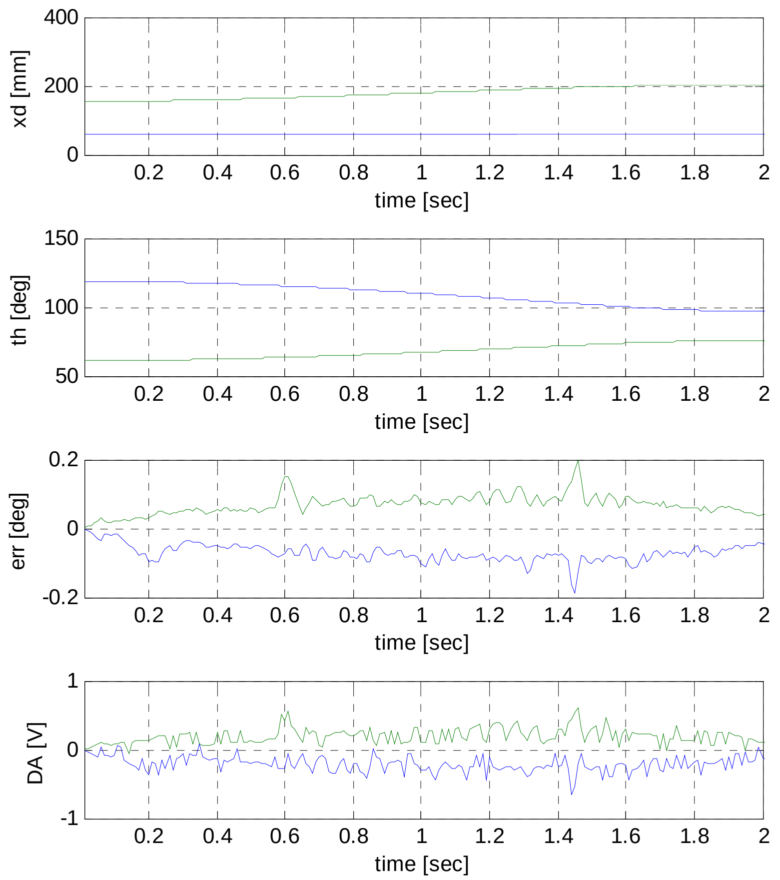
- Cartesian-space Control ((Motor1, 2) Kp=160, Kd=1.2)
- File name: Cart_Control_Fivebar_Type1_1.mdl



- Function: Move along the X and Y axes by 50 mm



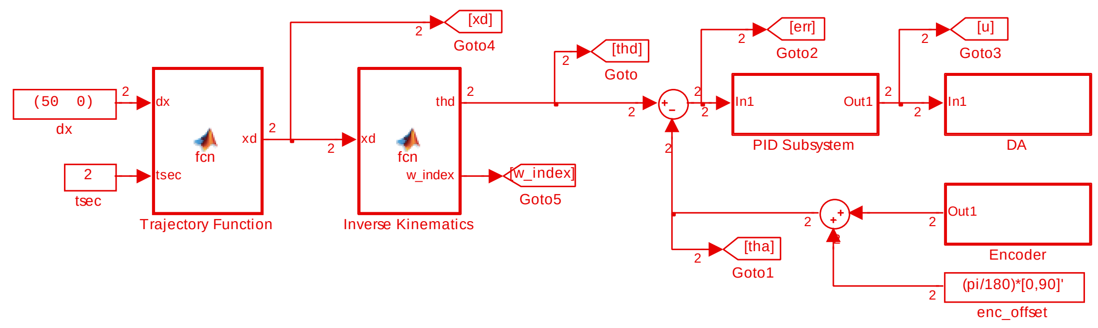
<along +X axis >



<along +Y axis >

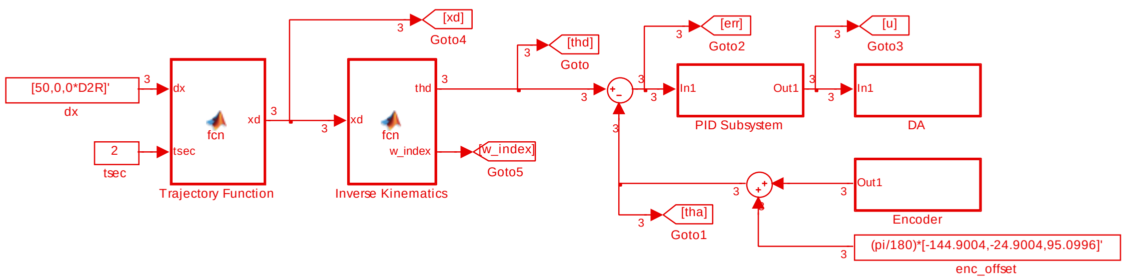
4) 5-bar (Type II) robot

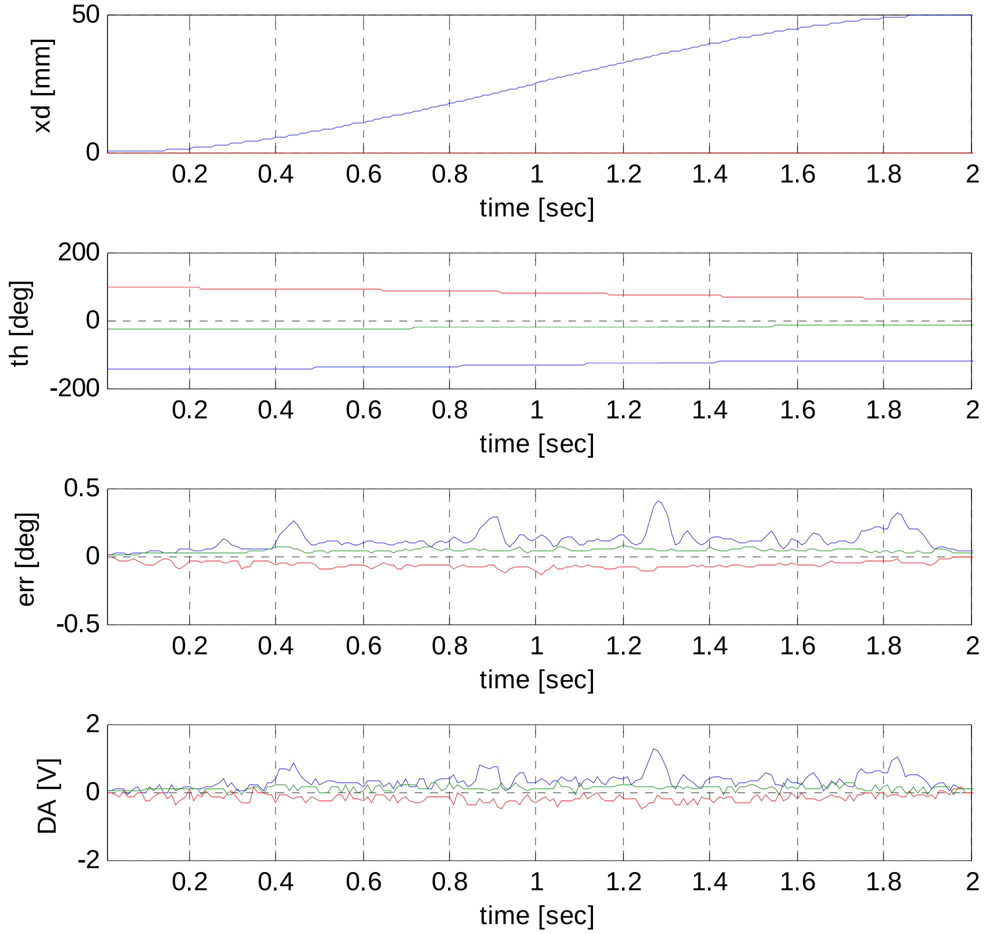
- Cartesian-space Control ((Motor1, 2) Kp=160, Kd=1.2)
- File name: Cart_Control_Fivebar_Type2_1.mdl
- Function: Move along the X and Y axes by 50 mm



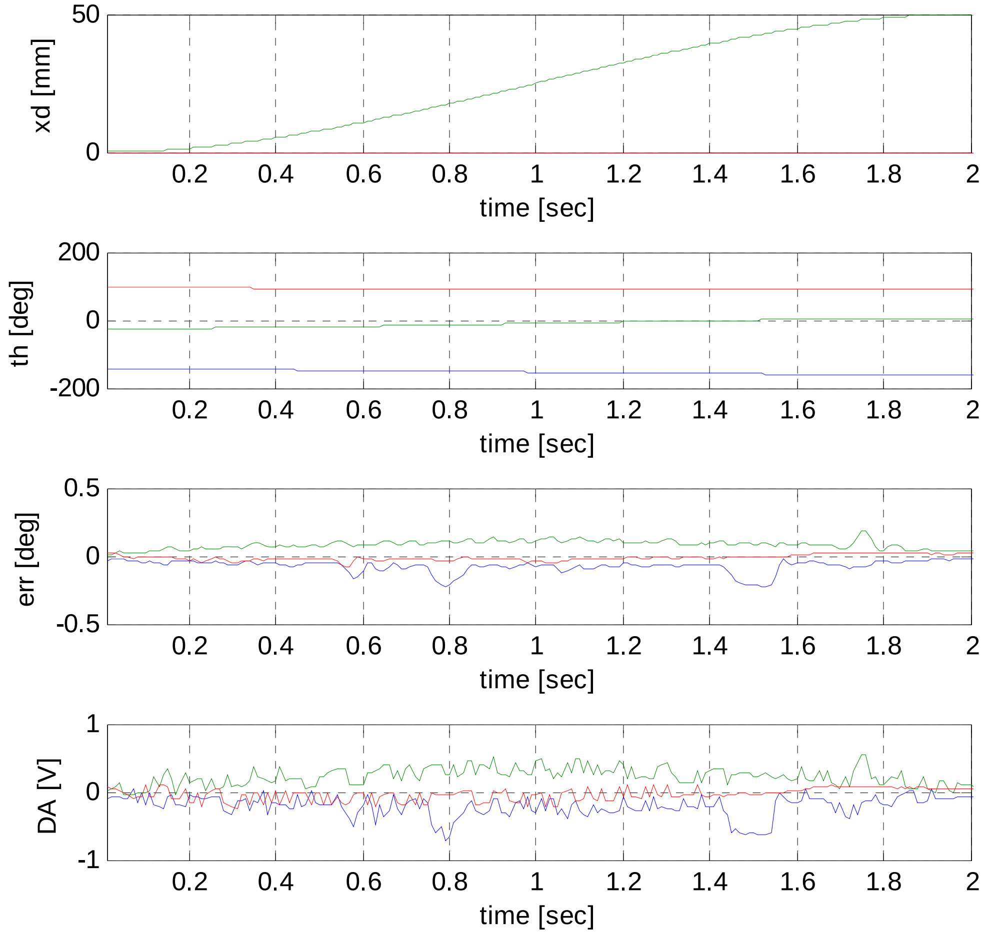
5) 3-DOF parallel robot

- Cartesian-space Control ((Motor1, 2, 3) Kp=160, Kd=1.2)
- File name: Cart_Control_PKM_3RRR_1.mdl
- Move along the X and Y axes by 50 mm




50
0
xd [mm]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]
200
0
-200
th [deg]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]
0.5
0
-0.5
err [deg]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]
2
0
-2
DA [V]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]

<along +X axis >


50
0
xd [mm]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]
200
0
-200
th [deg]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]
0.5
0
-0.5
err [deg]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]
1
0
-1
DA [V]
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time [sec]

<along +Y axis >

(4) Trajectory move

1) Trajectory format

- Format:

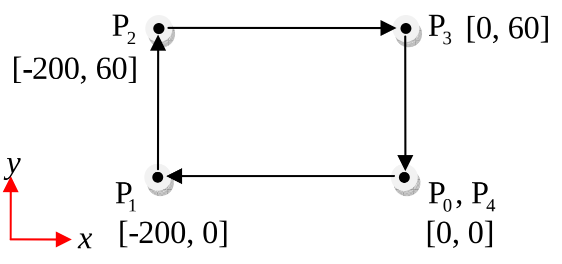
X	Y	W	L	A
[mm]	[mm]	[deg]	[mm/s]	[deg/s]

- Data output format:
  $[p_x, p_y, \theta]$

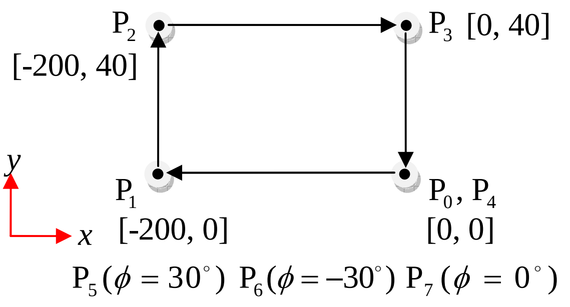
- Output port width:
  $8 \times (\text{time}, p_x, p_y, \theta) = 32$

- Linear velocity: 80mm/sec

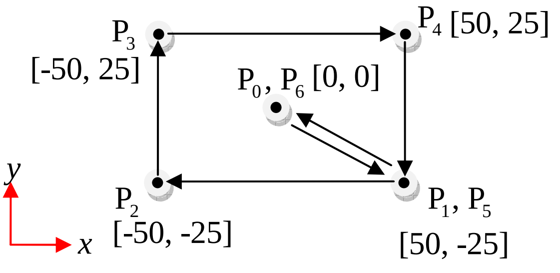
- Control paths:



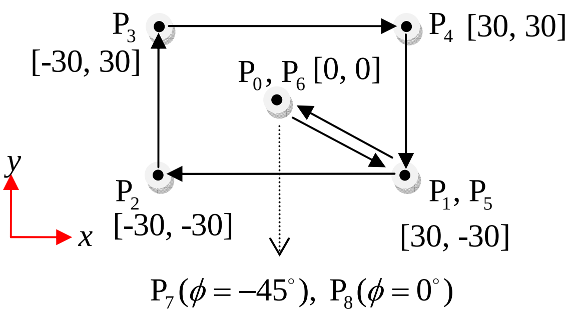
[2-DOF serial robot]



[3-DOF serial robot]



[5-bar robot]



[3-DOF parallel robot]

- For example, make the script similar to G-code, then save it with txt format, and run tr1.m.

```
% 3-DOF SKM %
G01 X0 Y0 W0 L50 A30
% -X Move
G01 X-200 Y0 W0
S00 T0.1
% +Y Move
G01 X-200 Y40 W0
S00 T0.1
% +X Move
G01 X0 Y40 W0
S00 T0.1
% -Y Move
G01 X0 Y0 W0
S00 T0.1
% +ANG %
G01 X0 Y0 W30
S00 T0.1
% -ANG %
G01 X0 Y0 W-30
S00 T0.1
% HOME %
G01 X0 Y0 W0
S00 T0.1
M02
```

- G-code like format

  % : comment line

  G01 : ptp move (cubic trajectory)

Format:	X	Y	W	L	A
	[mm]	[mm]	[deg]	[mm/s]	[deg/s]

  S00 T : setting of holding time in second

  M02 : End of script

- Type tr1.m in the command window:

  Type script file name only.

  P/D/T (P: Trajectory Plot, D: Data file output, T: file transfer to xPC Target)

- File name:

  skm1 : 2-DOF SKM

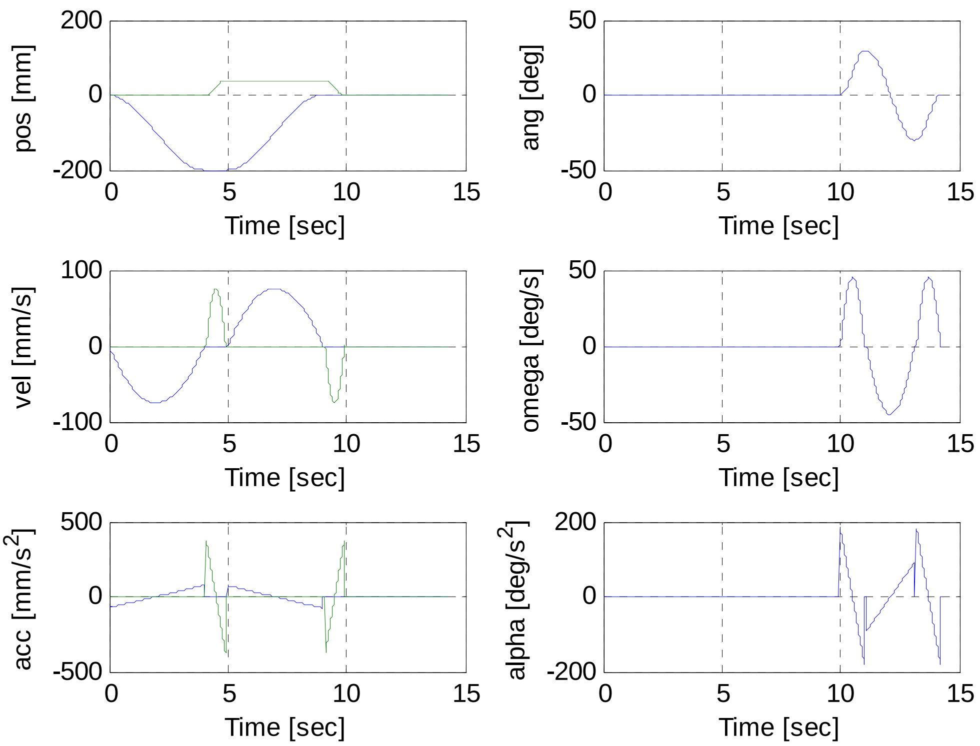
  skm2 : 3-DOF SKM

five1 : 5-bar Type I

five2 : 5-bar Type II

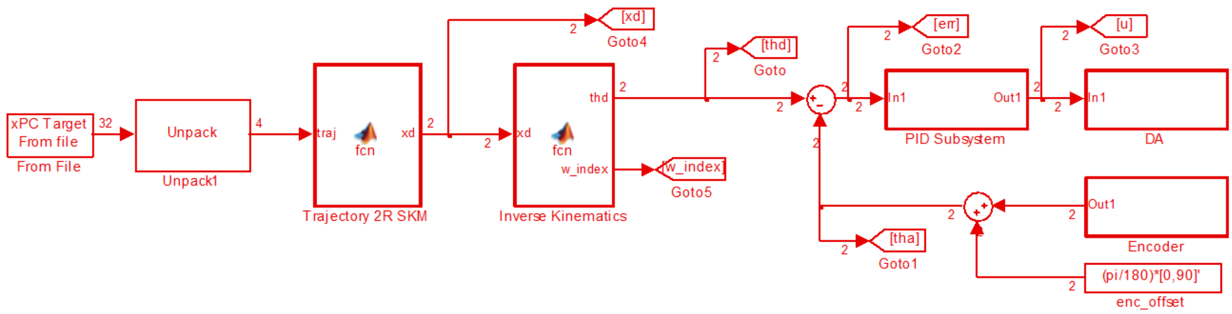
pkm1 : 3-DOF PKM

```
Command Window
File Name Only: skm2
    1.0000         0         0         0   50.0000   30.0000    0.1000
    1.0000 -200.0000         0         0   50.0000   30.0000    0.1000
    5.0000 -200.0000         0         0   50.0000   30.0000    0.1000
    1.0000 -200.0000   40.0000         0   50.0000   30.0000    0.1000
    5.0000 -200.0000   40.0000         0   50.0000   30.0000    0.1000
    1.0000         0   40.0000         0   50.0000   30.0000    0.1000
    5.0000         0   40.0000         0   50.0000   30.0000    0.1000
    1.0000         0         0         0   50.0000   30.0000    0.1000
    5.0000         0         0         0   50.0000   30.0000    0.1000
    1.0000         0         0   30.0000   50.0000   30.0000    0.1000
    5.0000         0         0   30.0000   50.0000   30.0000    0.1000
    1.0000         0         0  -30.0000   50.0000   30.0000    0.1000
    5.0000         0         0  -30.0000   50.0000   30.0000    0.1000
    1.0000         0         0         0   50.0000   30.0000    0.1000
    5.0000         0         0         0   50.0000   30.0000    0.1000
    6.0000         0         0         0   50.0000   30.0000    0.1000

     1

Plot/Data Out/Data Transmission
fx Plotting, Simulator or Control [P/D/T]:
```

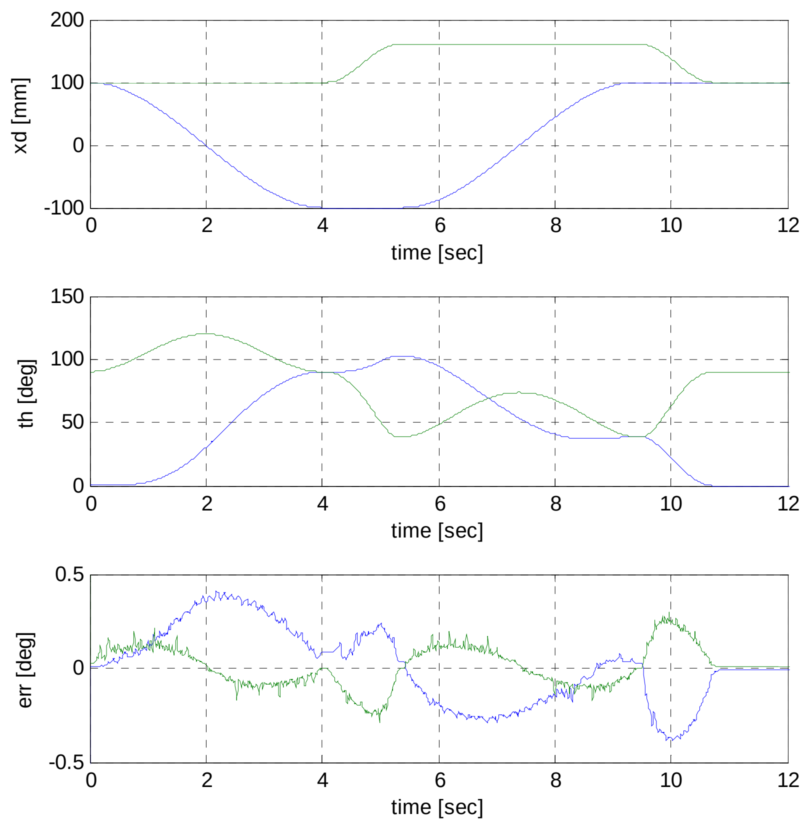


[Linear and Angular Trajectories]

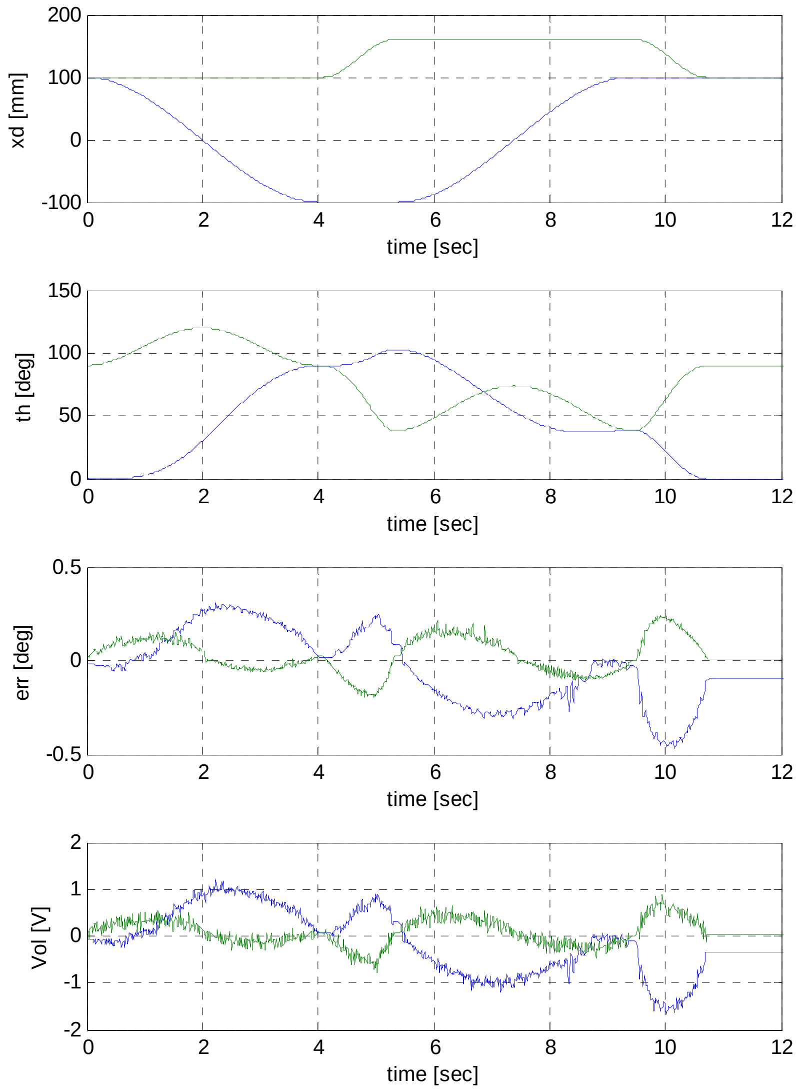
2) 2-DOF serial robot



<Horizontal configuration >

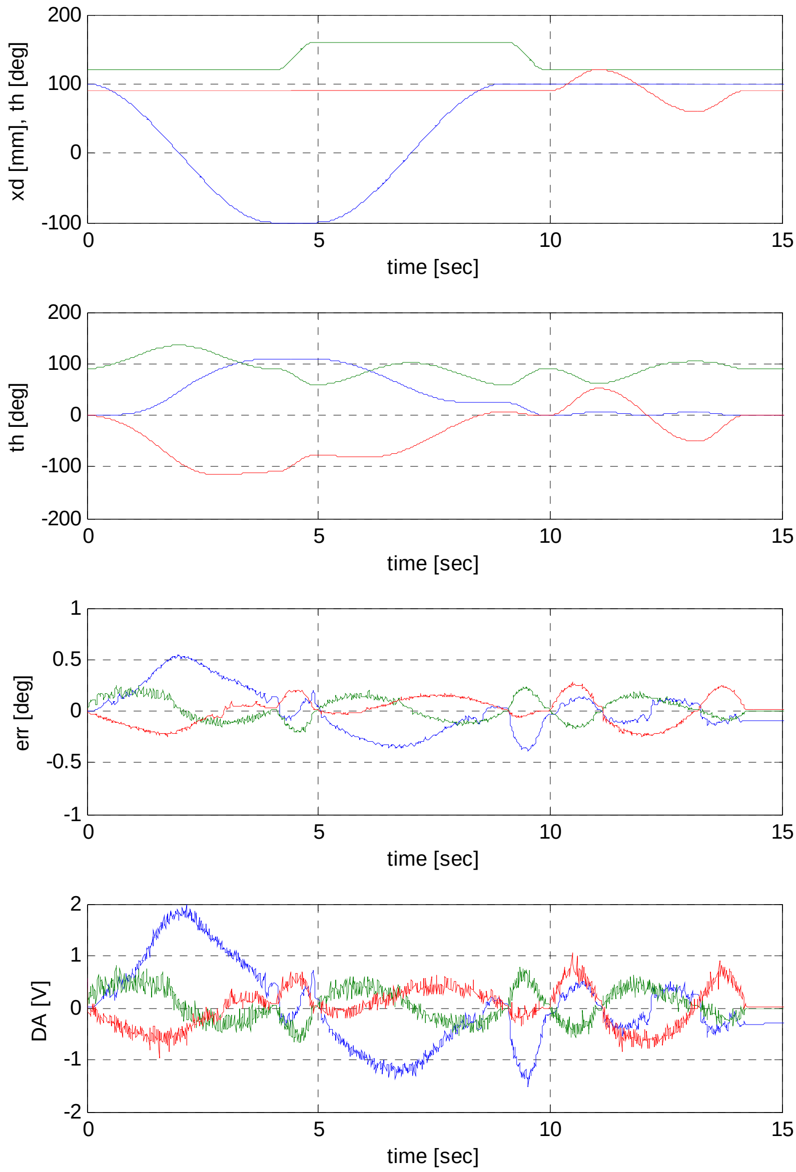


<Vertical configuration>

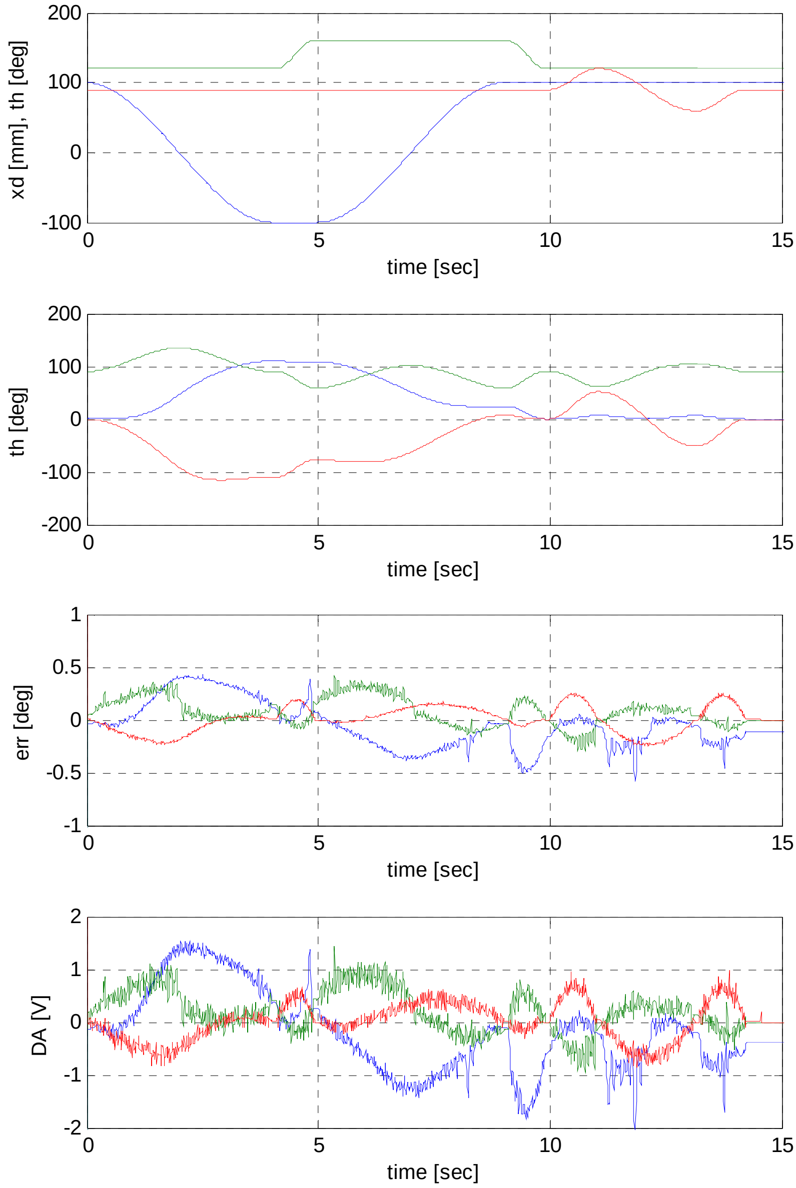


3) 3-DOF serial robot

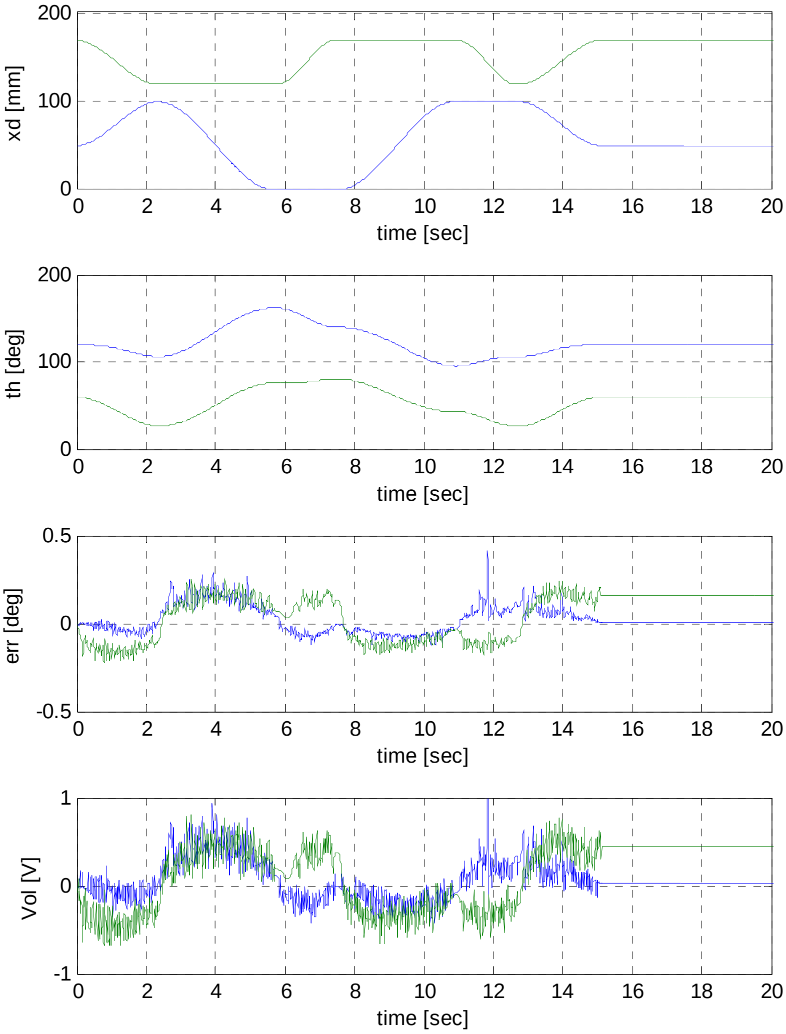
<Horizontal configuration>



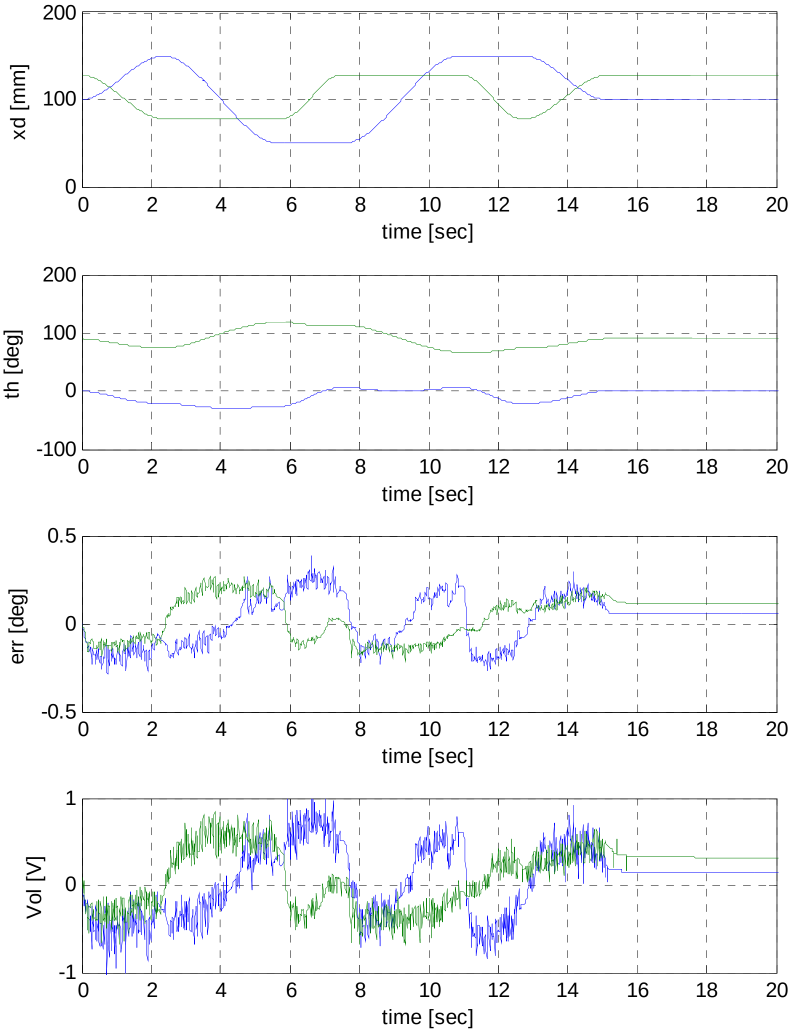
<Vertical configuration>



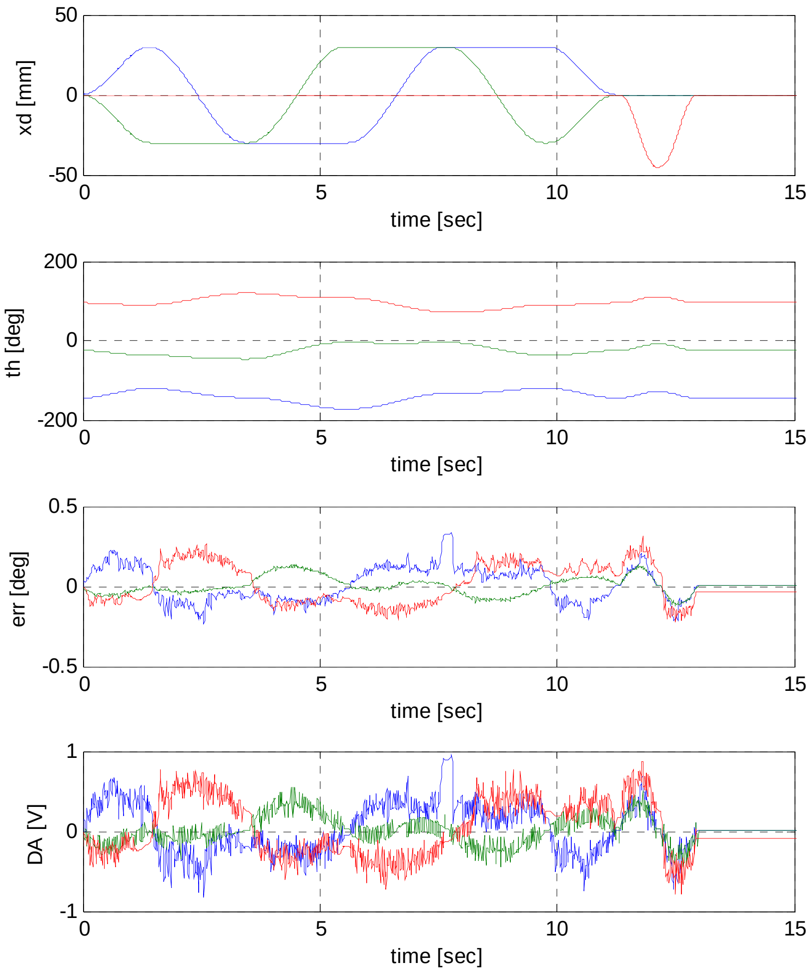
4) 5-bar (Type I) robot



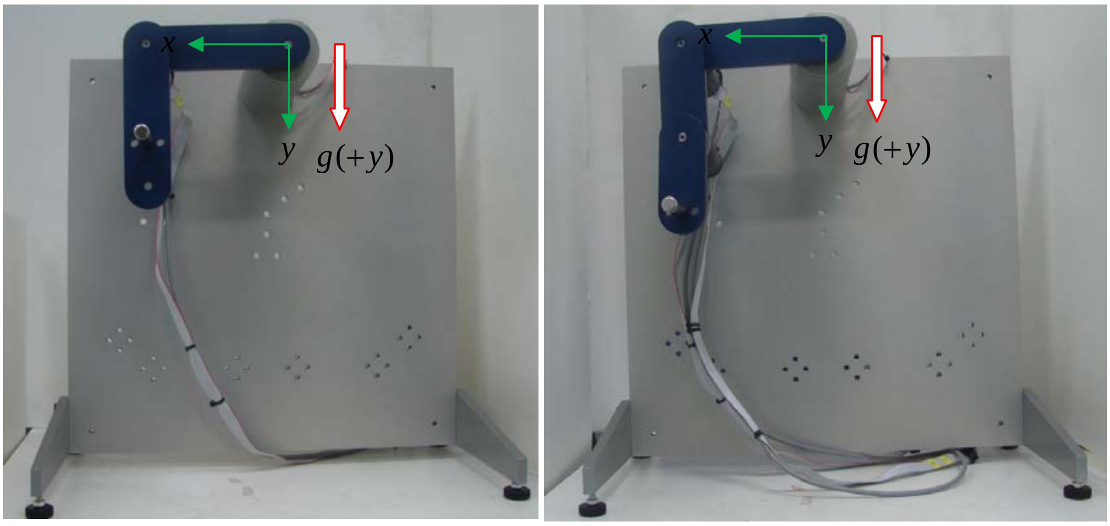
5) 5-bar (Type II) robot



6) 3-DOF parallel robot

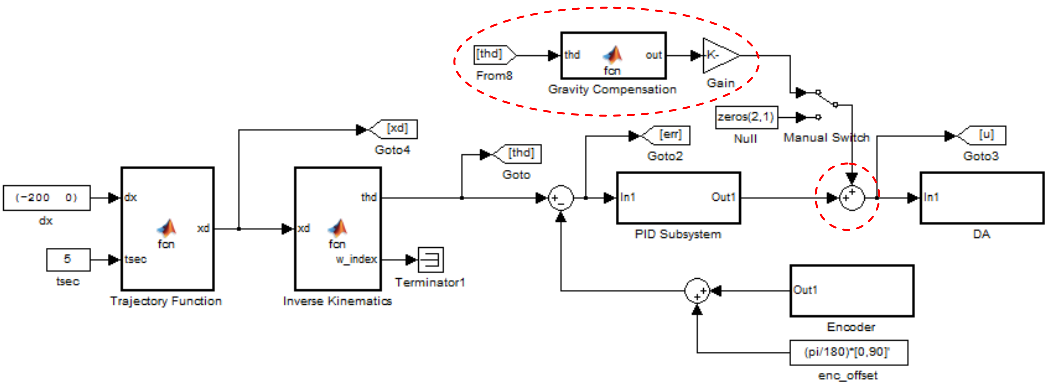


(5) Gravity compensation



[Vertical configurations of the 2-DOF and 3-DOF robots]

- Add the gravity compensation term to DA input as follow.



- Gravity Compensation Embedded MATLAB Code

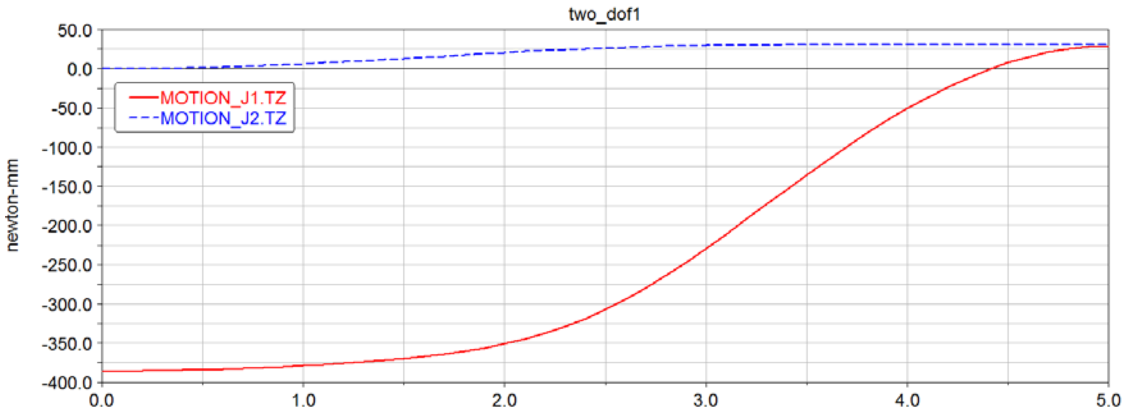
```
function out = fcn(thd)

MM2M=0.001;

th1=thd(1,1); th2=thd(2,1);
tau=zeros(2,1); out=zeros(2,1);

m1=0.363; a1=MM2M*100; ac1=MM2M*87.74;
m2=0.075; ac2=MM2M*41.68;
```

```
g=-9.81;        % Gravity Direction -Y axis %

tau(1,1)=g*(m1*ac1*cos(th1)+m2*(a1*cos(th1)+ac2*cos(th1+th2)));
tau(2,1)=m2*g*ac2*cos(th1+th2);

% Gear Ratio between Two Motors %
ratio=66/23;

out(1,1)=tau(1,1);
out(2,1)=ratio*tau(2,1);
```

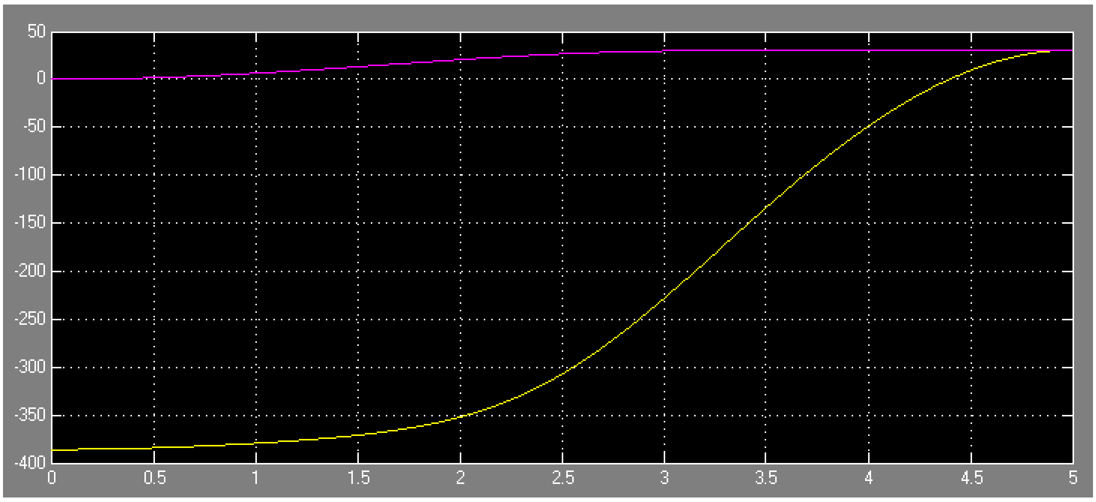
- Torque gain setting: Motor1=10V/3.1Nm, Motor2=10V/1.1Nm.

1) 2-DOF serial robot

<Motor torque for full dynamics>

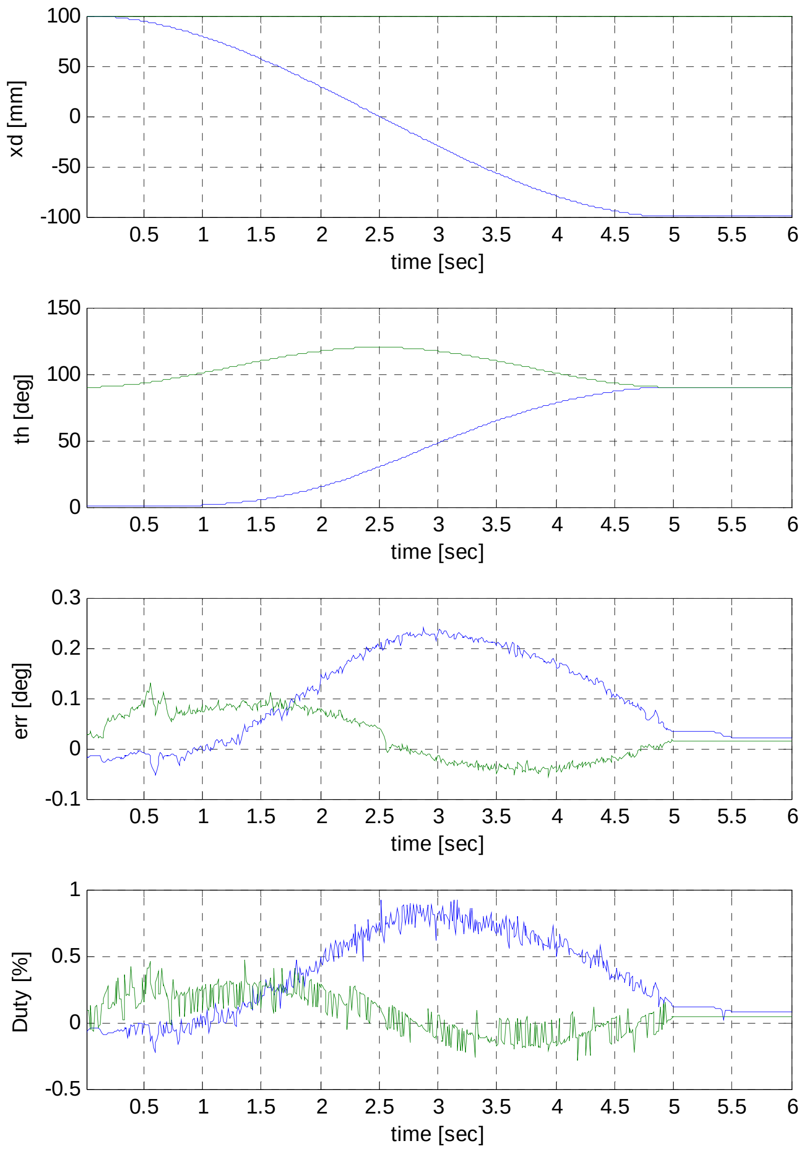


<Motor torque for gravity force >

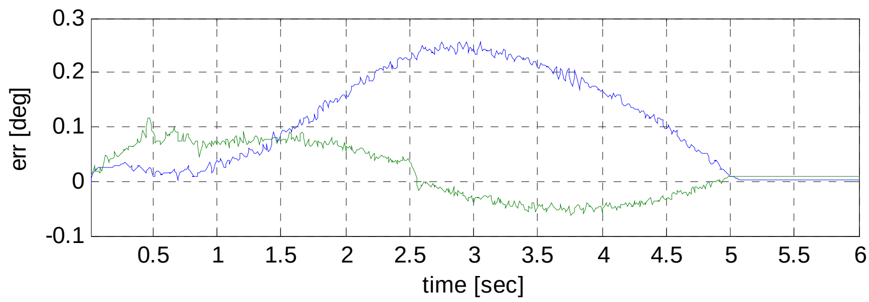


<Trajectory: move along –X axis>

<Vertical configuration: before gravity compensation>

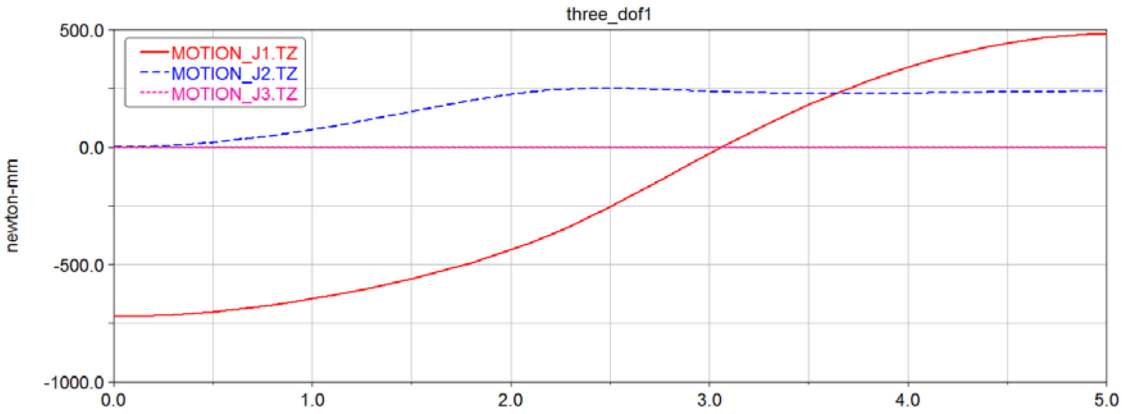


<Vertical configuration: after gravity compensation>

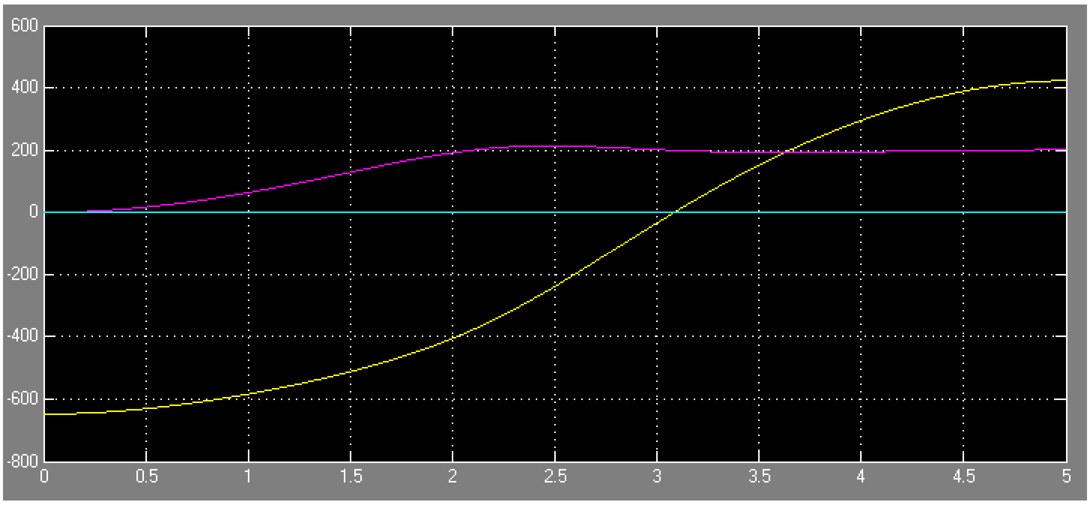


2) 3-DOF serial robot

<Motor torque for full dynamics>

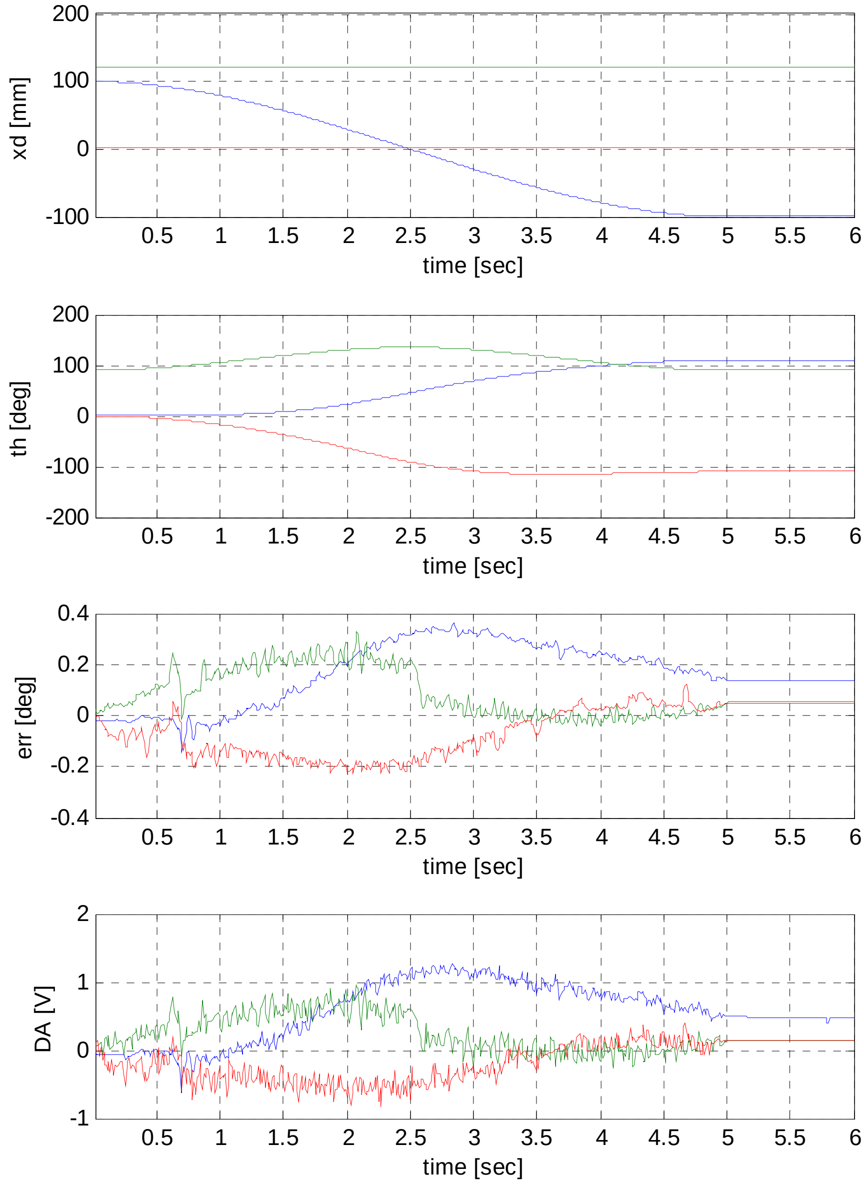


<Motor torque for gravity force >



<Trajectory: move along –X axis >

<Vertical configuration: before gravity compensation>



<Vertical configuration: after gravity compensation>