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Sustainable Utilization & Development in Engineering & Technology

Control of a Cable-Driven 2-DOF Joint Module with a Flexible Backbone

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Presented By
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Introduction

Kinematic analysis

Motion control system

Experiment and Results

Conclusion

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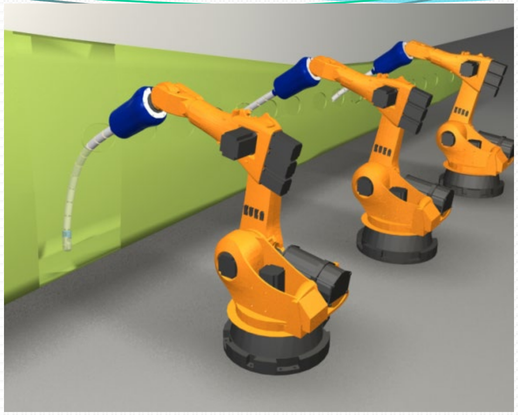
Dexterous Robotic Arms and Applications



http://www.ocrobotics.com/images/applications/aerospace/fullsize/aerospace01.jpg

Aerospace application

http://news.bbc.co.uk/2/hi/technology/5324708.stm

Nuclear inspection

http://dart2.arc.nasa.gov/Exercises/TMR2004/TMR-d2/images/23DSC00207.jpg

Search and rescue

Motivation

Why is the cable–driven dexterous robotic arm preferred?

Advantages

- Cables and flexible backbone are light, low power consumption
- Low inertia so high velocity is achievable.
- More modules can be added to improve dexterity

Disavantages

- Complicate analysis

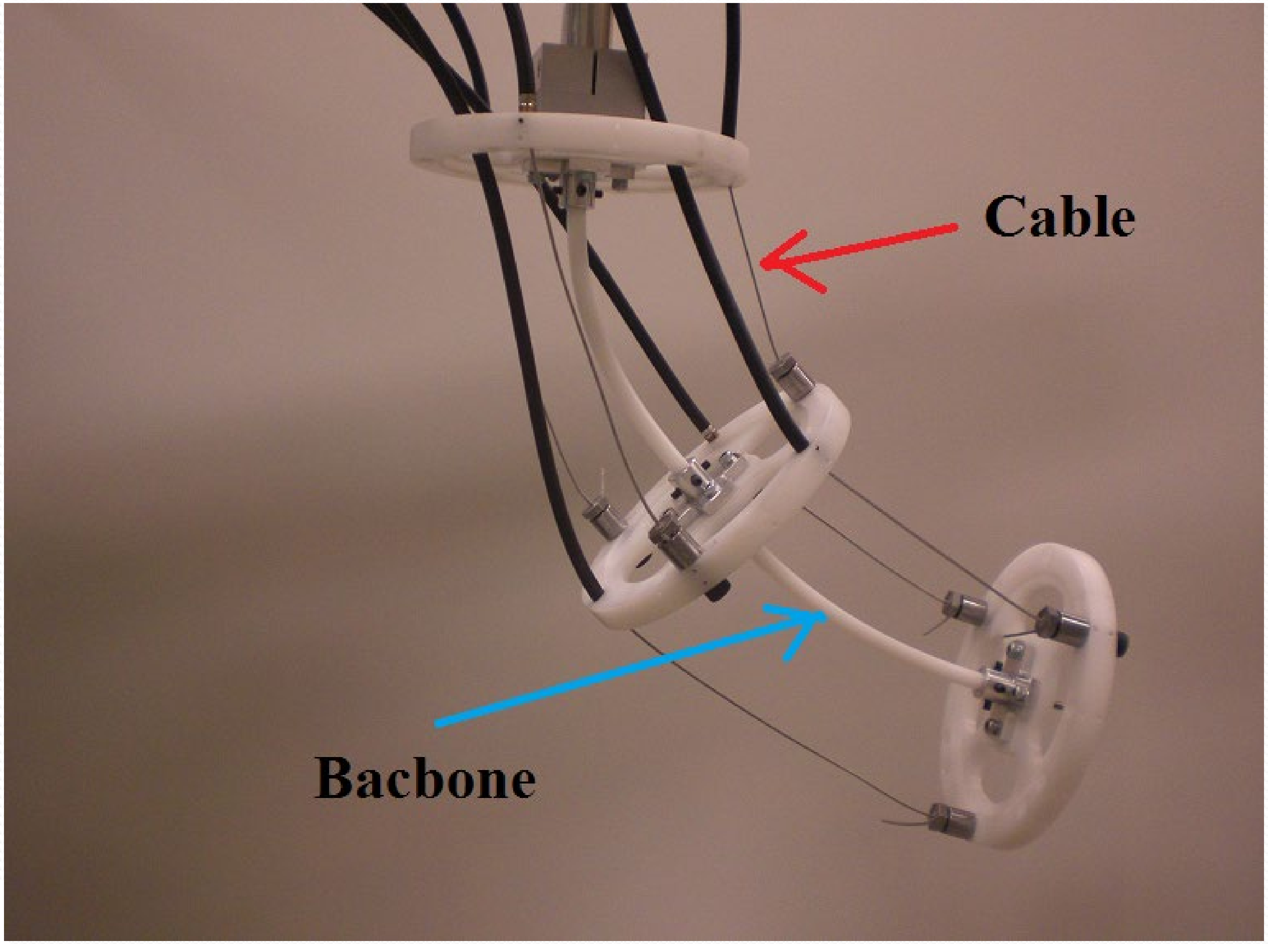
Objective and Scope

- Objective:
  To implement position control on the cable-driven dexterous robotic arm

- Scope:

1. Formulation of the forward and inverse kinematics
2. PID position control based on kinematic model
3. Experiment and evaluation of position control performance

Cable-driven Dexterous Robotic Arm



- Introduction
- **Kinematic analysis**
  - Module Design
  - Forward kinematic
  - Inverse kinematic
- Motion control system
- Experiment and Results
- Conclusion

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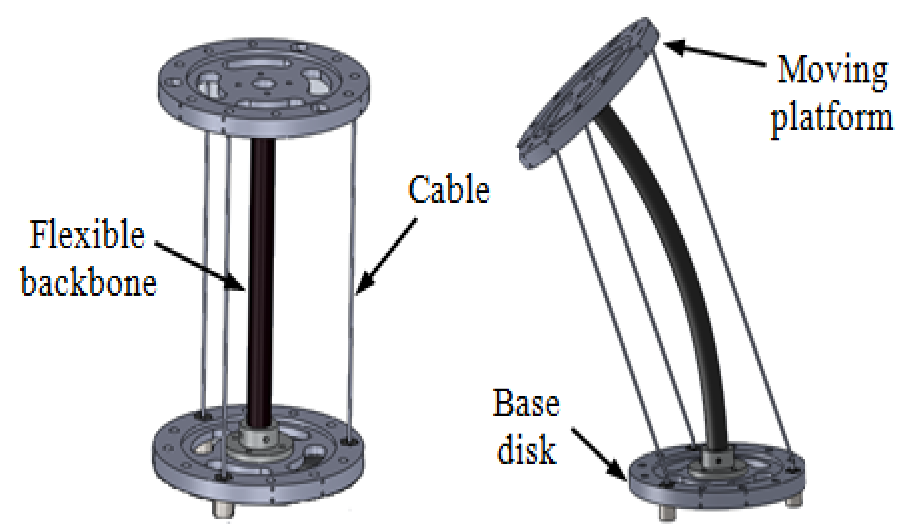
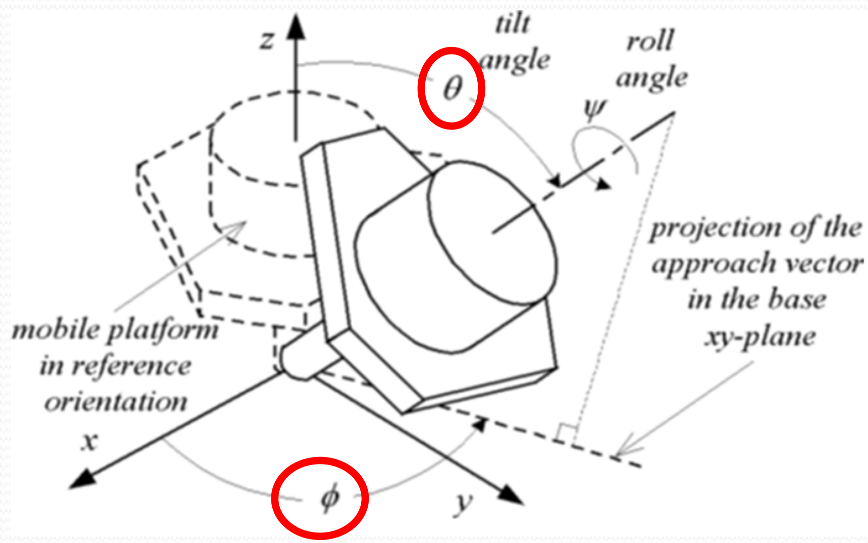
Module Design

2 DOF: defined by θ *and* ϕ

Without torsion: $\Psi = 0$

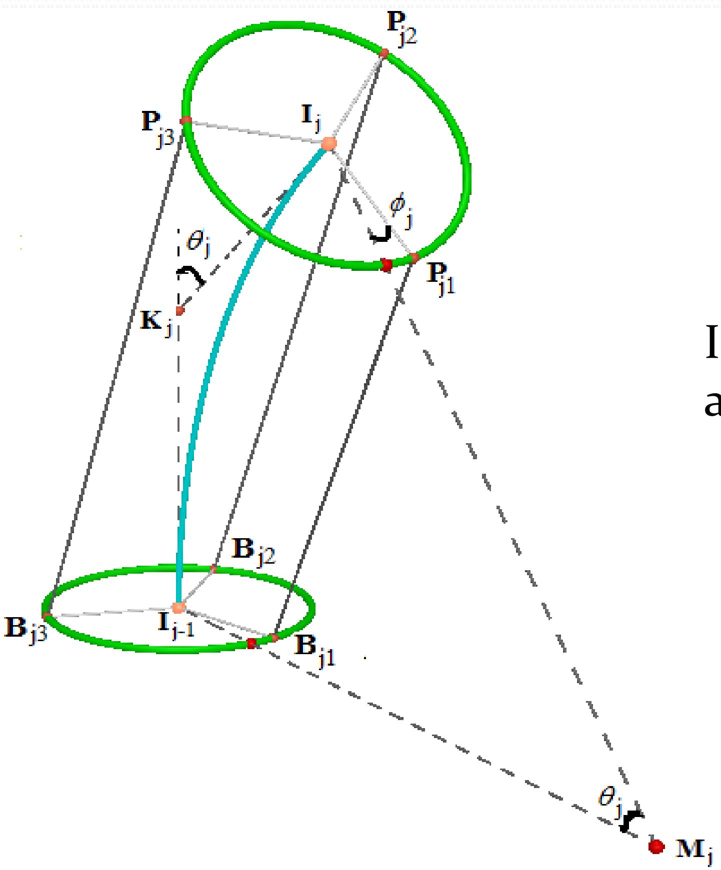


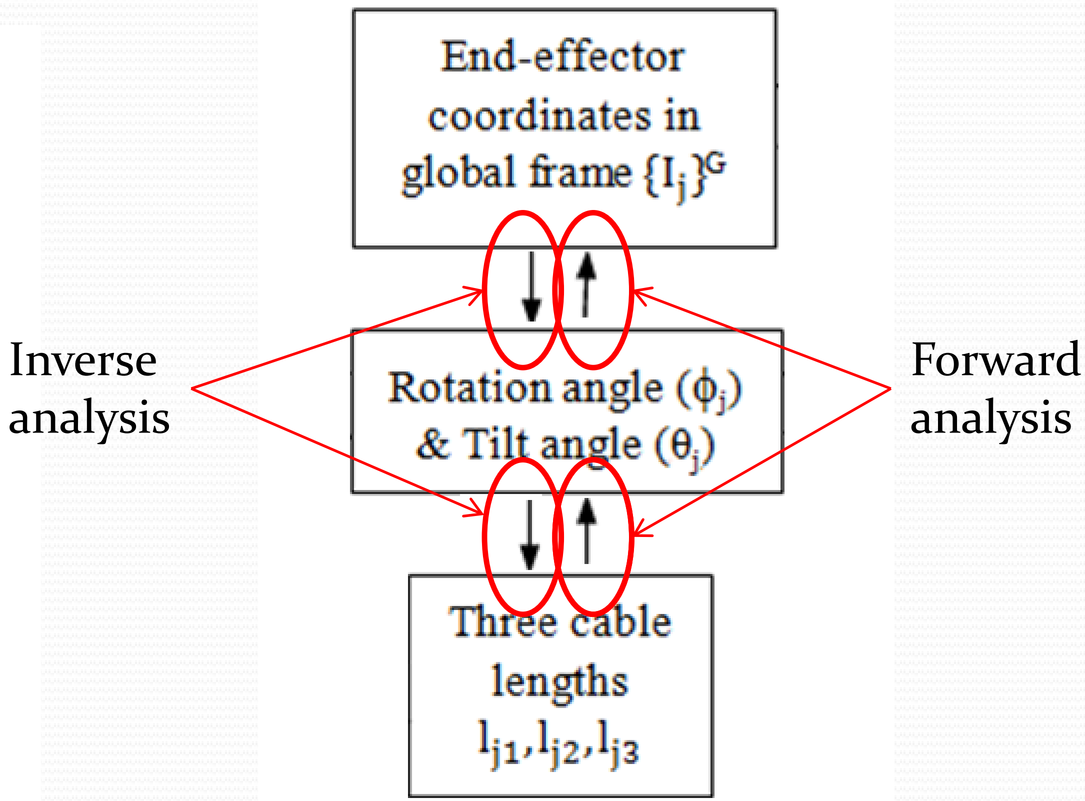
Two-DOF Joint Module design



Bonev I.A. and Ryu J., "Orientation workspace analysis of 6-dof parallel manipulators", *ASME Design Engineering Technical Conferences*, Las Vegas, Nevada, pp. 1-8, 1999.

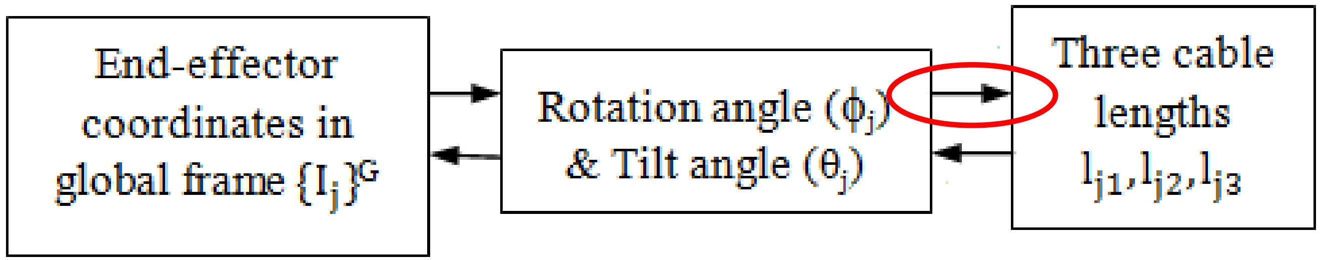
Kinematic Analysis





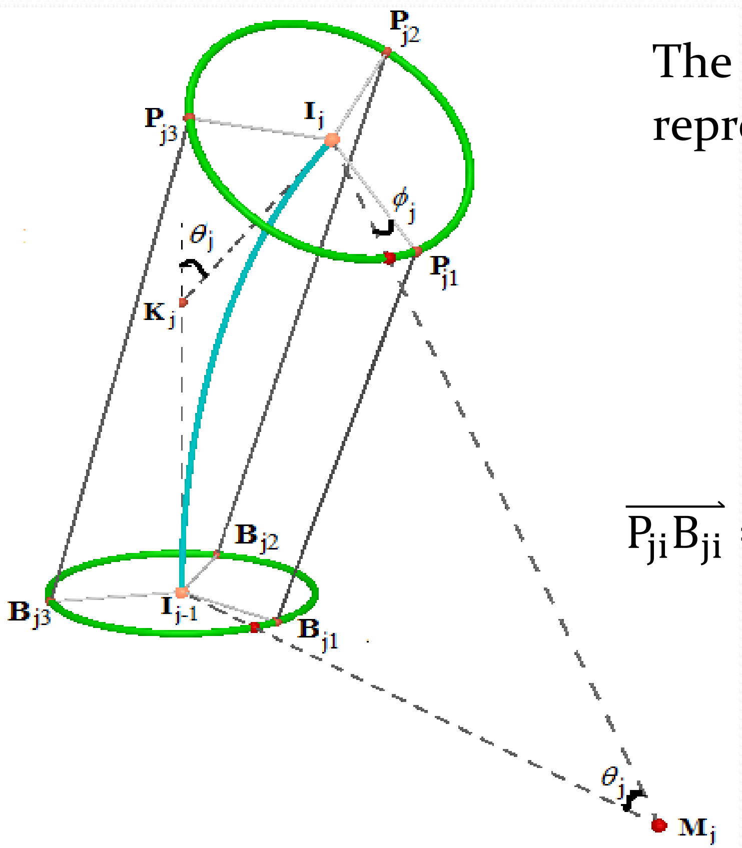
Kinematic analysis block diagram

Inverse kinematic



Kinematic analysis block diagram

Inverse kinematic

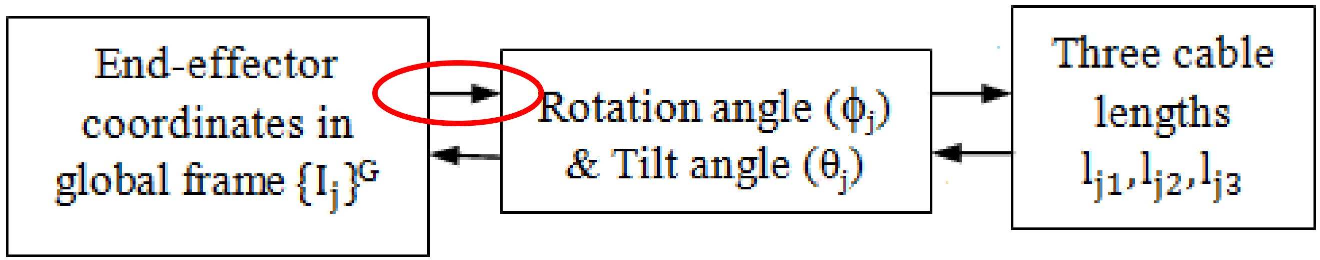


The length of vector $\overrightarrow{B_{ji}P_{ji}}$, (i=1,2,3) represents the cable length l_{ji} of i^{th} cable.

$$\overrightarrow{P_{ji}B_{ji}} = \overrightarrow{P_{ji}I_j} + \overrightarrow{I_jK_j} + \overrightarrow{K_jI_{j-1}} + \overrightarrow{I_{j-1}B_{ji}}$$

$$\overrightarrow{P_{ji}B_{ji}} = \left(\mathbf{I}_{3x3} - \mathbf{R}_{(\phi_j,\theta_j)}\right)\begin{pmatrix} r\cos(j\pi - 2\pi(i-1)/3 \\ r\sin(j\pi - 2\pi(i-1)/3 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ L_j \end{pmatrix}$$

Inverse kinematic



Kinematic analysis block diagram

Inverse kinematic

- Module 1

$$^{0}\{E_1\} = R_{(\phi_1\,;\,\theta_1)}\begin{pmatrix}0\\0\\L_1\end{pmatrix}+\begin{pmatrix}0\\0\\L_1\end{pmatrix}$$

$$LHS = \begin{pmatrix}x_{E_1}\\y_{E_1}\\z_{E_1}\end{pmatrix} \qquad RHS = \begin{pmatrix}L_1\cos\phi_1\sin\theta_1\\L_1\sin\phi_1\sin\theta_1\\L_1\cos\theta_1 + L_1\end{pmatrix}$$

$$\rightarrow \phi_1 = \tan^{-1}\left(\frac{y_{I_1}}{x_{I_1}}\right) \quad \text{and} \quad \theta_1 = \cos^{-1}\left(\frac{-A+1}{A+1}\right) \quad \text{with} \quad A = \left(\frac{y_{I_{10}}}{z_{I_{10}}}\sin\phi_1\right)^2$$

Inverse kinematic

- Module 2

$$ {}^{0}\{E_2\} = {}^{0}_{4}T\,{}^{4}\{E_2\} $$

$$\begin{pmatrix} x_{E_2} \\ z_{E_2} \\ z_{E_2} \\ 1 \end{pmatrix} = \begin{bmatrix} R(\phi_1;\theta_1) & \begin{pmatrix} 0 \\ 0 \\ L_1 \end{pmatrix} \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R(\phi_2;\theta_2) & \begin{pmatrix} 0 \\ 0 \\ L_1 + L_2 \end{pmatrix} \\ 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ L_2 \\ 1 \end{pmatrix}$$

Let $\begin{bmatrix} R(\phi_1;\theta_1) & \begin{pmatrix} 0 \\ 0 \\ L_1 \end{pmatrix} \\ 0 & 1 \end{bmatrix}^{-1} \begin{pmatrix} x_{E_2} \\ z_{E_2} \\ z_{E_2} \\ 1 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ L_1 \\ 0 \end{pmatrix} = \begin{pmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{pmatrix}$ is known

$$\rightarrow \phi_2 = \tan^{-1}\left(\frac{y_2}{x_2}\right) \text{ and } \theta_2 = \cos^{-1}\left(\frac{-B+1}{B+1}\right)$$

with $B = \left(\frac{y_2}{z_2}\sin\phi_2\right)^2$

Inverse kinematic

- Module nth :

Given the coordinates of all end-points of all modules find the torsion and tilt angles of all modules

$$^{0}\{E_n\} = {}_{2n}^{0}T \, ^{2n}\{E_n\}$$

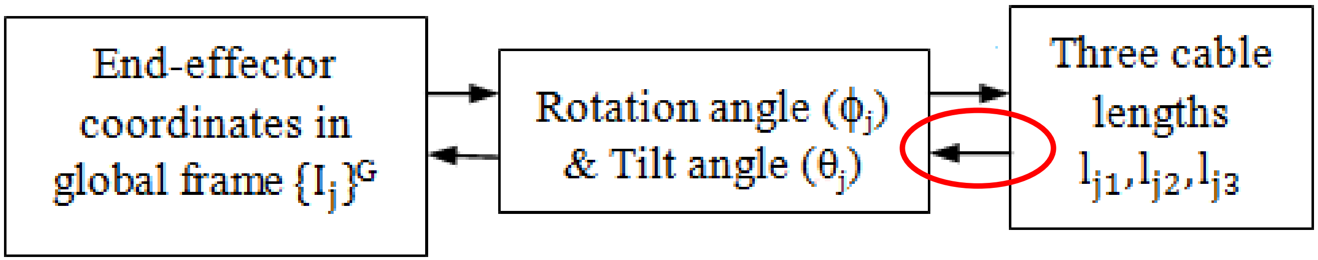
$$\rightarrow \phi_n = \tan^{-1}\left(\frac{y_n}{x_n}\right) \quad \text{and} \quad \theta_n = \cos^{-1}\left(\frac{-C+1}{C+1}\right)$$

with

$$\begin{pmatrix} x_n \\ y_n \\ z_n \\ 1 \end{pmatrix} = \begin{bmatrix} R(\phi_{n-1};\theta_{n-1}) & \begin{pmatrix} 0 \\ 0 \\ L_{n-2}+L_{n-1} \end{pmatrix} \\ 0 & 1 \end{bmatrix} \cdots \begin{bmatrix} R(\phi_2;\theta_2) & \begin{pmatrix} 0 \\ 0 \\ L_1+L_2 \end{pmatrix} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} R(\phi_1;\theta_1) & \begin{pmatrix} 0 \\ 0 \\ L_1 \end{pmatrix} \\ 0 & 1 \end{bmatrix} \begin{pmatrix} x_{I_n} \\ y_{I_n} \\ z_{I_n} \\ 1 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ L_{n-1} \\ 0 \end{pmatrix}$$

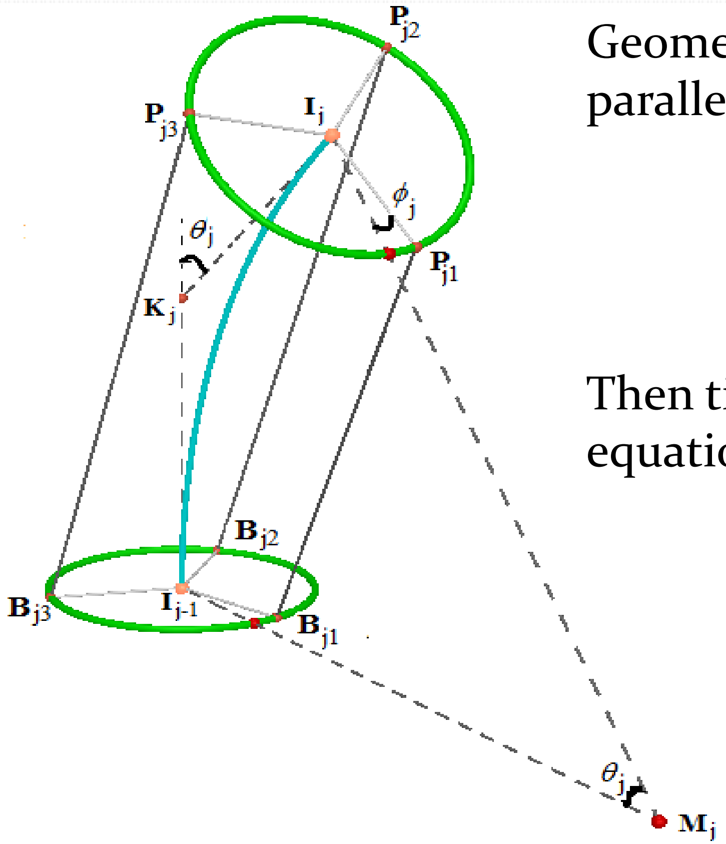
$$C = \left(\frac{y_n}{z_n}\sin\phi_n\right)^2$$

Forward kinematic



Kinematic analysis block diagram

Forward kinematic



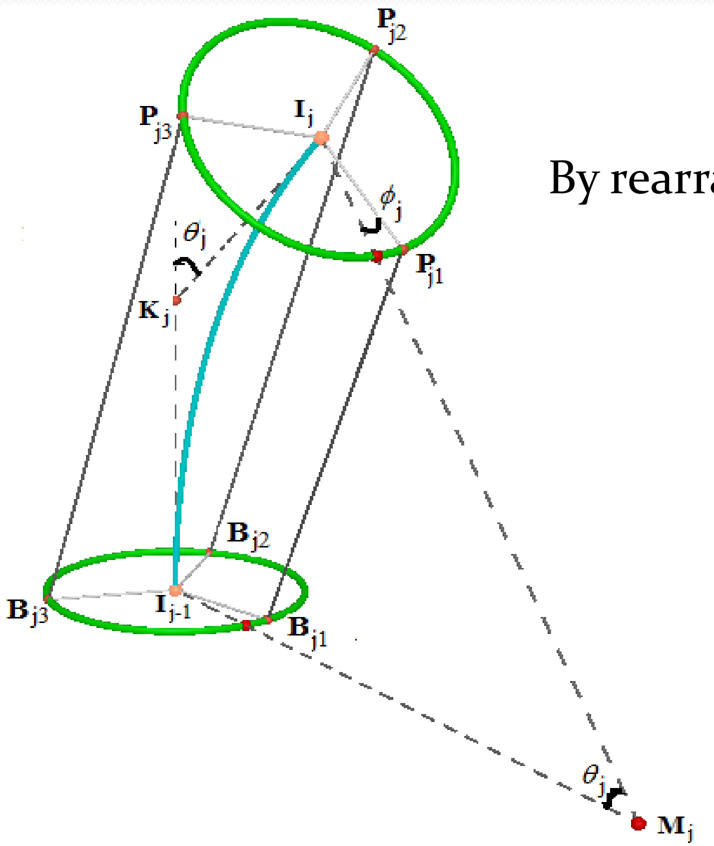
Geometrically, the three cables within a joint module are parallel:

$$P_{j1}B_{j1}//P_{j2}B_{j2}//P_{j3}B_{j3}//I_{j-1}I_j$$

Then titling angle θ_j can be obtained from following equation, in which L_o is backbone length:

$$\sin\left(\frac{\theta_j}{2}\right) = \frac{\theta_j\left(l_{j1} + l_{j2} + l_{j3}\right)}{12L_0}$$

Forward kinematic



Cable 1:

$$
\begin{aligned}
l_{j1}^{\ 2} = {} & \left[(-1)^{j+1} r\left(1 - c_\phi^{\ 2} c_\theta - s_\phi^{\ 2}\right) + L_j c_\phi s_\theta\right]^2 \\
& + \left[(-1)^{j+1} r\left(s_\phi c_\theta c_\phi - s_\phi c_\phi\right) + L_j s_\phi s_\theta\right]^2 \\
& + \left[(-1)^{j} r s_\theta c_\phi + L_j(1 + c_\theta)\right]^2
\end{aligned}
$$

By rearranging the terms, a quadratic equation is obtained :

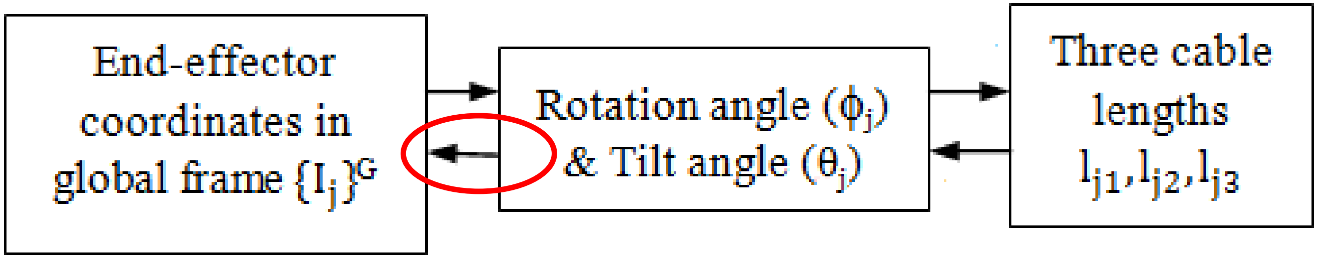
$$A c_\phi^{\ 2} + B c_\phi + C = 0$$

$$A = 2r^2(c_\theta - 1), B = (-1)^{j+1} \times 4 L_j r s_\theta,$$

$$\text{and } C = l_{j1}^{\ 2} - 2L_j^{\ 2}(1 + c_\theta)$$

$$\therefore \phi_j = \cos^{-1}\left(\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right)$$

Forward kinematic



Kinematic analysis block diagram

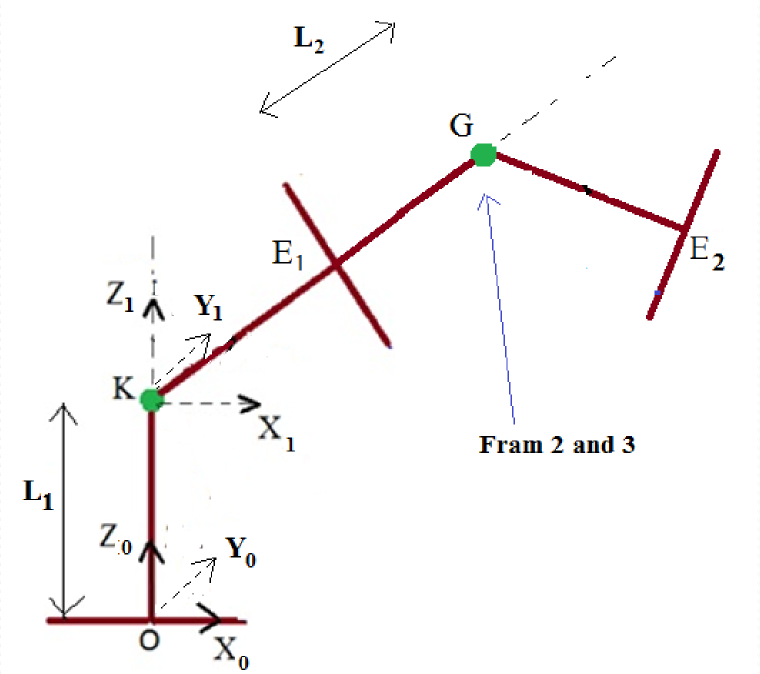
Forward kinematic

- For n-modules:

  - There are 2 frames in one module n0, n1 and n2 based on the translation:

Frame (2n-2) $(O_{2n-1}X_{2n-1}Y_{2n-1}Z_{2n-1}) \xrightarrow[(0 \quad 0 \quad L_{n-1}+L_n)]{translating}$ Frame (2n-1) $(O_{2n-1}X_{2n-1}Y_{2n-1}Z_{2n-1}) \xrightarrow[(\phi_n, \theta_n)]{rotating, tilting}$

Frame 2n $(O_{2n}X_{2n}Y_{2n}Z_{2n})$



Forward kinematic

- Transformation matrix from frame n2 to 10:

$$ {}^{0}_{2n}T = {}^{0}_{1}Q\,{}^{1}_{2}P\,{}^{2}_{3}Q\,{}^{3}_{4}P \ldots {}^{2n-2}_{2n-1}Q\,{}^{2n-1}_{2n}P $$

- The coordinate of end-point I_n in frame 10

$$ {}^{0}\{E_n\} = {}^{0}_{2n}T\,{}^{2n}\{E_n\} $$

$$ = \begin{bmatrix} R_{(\phi_1;\theta_1)} & \begin{pmatrix} 0 \\ 0 \\ L_1 \end{pmatrix} \\ 0 & 1 \end{bmatrix} . \begin{bmatrix} R_{(\phi_2;\theta_2)} & \begin{pmatrix} 0 \\ 0 \\ L_1 + L_2 \end{pmatrix} \\ 0 & 1 \end{bmatrix} \ldots \begin{bmatrix} R_{(\phi_n;\theta_n)} & \begin{pmatrix} 0 \\ 0 \\ L_{n-1} + L_n \end{pmatrix} \\ 0 & 1 \end{bmatrix} . \begin{pmatrix} 0 \\ 0 \\ L_n \\ 1 \end{pmatrix} $$

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- Hardware setup
- PID tuning
- Lab-view program

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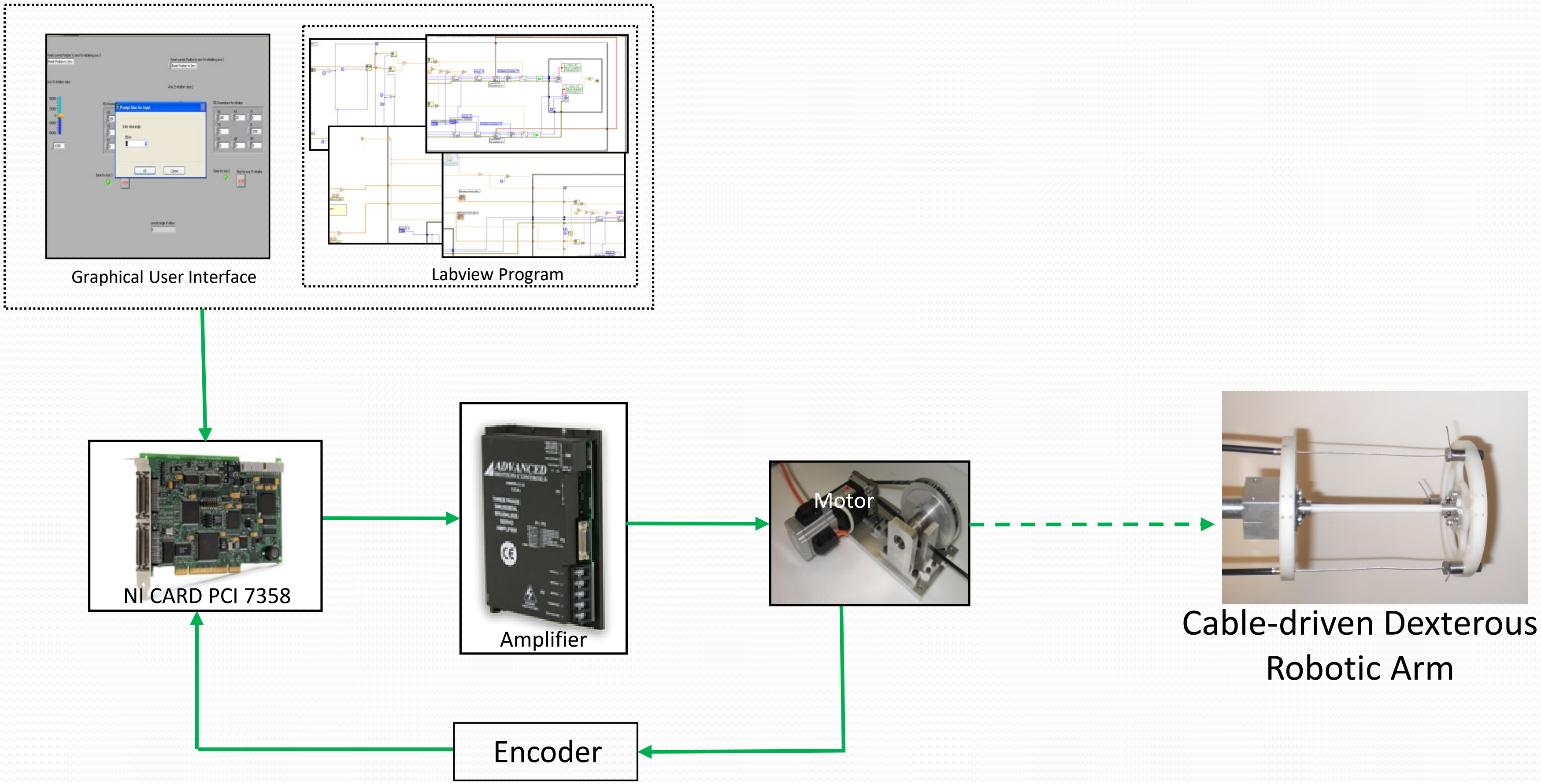
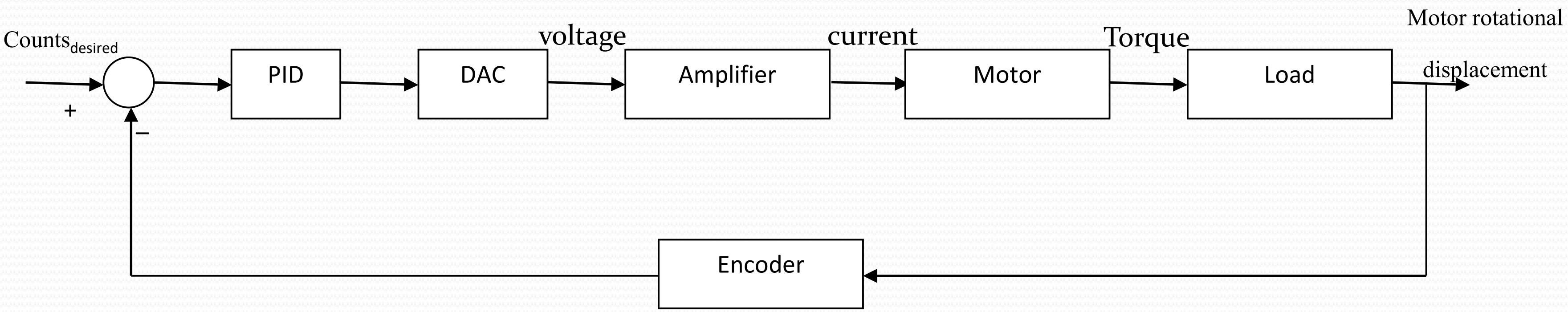
Hardware Setup for one axis



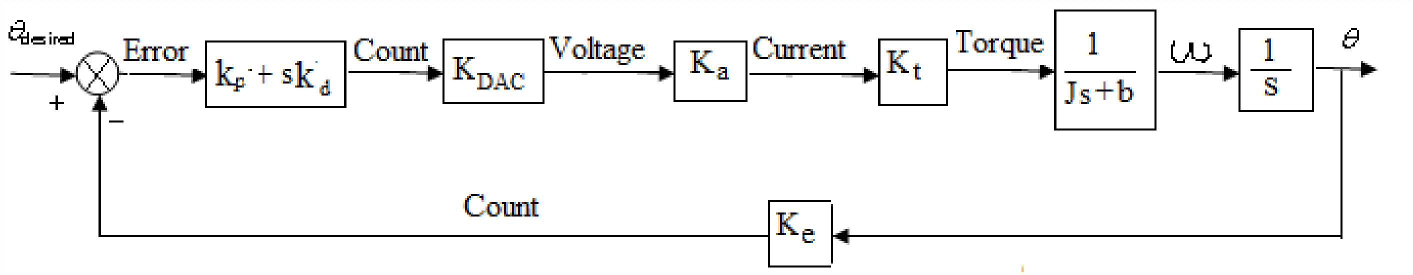
Hardware Setup for one axis



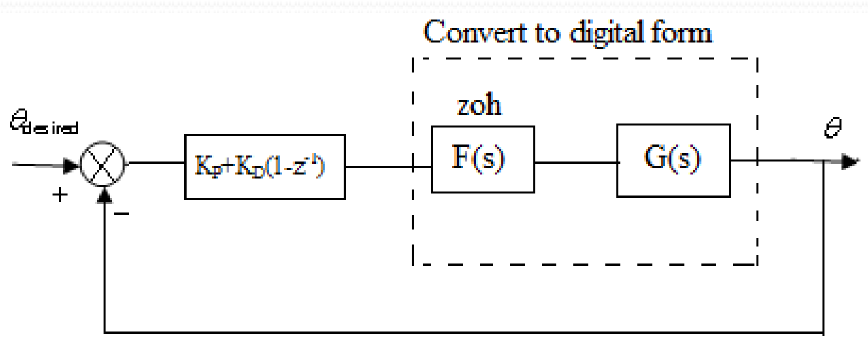
Equivalent Block Model for one axis

PID tuning

- **<u>In continuous method</u>**: All the models of the mixed s-domain and z-domain system are all converted to the s-domain



- **<u>In digital method</u>**: only digital component in a motion control system is the controller. All other components after treated as continuous time will be convert to z-domain.



PID tuning

Settling time, overshoot $\longrightarrow$ Damping ratio and Nature frequency $\longrightarrow$ Closed-loop poles

- **In continuous method**:

The open-loop transfer function of system:

$$L_{(S)} = (k_P + k_D s) * K_{DAC} * K_a * K_t * \frac{1}{Js} * \frac{1}{s} * K_e$$

$$L_{(S)} = (\frac{k_P + sk_D}{s^2})154.53$$

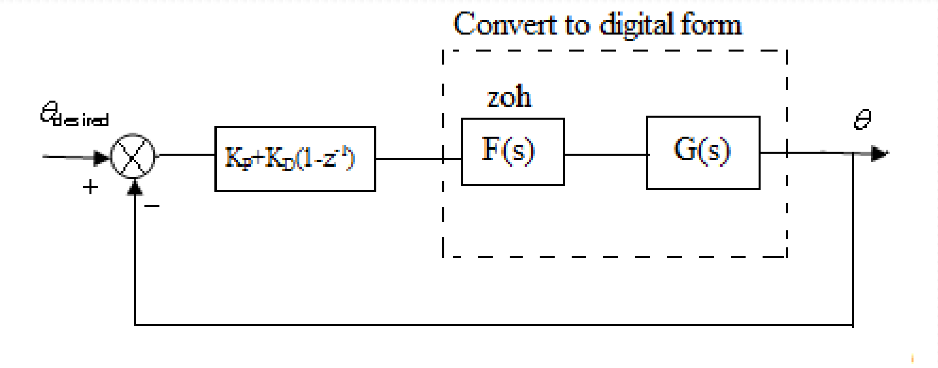
In any system: $|L(j\omega_c)|=1$ and $\angle L(j\omega_c) = \gamma - \pi$

$K_P = k_p$; $K_D = k_D/T$; $K_I = T*k_I$ (T:sampling time)

PID tuning

Settling time, overshoot → Damping ratio and Nature frequency → Closed-loop poles

- **In digital method**:



$$G_0(z) = Z\{F(s)G(s)\} = (1-z^{-1})Z\{\frac{G(s)}{s}\} = (1-z^{-1})Z\{\frac{154.53}{s^3}\} = \frac{154.53}{2}\left(\frac{T^2(z+1)}{(z-1)^2}\right)$$

PID tuning

The closed-loop transfer function of the system:

$$T(z) = \frac{D(z)G_0(z)}{1 + D(z)G_0(z)}$$

The characteristic equation given by:

$$1 + D(z)G_0(z) = 0$$

Using the pole-zero mapping:

$$z = e^{sT}$$

To find D(z)

PID tuning

Sets of PID values for theoretical approach

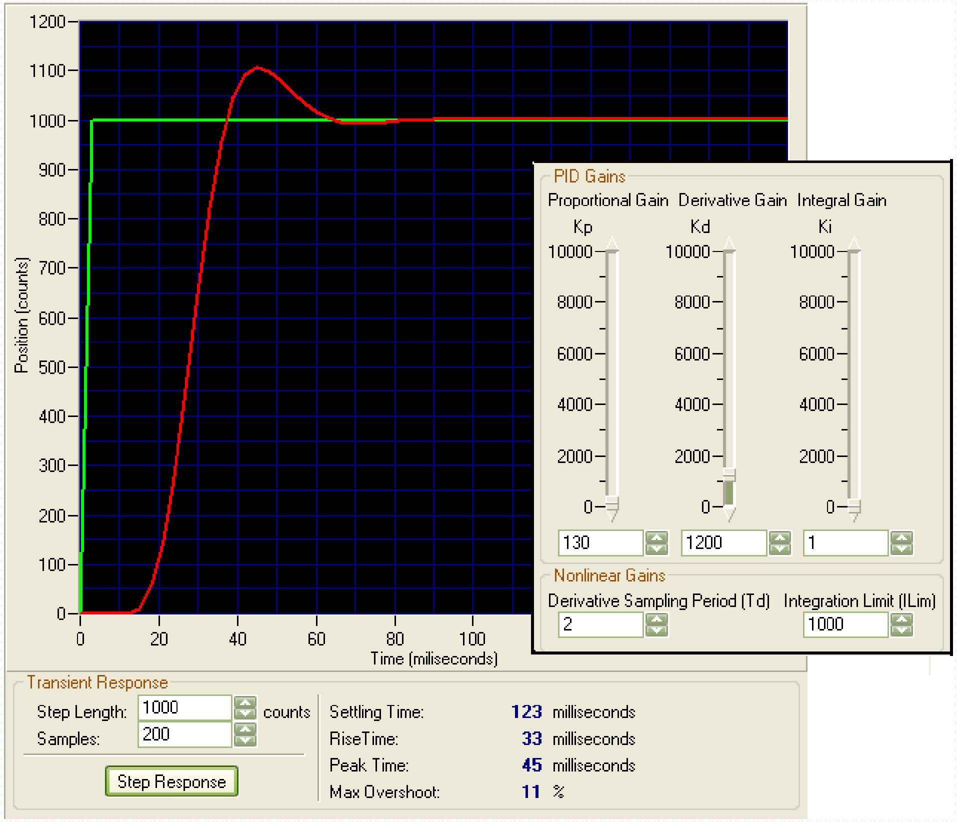
	Digital	Continuous Approximation	Selected PID values
Set 1	$K_p = 128$ $K_D = 1058$ $K_I = 1$	$K_p = 110$ $K_D = 996$ $K_I = 1$	$K_p = 128$ $K_D = 1058$ $K_I = 1$
Set 2	$K_p = 69$ $K_D = 885$ $K_I = 1$	$K_p = 38$ $K_D = 677$ $K_I = 1$	$K_p = 69$ $K_D = 885$ $K_I = 1$
Set 3	$K_p = 49$ $K_D = 722$ $K_I = 1$	$K_p = 28$ $K_D = 581$ $K_I = 1$	$K_p = 49$ $K_D = 722$ $K_I = 1$

PID tuning

- Practical approach: Using Measurement & Automation Explorer (MAX) to adjust the PID parameters K_P K_D K_I

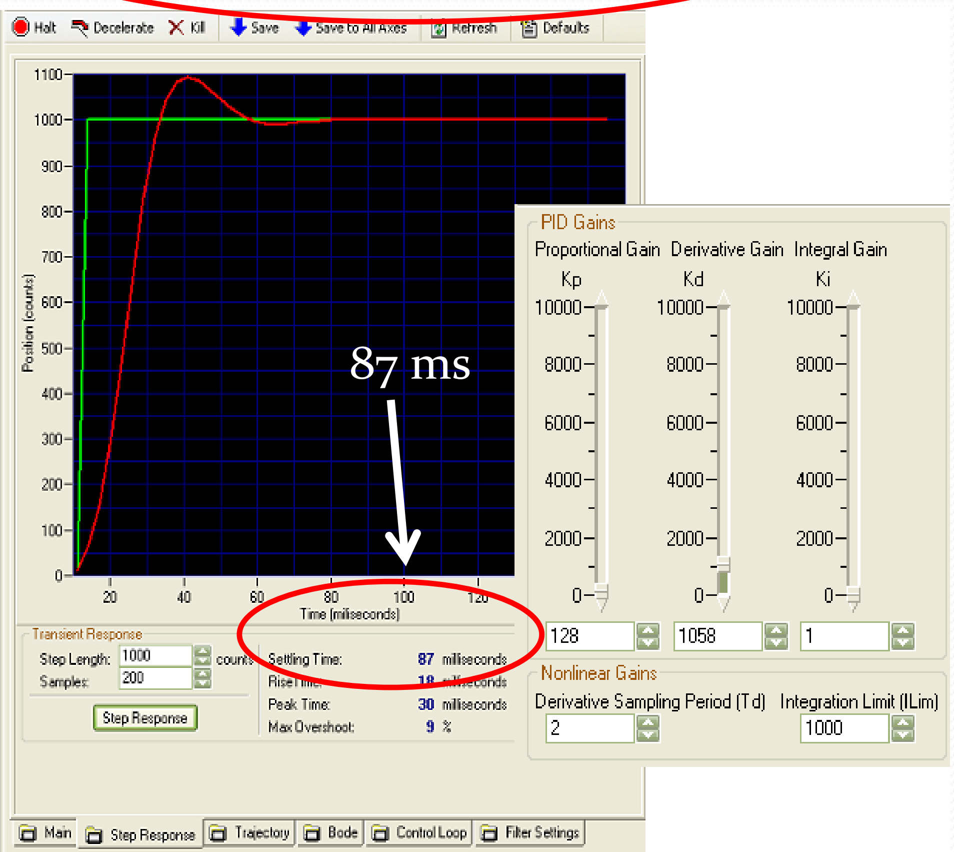
Finding value is

K_P = 130 , K_D = 1200, K_I = 1

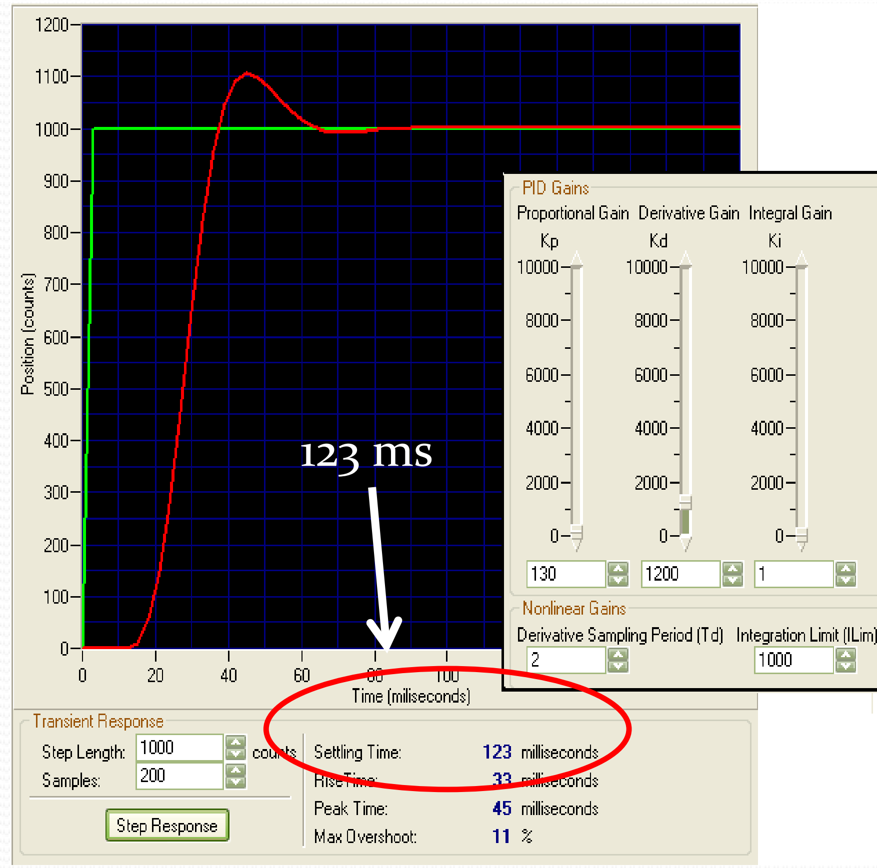


PID tuning

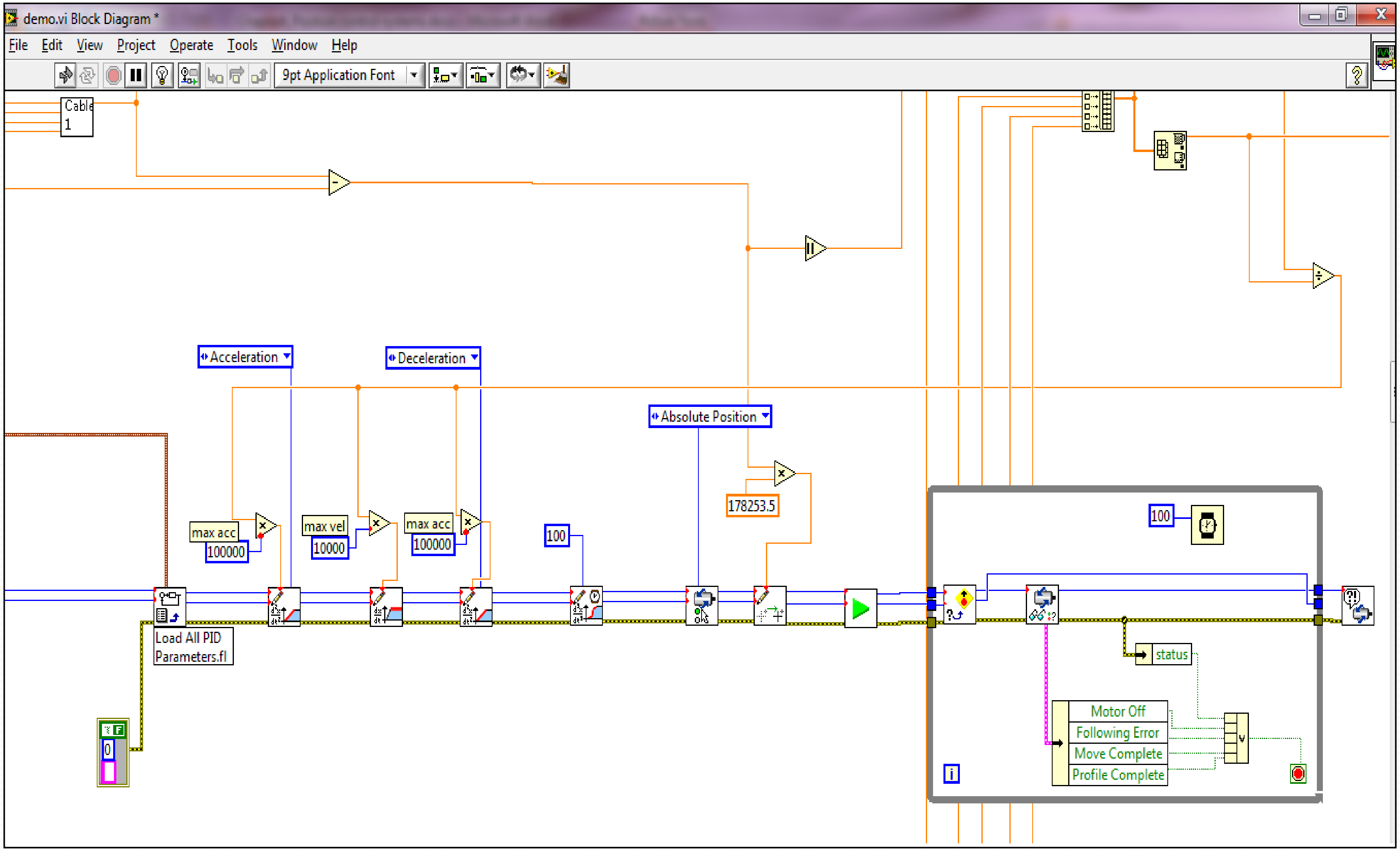
With **analytical approach**:
$K_P = 128$, $K_D = 1058$, $K_I = 1$ (Set1)



With **practical approach**:
$K_P = 130$, $K_D = 1200$, $K_I = 1$

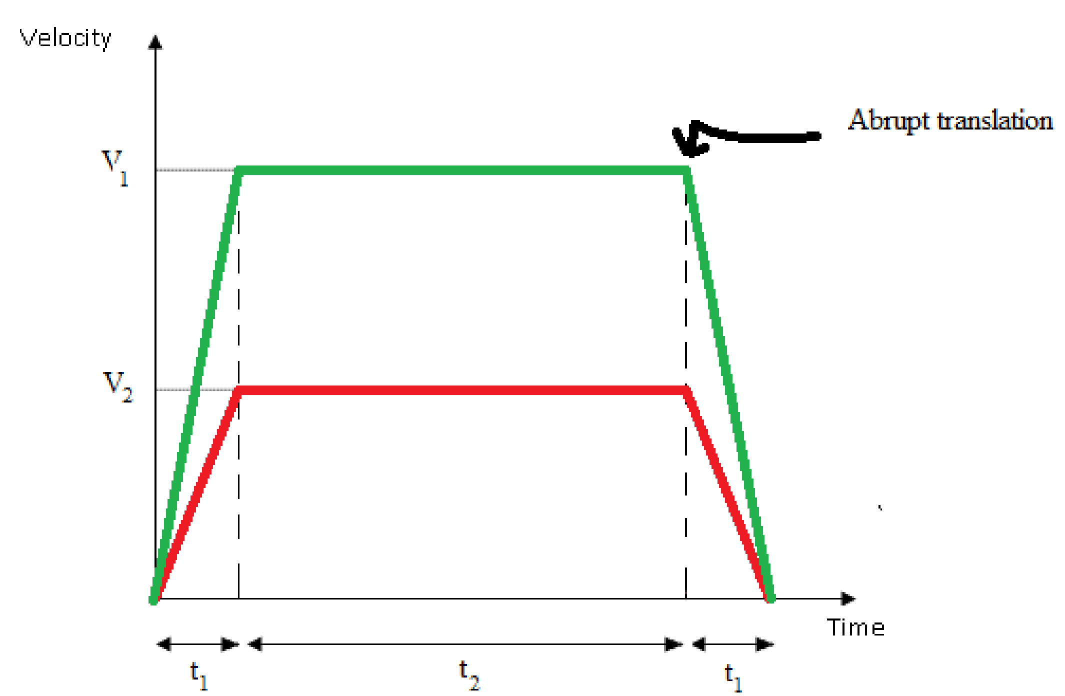


Lab-view program



Lab-view program

Algorithm for motion of motor: all motors operate simultaneously



Velocity profile of any 2 motors

$\Delta L_1 = D_1 = V_1 * (t_1 + t_2)$

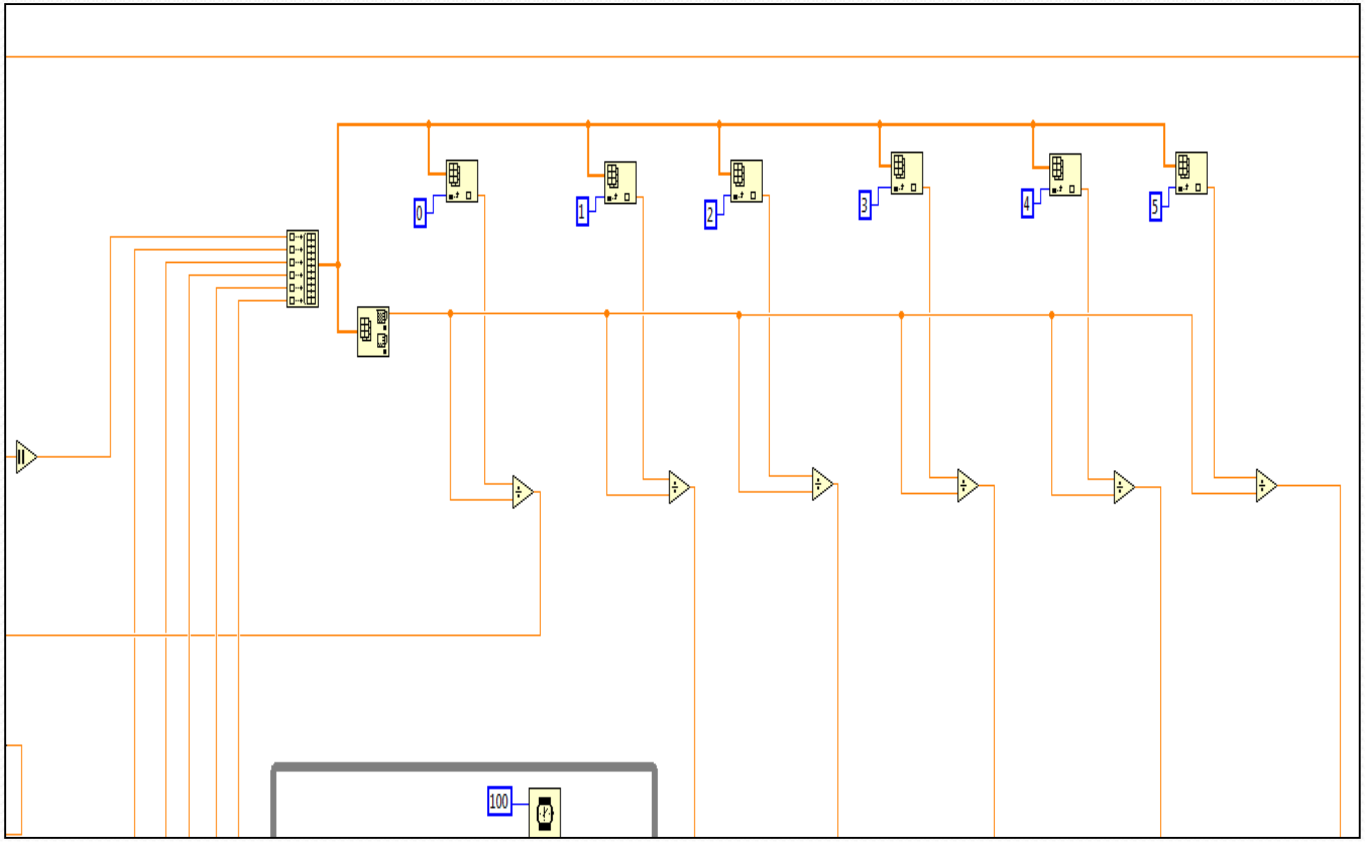
$\Delta L_2 = D_2 = V_2 * (t_1 + t_2)$

$$\frac{\Delta L_1}{\Delta L_2} = \frac{V_1}{V_2}$$

$$\frac{A_1}{A_2} = \frac{V_1 / t_1}{V_2 / t_1} = \frac{\Delta L_1}{\Delta L_2}$$

$$\therefore \frac{A_1}{A_2} = \frac{V_1}{V_2} = \frac{\Delta L_1}{\Delta L_2}$$

Lab-view program



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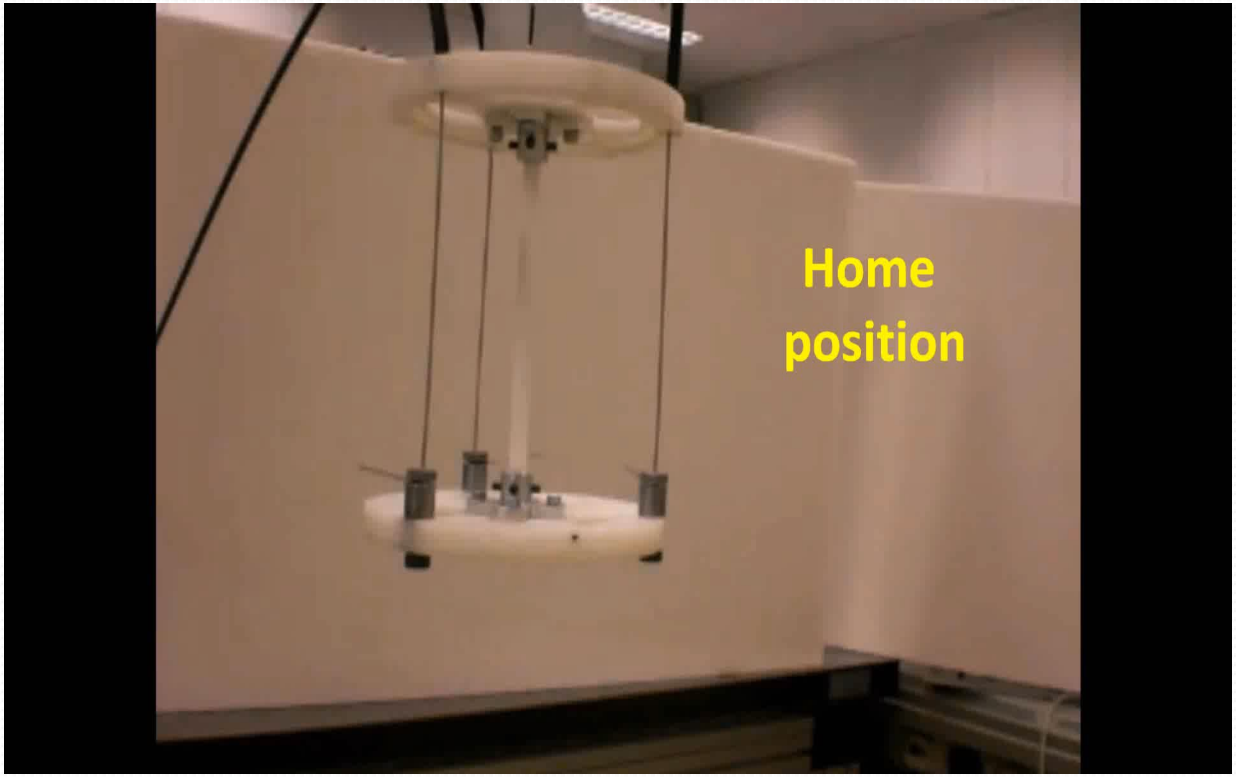
Experiment



	$\theta(°)$	$\phi(°)$
Set 1	30	5
	30	15
	30	25
Set 2	40	5
	40	15
	40	25
Set 3	50	5
	50	15
	50	25
Set 4	60	5
	60	15
	60	25

Experiment

Backbone distance	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
Theoretical value(mm)	118.634	118.634	118.634	117.578	117.578	117.578	116.228	116.228	116.228	114.592	114.592	114.592
Practical value(mm)	119	119	118.5	117	116	117	116	115	116.5	113	112.5	112
Error (%)	-0.31	-0.31	0.11	0.49	1.34	0.49	0.20	1.06	-0.23	1.39	1.83	2.26

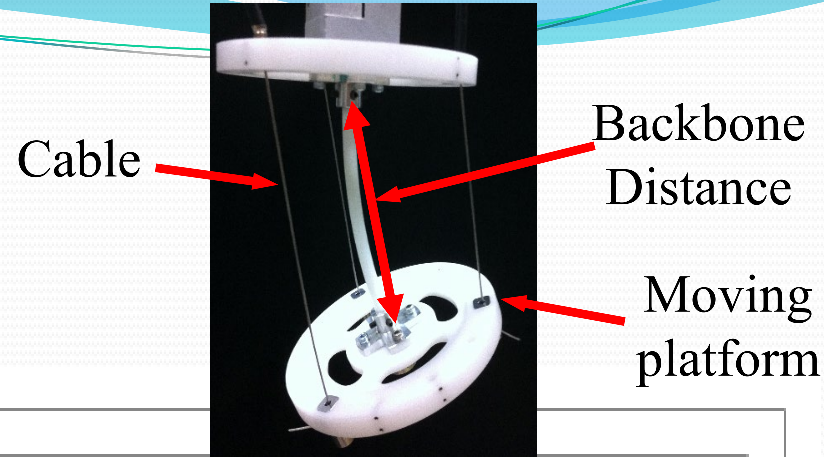
Cable 1	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
Theoretical value(mm)	92.8505	93.6339	95.1769	83.506	84.5413	86.5803	74.1274	75.4066	77.9261	64.7818	66.2953	69.2762
Practical value(mm)	99	99	99.5	84	88.5	90.5	77.5	79.5	80.5	66	66	73
Error (%)	-6.62	-5.73	-4.54	-0.59	-4.68	-4.53	-4.55	-5.43	-3.30	-1.88	0.45	-5.38

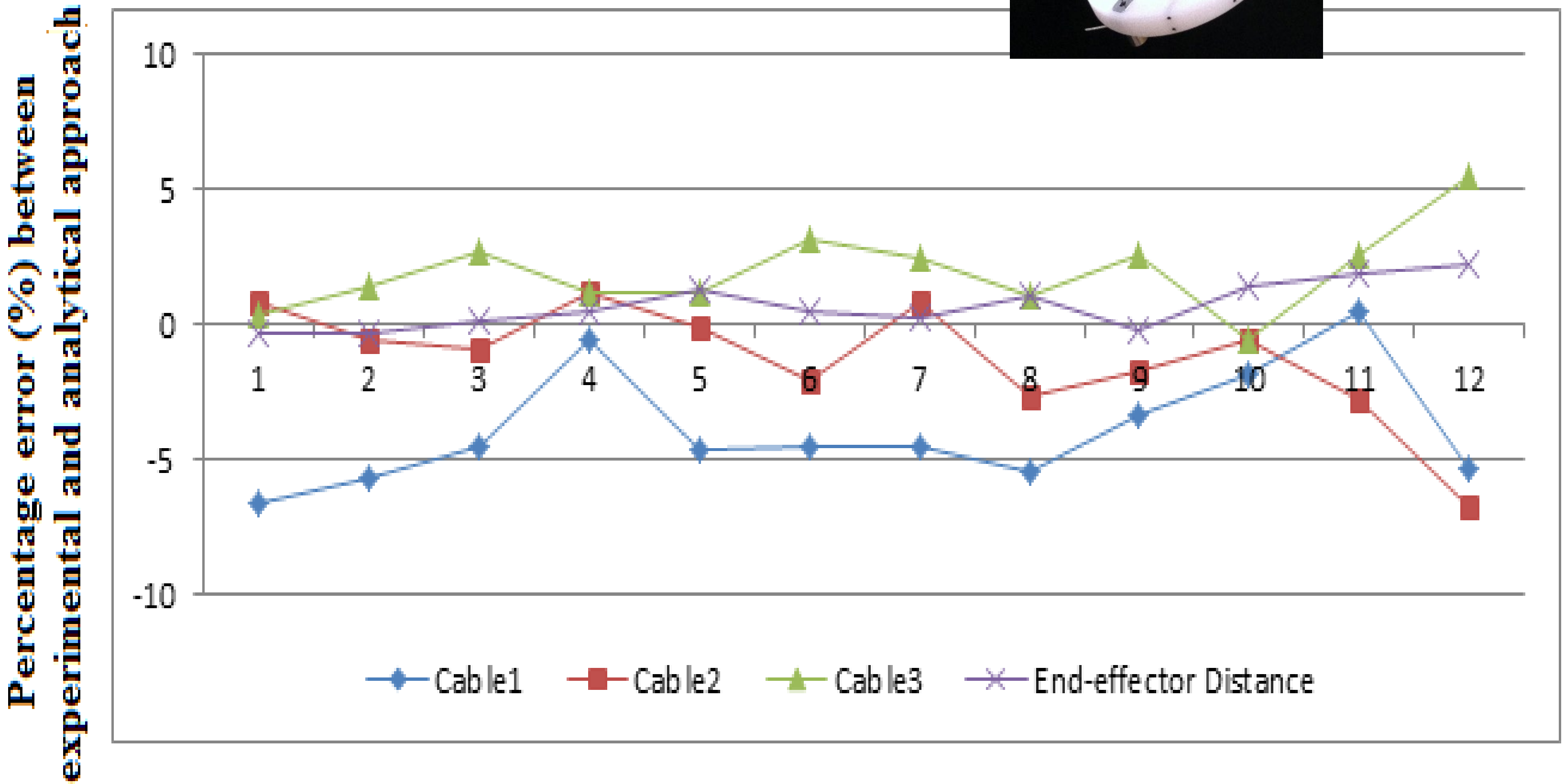
Experiment

Cable 2	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
Theoretical value(mm)	129.572	125.333	120.89	132.032	126.43	120.559	134.089	127.167	119.912	135.722	127.533	118.949
Practical value(mm)	128.5	126	122	130.5	126.5	123	133	130.5	122	136.5	131	127
Error (%)	0.83	-0.53	-0.92	1.16	-0.06	-2.02	0.81	-2.62	-1.74	-0.57	-2.72	-6.77

Cable 3	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
Theoretical value(mm)	133.479	136.935	139.835	137.195	141.762	145.595	140.469	146.112	150.847	143.27	149.947	155.549
Practical value(mm)	133	135	136	135.5	140	141	137	144.5	147	144	146	147
Error (%)	0.36	1.41	2.74	1.24	1.24	3.16	2.47	1.10	2.55	-0.51	2.63	5.50

Results





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Introduction

Kinematic analysis

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Conclusion

- Current design:
  - Lower cost of fabrication
  - Low weight
  - High flexibility
- Good position control error: less than 3%.
- Application:
  - High speed operation, accuracy
  - Constrained workspace and some
  - Preplacing the appearance of human

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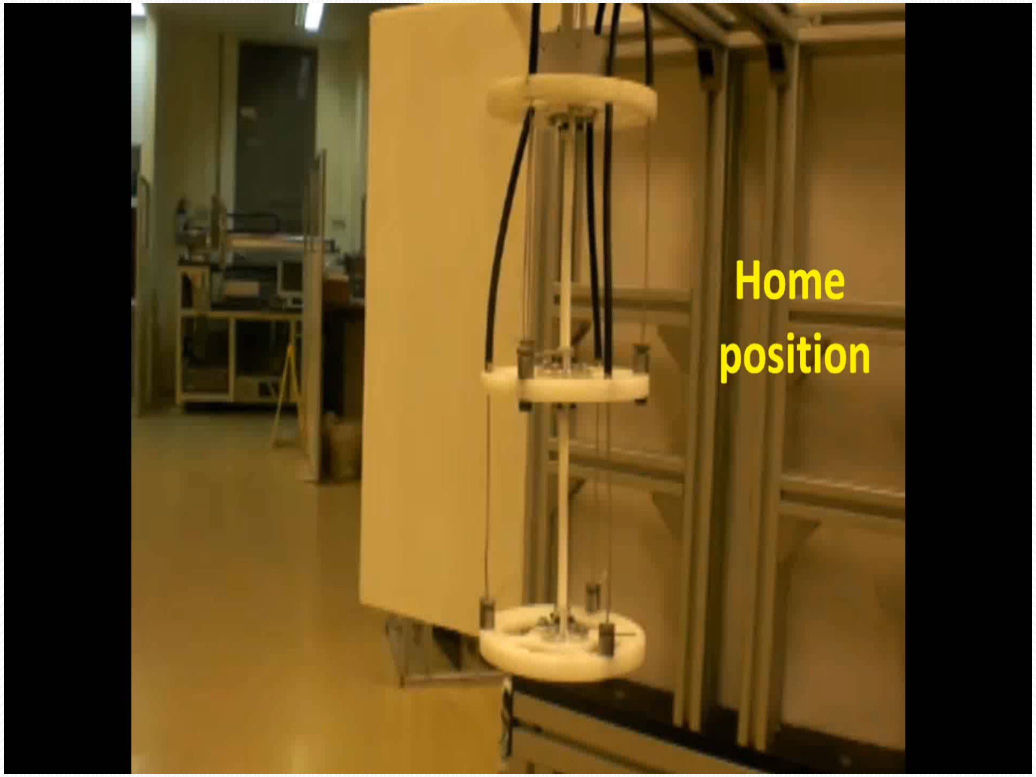
Future Works

- Force control with position control on cable-driven mechanism as this can ensures that all cables are in tension.

- Velocity control is also one important aspect that is needed to investigate.

Video Demonstration



	$\phi1(°)$	$\theta1(°)$	$\phi2(°)$	$\theta2(°)$
Pose 1	5	30	5	30
Pose 2	45	40	45	40
Pose 3	75	50	75	50
Pose 4	125	30	125	30
Pose 5	185	0	185	0

THANK YOU!

Q&A