

Trabajo final de grado

Grado en Ingeniería Mecánica



Escuela Técnica Superior de Ingeniería del Diseño



UNIVERSITAT
POLITÈCNICA
DE VALÈNCIA

Modelado y simulación dinámica del robot industrial Saübli Unimation PUMA 560

Valencia, Julio 2018

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Contenido de la presentación

- ▶ Introducción al robot PUMA 560
- ▶ Desarrollo del trabajo realizado
- ▶ Resultados obtenidos
- ▶ Conclusiones y futuros desarrollos
- ▶ Presupuesto del trabajo

Introducción al robot PUMA 560

- ▶ “Programmable Universal Machine for Assembly”
- ▶ Creado por Victor Scheinman en la compañía robótica Unimation
- ▶ Finalmente comprado por la empresa Staübli en 1988
- ▶ Seis grados de libertad
- ▶ Muñeca esférica
- ▶ Capacidad de carga máxima de entre 2,5 a 4 kg
- ▶ Con unas velocidades máximas de aproximadamente 500mm/segundo
- ▶ Usado en innumerables empresas industriales y estudios

Introducción al robot PUMA 560

Motivos principales de la elección del PUMA 560:

- ▶ Largo tiempo en el mundo de la industria y la investigación (muchas bibliografías)
- ▶ El departamento de Ingeniería Mecánica y de Materiales es propietario de un prototipo
- ▶ Motivación por modelizar dicho robot con programas informáticos que hoy en día están a la vanguardia en el mundo de la ingeniería



Desarrollo del trabajo realizado

- A. Desarrollo del modelo analítico para la cinemática directa del robot en MATLAB
- B. Desarrollo del modelo analítico para la cinemática inversa del robot en MATLAB
- C. Desarrollo del modelo de robot como sistema multicuerpo en ADAMS View para la cinemática directa e inversa
- D. Desarrollo del modelo de robot como sistema multicuerpo en ADAMS View para la dinámica inversa
- E. Desarrollo del modelo analítico para la dinámica inversa del robot en MATLAB
- F. Análisis de resultados (al final de cada una de las partes)

Modelo analítico del robot

- Determinar las coordenadas de Denavit y Hartenberg del robot a partir de los datos obtenidos en la bibliografía.

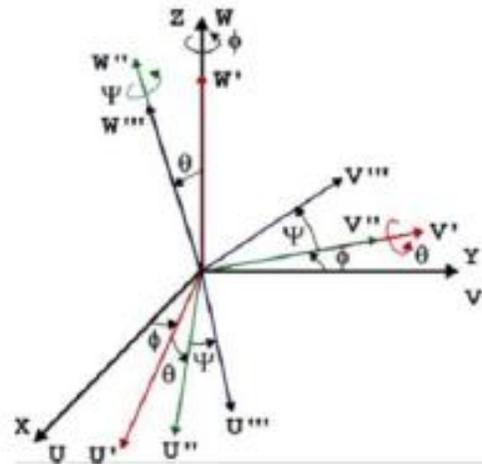
i	Alfa (rad)	a (mm)	d (mm)	Theta (rad)
1	-pi/2	0	0	q1
2	0	431.8	129.54	q2
3	Pi/2	-20.32	0	q3
4	-pi/2	0	432.09	q4
5	Pi/2	0	0	q5
6	0	0	56.26	q6

- Generar las matrices de transformation homogénea

$${}^{i-1}A_i = {}^{i-1}A_{int} \cdot {}^{int}A_i = \begin{bmatrix} \cos(\theta_i) & -\cos(\alpha_i) \cdot \text{sen}(\theta_i) & \text{sen}(\alpha_i) \cdot \text{sen}(\theta_i) & a_i \cdot \cos(\theta_i) \\ \text{sen}(\theta_i) & \cos(\alpha_i) \cdot \cos(\theta_i) & -\text{sen}(\alpha_i) \cdot \cos(\theta_i) & a_i \cdot \text{sen}(\theta_i) \\ 0 & \text{sen}(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Modelo analítico del robot

- ▶ Obtención de los ángulos de Euler del elemento terminal



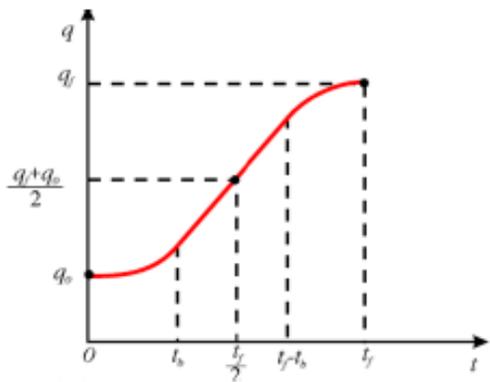
- ▶ Obtención de las ecuaciones cinemáticas (Velocidad y aceleración)

$$\vec{\dot{p}} = J \cdot \vec{\dot{q}}$$

$$\vec{\ddot{p}} = \dot{J} \cdot \vec{\dot{q}} + J \cdot \vec{\ddot{q}}$$

Modelo analítico del robot

- Generación de trayectorias en los nudos y estudio diferencial (ejemplo mostrado: cinemática directa)



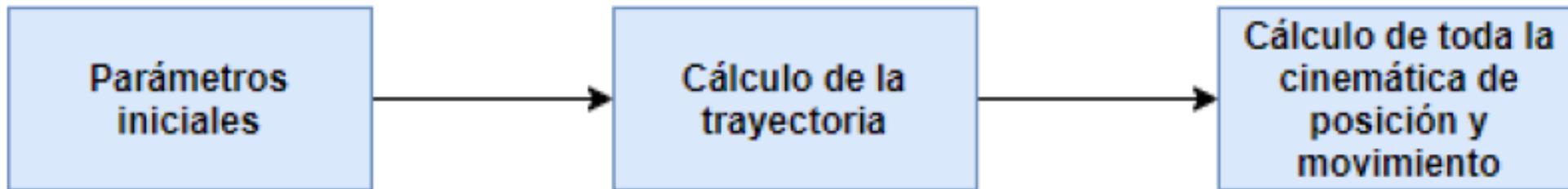
	tf	tb	tf-tb	V	qf rad	q0 rad	qf	q0	q mov
Eje 1	3	1	2	0.218166156	0.43633231	0	25	0	25
Eje 2	3	1	2	0.130899694	0.26179939	0	15	0	15
Eje 3	3	1	2	0.392699082	0.78539816	0	45	0	45
Eje 4	3	1	2	0	0	0	0	0	0
Eje 5	3	1	2	0.261799388	0.52359878	0	30	0	30
Eje 6	3	1	2	0	0	0	0	0	0

	Tramo Parab 1		Tramo recto		Tramo parab 2			1 der Parab 1	
	alfa	gamma	a	V	alfa	beta	gamma	alfa	gamma
Eje 1	0	0.10908308	-0.10908308	0.218166156	-0.54541539	0.65449847	-0.10908308	0	0.21816616
Eje 2	0	0.06544985	-0.06544985	0.130899694	-0.32724923	0.39269908	-0.06544985	0	0.13089969
Eje 3	0	0.19634954	-0.19634954	0.392699082	-0.9817477	1.17809725	-0.19634954	0	0.39269908
Eje 4	0	0	0	0	0	0	0	0	0
Eje 5	0	0.13089969	-0.13089969	0.261799388	-0.65449847	0.78539816	-0.13089969	0	0.26179939
Eje 6	0	0	0	0	0	0	0	0	0

	1 der Recto		1 der Parab 2		2 der 1parab	2 der recto	2 der parab
	V	alfa	beta	gamma	gamma	-	gamma
	0.21816616	0	0.65449847	-0.21816616	0.21816616	0	-0.21816616
	0.13089969	0	0.39269908	-0.13089969	0.13089969	0	-0.13089969
	0.39269908	0	1.17809725	-0.39269908	0.39269908	0	-0.39269908
	0	0	0	0	0	0	0
	0.26179939	0	0.78539816	-0.26179939	0.26179939	0	-0.26179939
	0	0	0	0	0	0	0

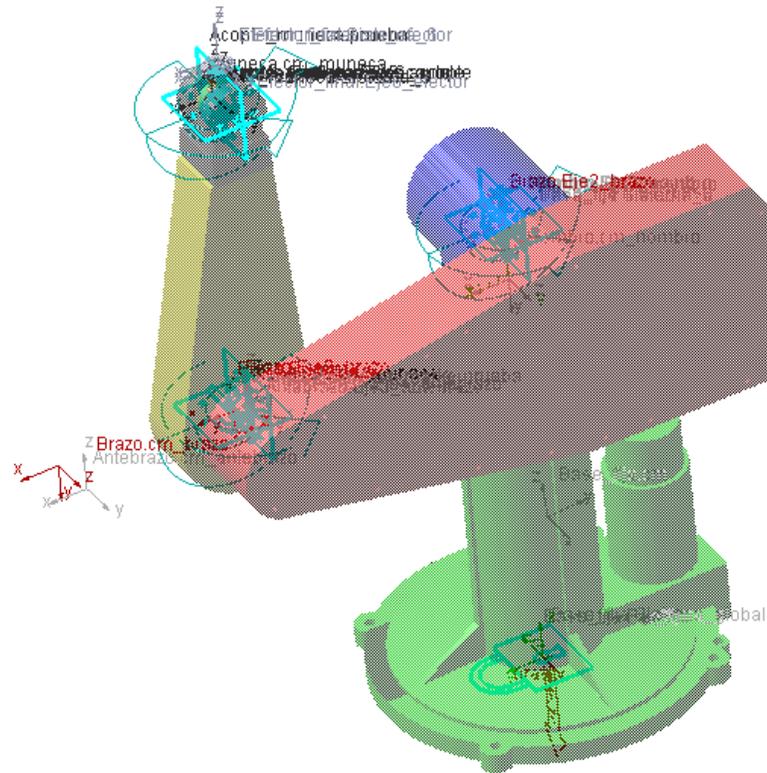
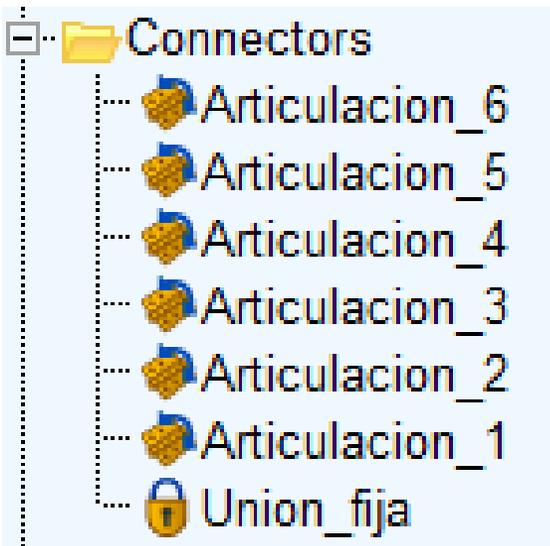
Modelo analítico del robot para la cinemática directa

- ▶ Estudio completo de cada punto de la trayectoria



Modelo con ADAMS View para la cinemática directa e inversa

- ▶ Correcto ensamblaje del robot

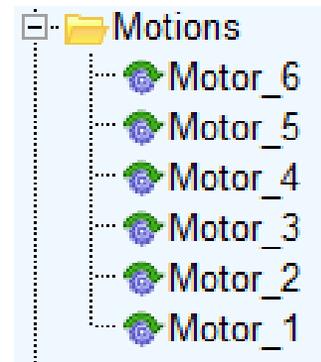


Modelo con ADAMS View para la cinemática directa e inversa

- Generación de funciones de movimiento en los nudos

	Tramo Parab 1		Tramo recto		Tramo parab 2			1 der Parab 1	
	alfa	gamma	a	V	alfa	beta	gamma	alfa	gamma
Eje 1	0	0.10908308	-0.10908308	0.218166156	-0.54541539	0.65449847	-0.10908308	0	0.21816616
Eje 2	0	0.06544985	-0.06544985	0.130899694	-0.32724923	0.39269908	-0.06544985	0	0.13089969
Eje 3	0	0.19634954	-0.19634954	0.392699082	-0.9817477	1.17809725	-0.19634954	0	0.39269908
Eje 4	0	0	0	0	0	0	0	0	0
Eje 5	0	0.13089969	-0.13089969	0.261799388	-0.65449847	0.78539816	-0.13089969	0	0.26179939
Eje 6	0	0	0	0	0	0	0	0	0

1 der Recto		1 der Parab 2		2 der 1parab	2 der recto	2 der parab
V	alfa	beta	gamma	gamma	-	gamma
0.21816616	0	0.65449847	-0.21816616	0.21816616	0	-0.21816616
0.13089969	0	0.39269908	-0.13089969	0.13089969	0	-0.13089969
0.39269908	0	1.17809725	-0.39269908	0.39269908	0	-0.39269908
0	0	0	0	0	0	0
0.26179939	0	0.78539816	-0.26179939	0.26179939	0	-0.26179939
0	0	0	0	0	0	0



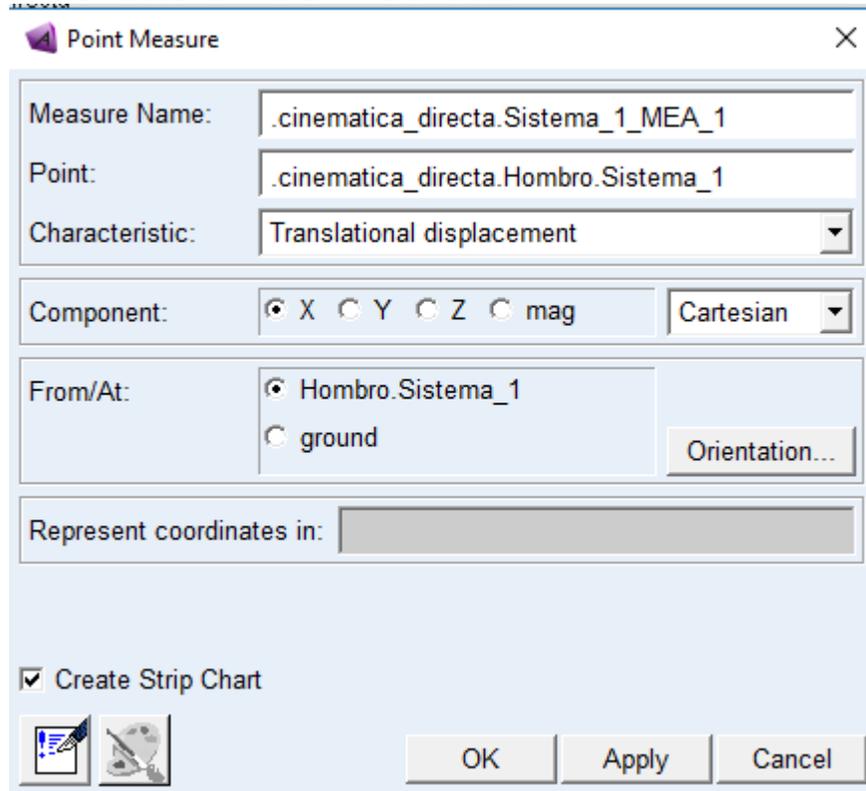
Define a runtime function

Full names Short names Adams ids

```
IF(time-1:POLY(time,0,0,0,0.10908308),POLY(time,0,0,0.10908308),IF(time-2:POLY(time,0,-0.10908308,0.21816616),POLY(time,0,-0.10908308,0.21816616),POLY(time,0,-0.54541539,0.65449847,-0.10908308)))
```

Modelo con ADAMS View para la cinemática directa e inversa

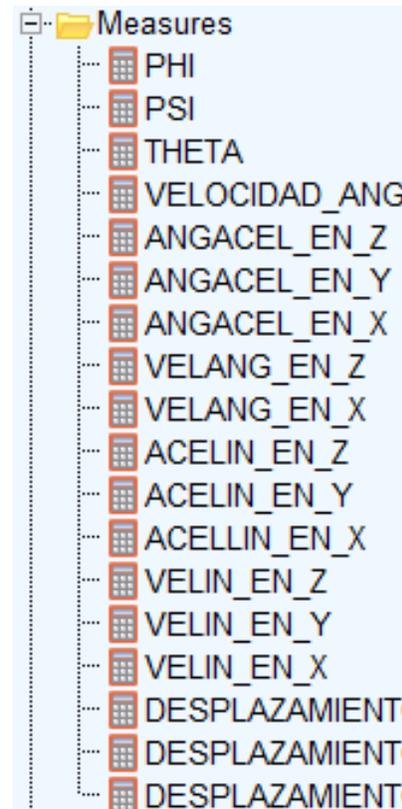
► Creación de medidas



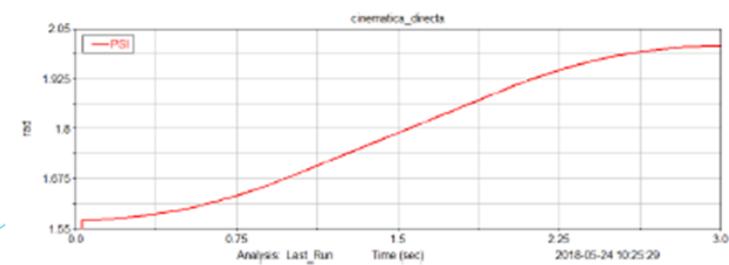
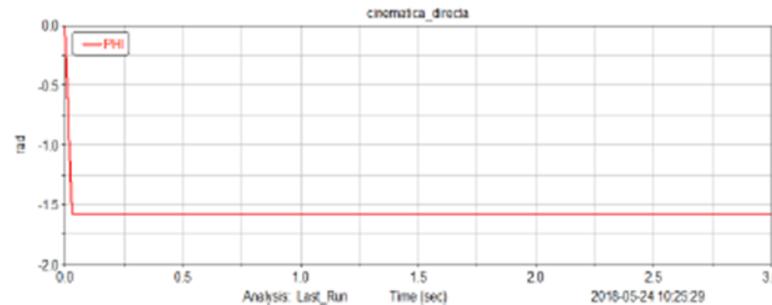
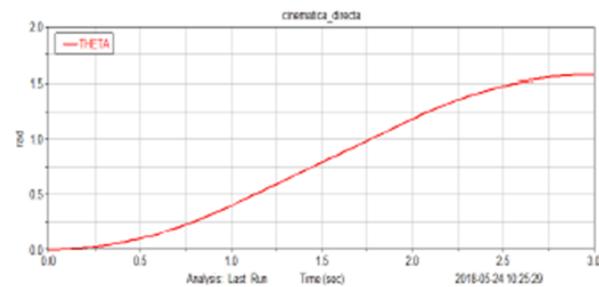
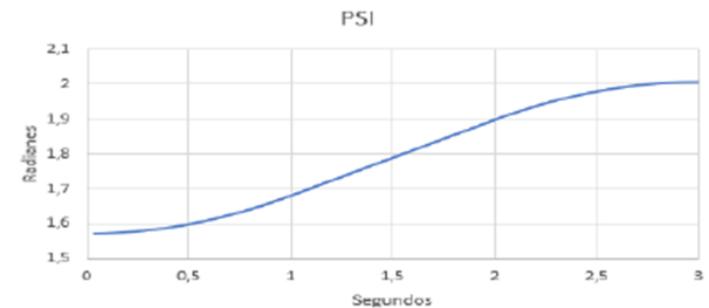
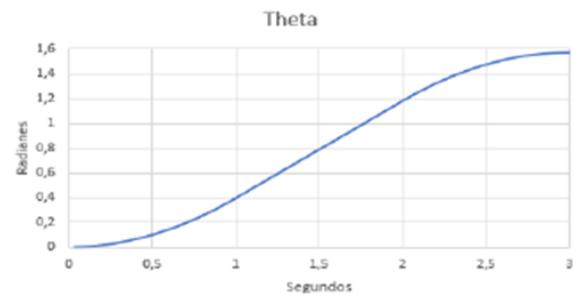
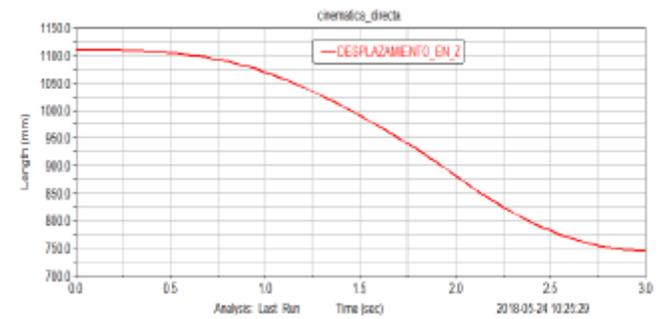
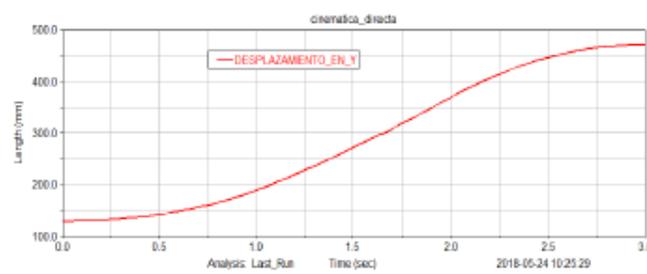
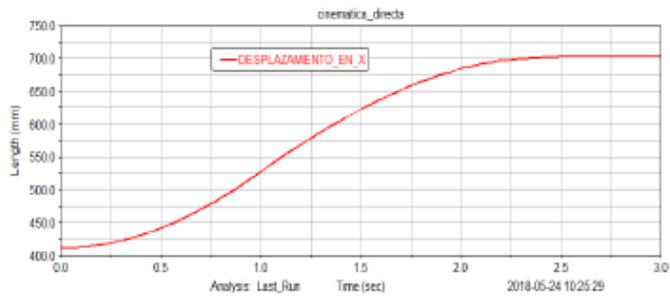
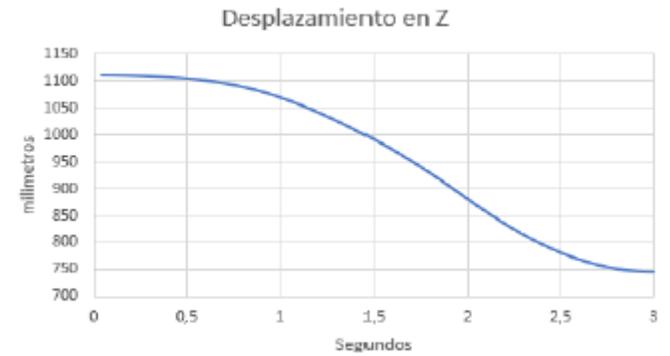
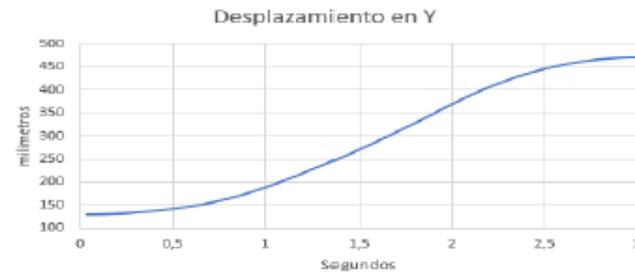
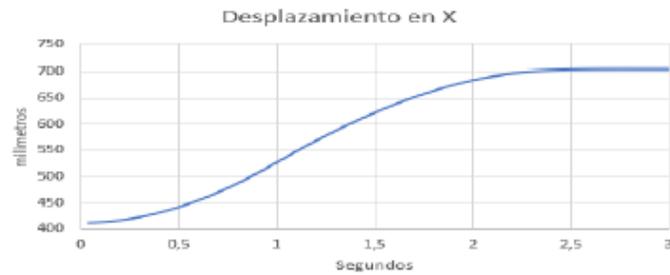
The screenshot shows the 'Point Measure' dialog box with the following configuration:

- Measure Name: .cinematica_directa.Sistema_1_MEA_1
- Point: .cinematica_directa.Hombro.Sistema_1
- Characteristic: Translational displacement
- Component: X Y Z mag
- Cartesian: Cartesian
- From/At: Hombro.Sistema_1 ground
- Orientation... button
- Represent coordinates in: (empty field)
- Create Strip Chart
- OK, Apply, and Cancel buttons

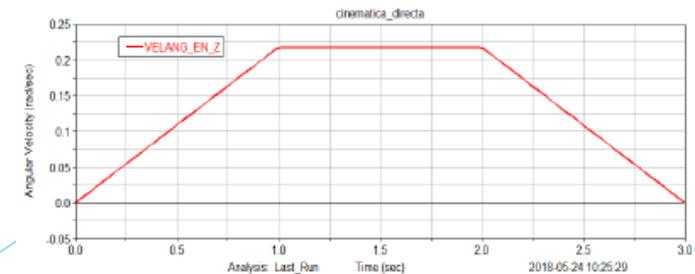
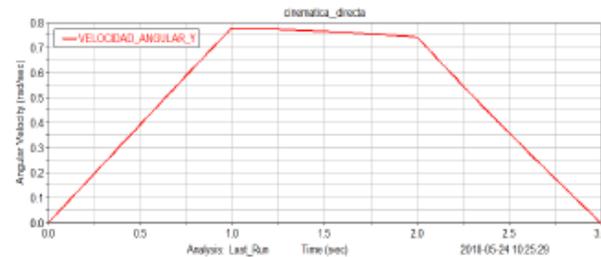
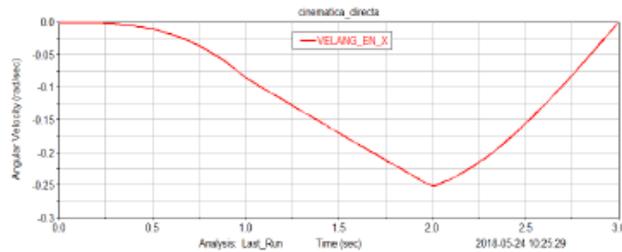
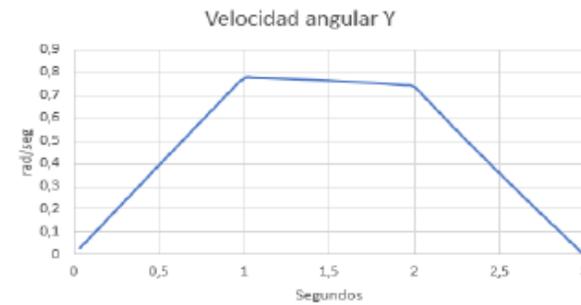
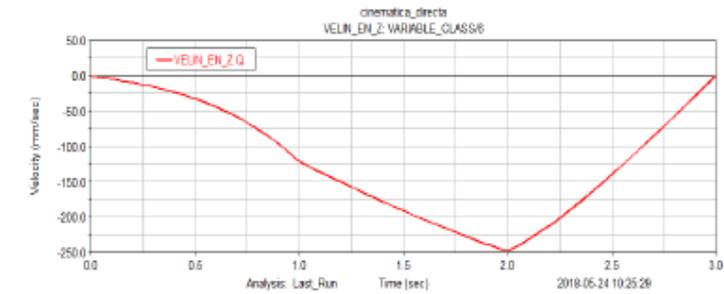
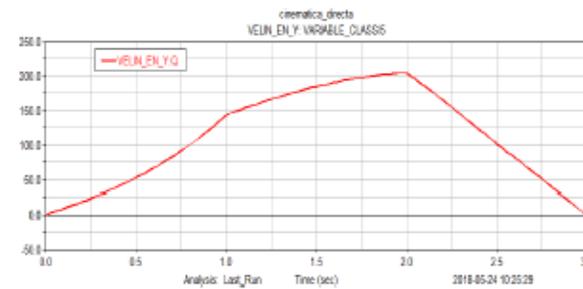
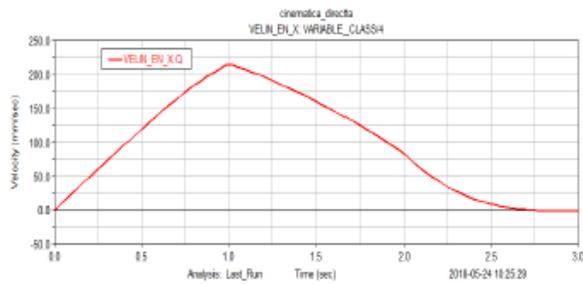
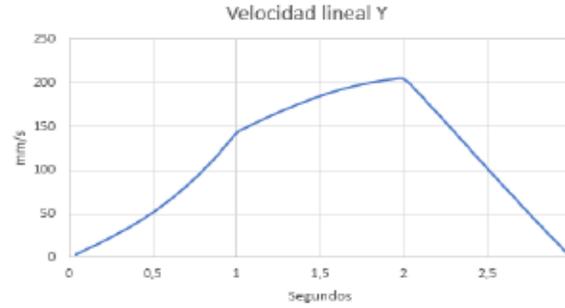
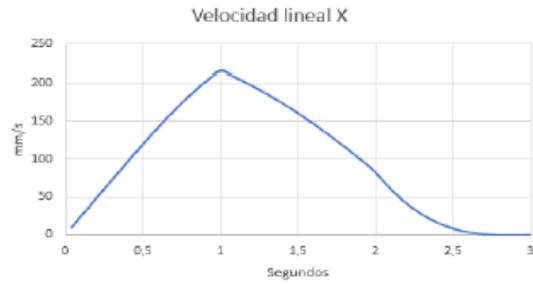


- 
- The screenshot shows a list of measures under the 'Measures' folder:
- PHI
 - PSI
 - THETA
 - VELOCIDAD_ANG
 - ANGACEL_EN_Z
 - ANGACEL_EN_Y
 - ANGACEL_EN_X
 - VELANG_EN_Z
 - VELANG_EN_X
 - ACELIN_EN_Z
 - ACELIN_EN_Y
 - ACELIN_EN_X
 - VELIN_EN_Z
 - VELIN_EN_Y
 - VELIN_EN_X
 - DESPLAZAMIENT
 - DESPLAZAMIENT
 - DESPLAZAMIENT

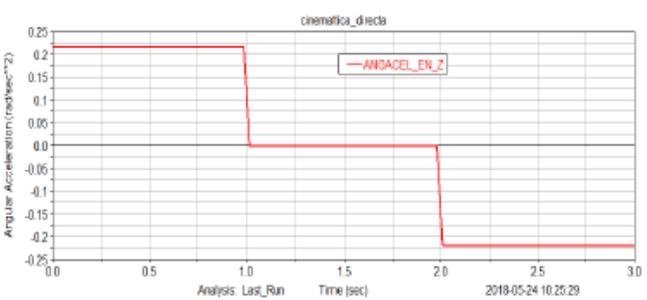
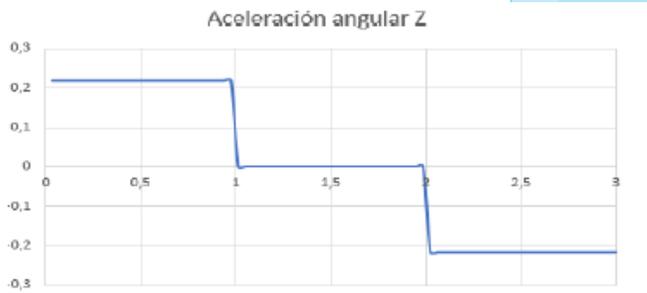
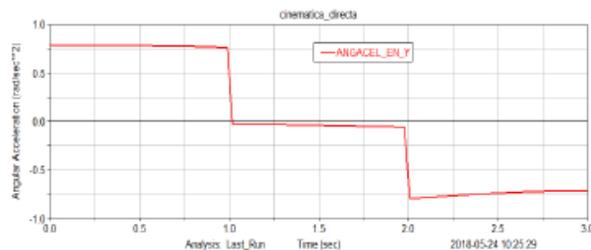
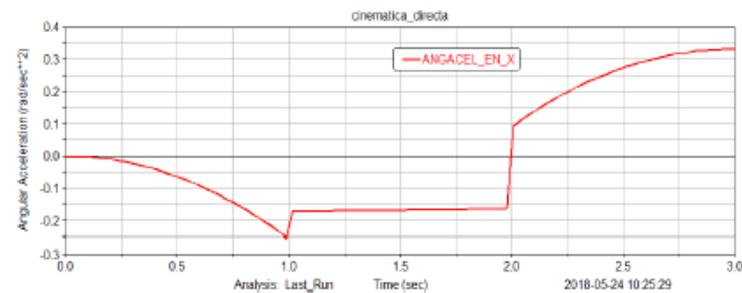
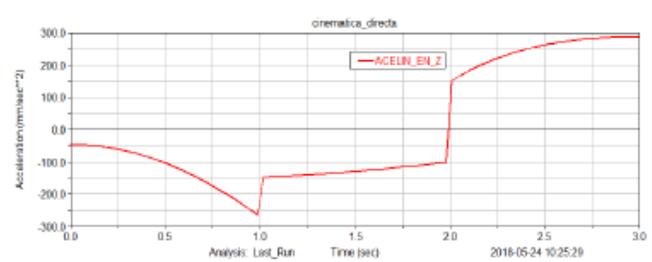
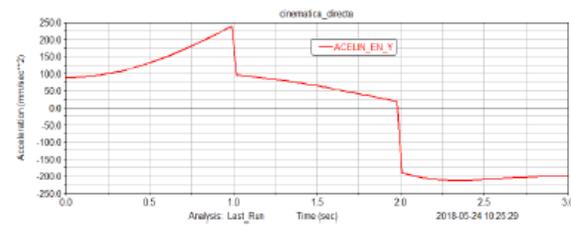
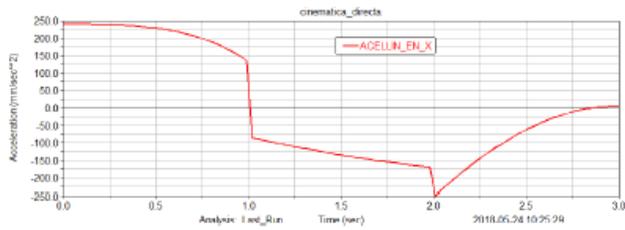
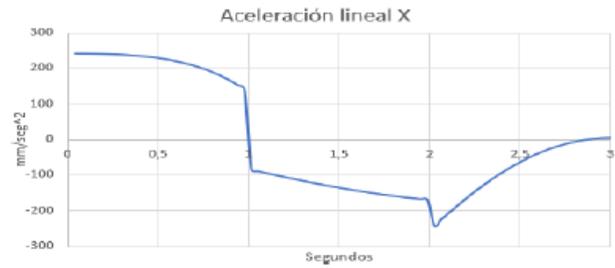
Resultados cinemática directa



Resultados cinemática directa



Resultados cinemática directa



Modelo analítico del robot para la cinemática inversa

- Estudio completo de cada punto de la trayectoria (de la misma manera que la cinemática directa, habiendo calculado primero las variables articulares)



$$\begin{aligned}
 p_{wx} &= p_x - d_6 \cdot a_x \\
 p_{wy} &= p_y - d_6 \cdot a_y \\
 p_{wz} &= p_z - d_6 \cdot a_z
 \end{aligned}$$

$$\lambda = \frac{(p_{wx} \cdot C_1 + p_{wy} \cdot S_1)^2 + p_{wz}^2 - a_3^2 - a_2^2 - d_4^2}{2 \cdot a_2}$$

$$\theta_1 = \text{atan2}\left(\frac{-p_{wx}}{p_{wy}}\right) + \text{atan2}\left(\frac{\pm \sqrt{p_{wx}^2 + p_{wy}^2 - d_2^2}}{d_2}\right)$$

$$\theta_3 = \text{atan2}\left(\frac{d_4}{a_2}\right) + \text{atan2}\left(\frac{\pm \sqrt{a_3^2 + d_4^2 - \lambda^2}}{\lambda}\right)$$

$$\theta_2 = \text{atan2}\left(\frac{(C_1 \cdot p_{wx} + S_1 \cdot p_{wy}) \cdot (-a_3 \cdot S_3 + d_4 \cdot C_3) - p_{wz} \cdot (a_2 + a_3 \cdot C_3 + d_4 \cdot S_3)}{(C_1 \cdot p_{wx} + S_1 \cdot p_{wy}) \cdot (a_2 + a_3 \cdot C_3 + d_4 \cdot S_3) + p_{wz} \cdot (-a_3 \cdot S_3 + d_4 \cdot C_3)}\right)$$

$$\theta_4 = \text{atan2}\left(\frac{-S_1 \cdot a_x + C_1 \cdot a_y}{C_1 \cdot C_{23} \cdot a_x + S_1 \cdot C_{23} \cdot a_y - S_{23} \cdot a_z}\right) \quad \text{ó} \quad \theta_4 = \text{atan2}\left(\frac{S_1 \cdot a_x - C_1 \cdot a_y}{-C_1 \cdot C_{23} \cdot a_x - S_1 \cdot C_{23} \cdot a_y + S_{23} \cdot a_z}\right)$$

$$\theta_5 = \text{atan2}\left(\frac{\pm \sqrt{(C_1 \cdot a_y - S_1 \cdot a_x)^2 + (C_1 \cdot C_{23} \cdot a_x + S_1 \cdot C_{23} \cdot a_y - S_{23} \cdot a_z)^2}}{C_1 \cdot S_{23} \cdot a_x + S_1 \cdot S_{23} \cdot a_y + C_{23} \cdot a_z}\right)$$

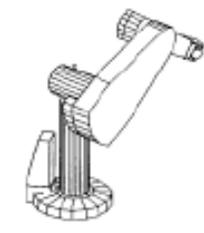
$$\theta_6 = \text{atan2}\left(\frac{C_1 \cdot S_{23} \cdot s_x + S_1 \cdot S_{23} \cdot s_y + C_{23} \cdot s_z}{-C_1 \cdot C_{23} \cdot n_x + S_1 \cdot C_{23} \cdot n_y + C_{23} \cdot n_z}\right) \quad \text{ó} \quad \theta_6 = \text{atan2}\left(\frac{-C_1 \cdot S_{23} \cdot s_x - S_1 \cdot S_{23} \cdot s_y - C_{23} \cdot s_z}{C_1 \cdot C_{23} \cdot n_x + S_1 \cdot C_{23} \cdot n_y + C_{23} \cdot n_z}\right)$$



Izquierda y Arriba



Izquierda y Abajo

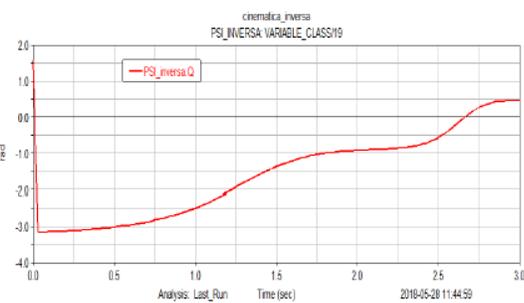
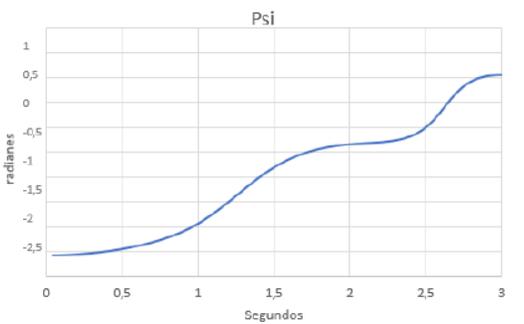
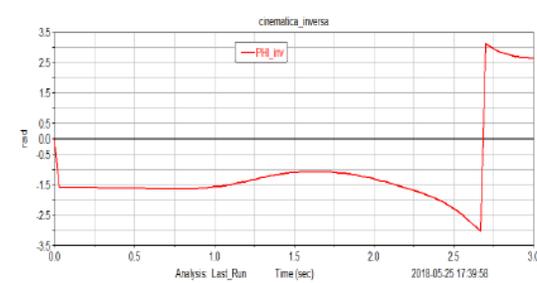
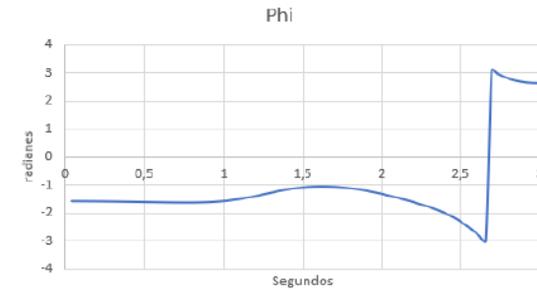
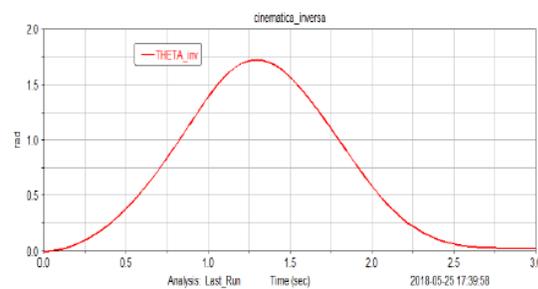
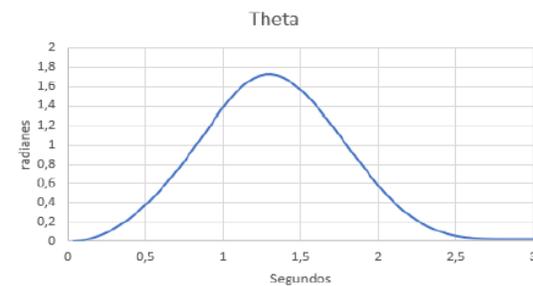
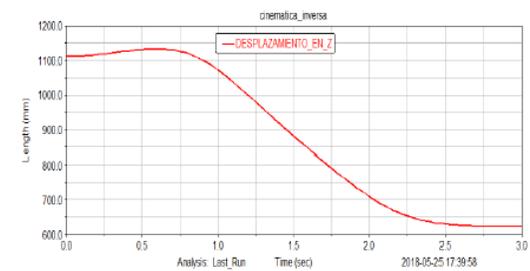
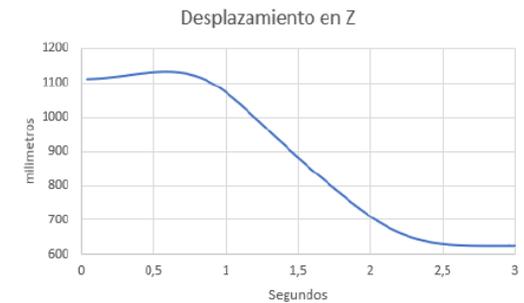
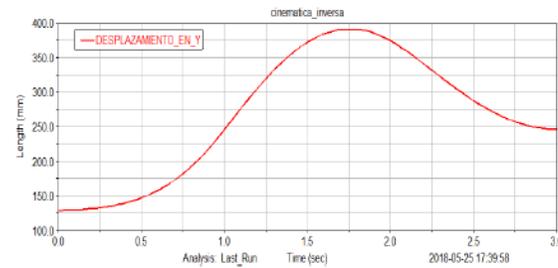
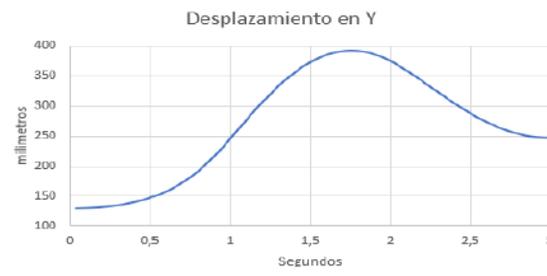
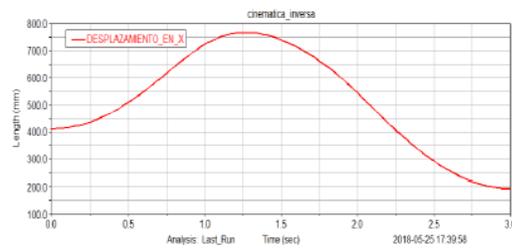
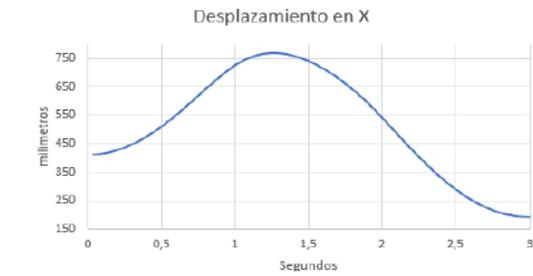


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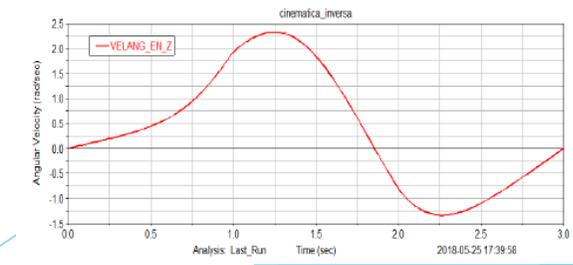
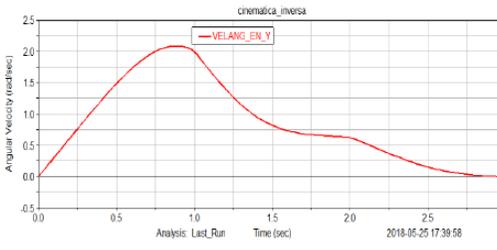
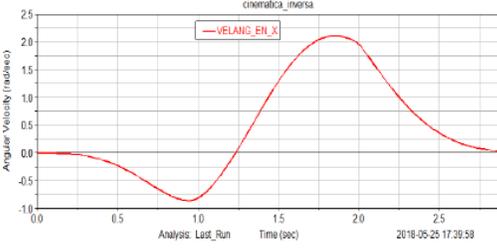
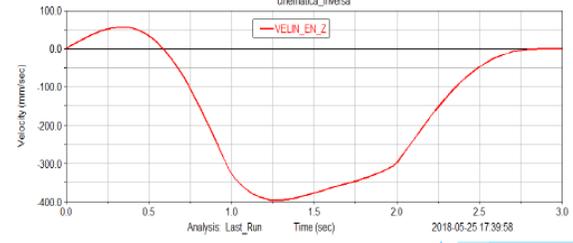
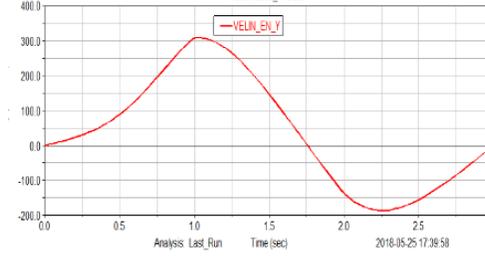
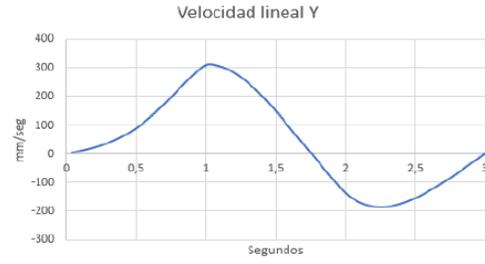
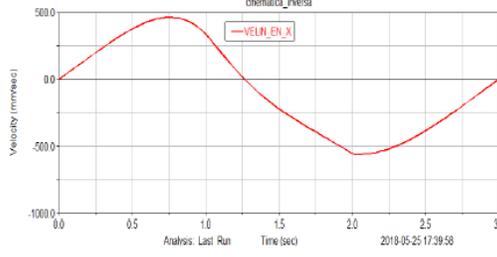
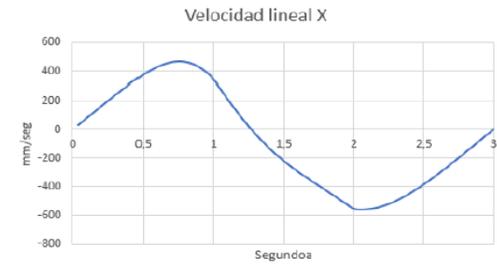


Derecha y Abajo

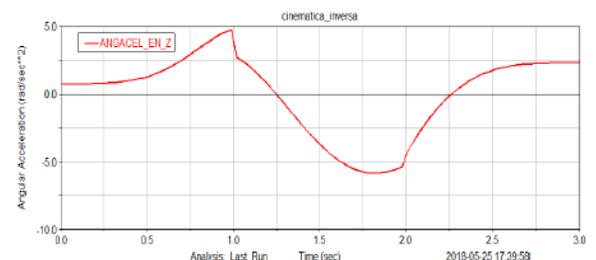
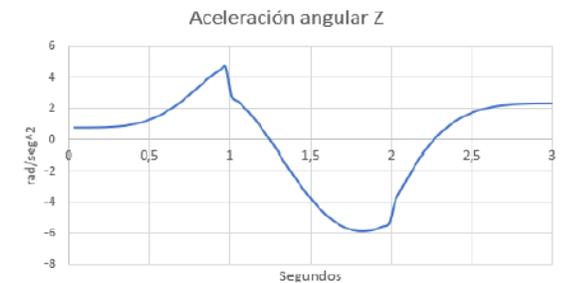
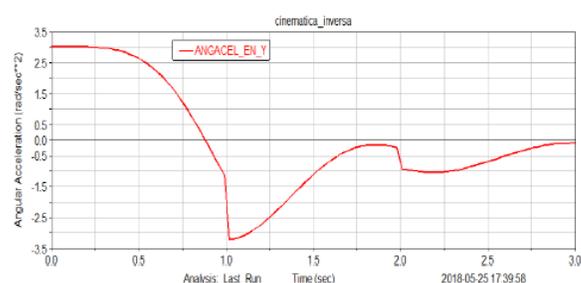
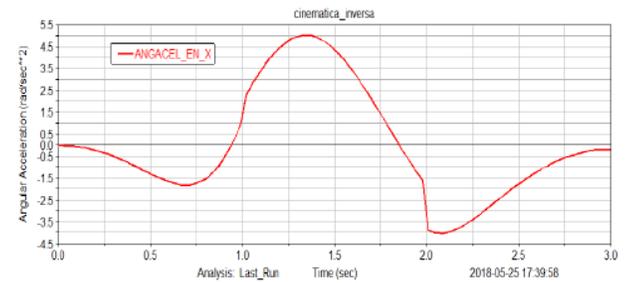
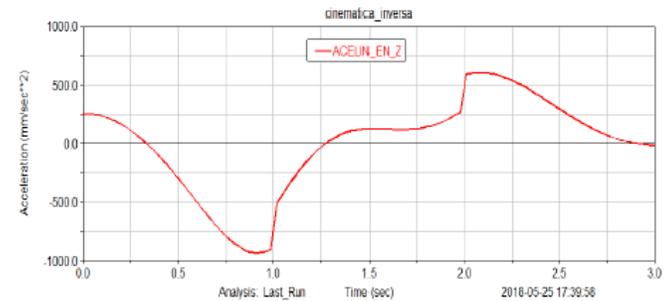
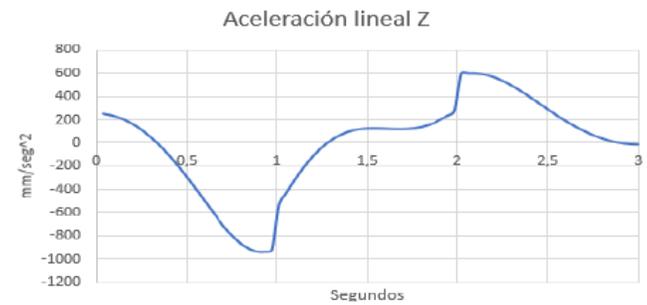
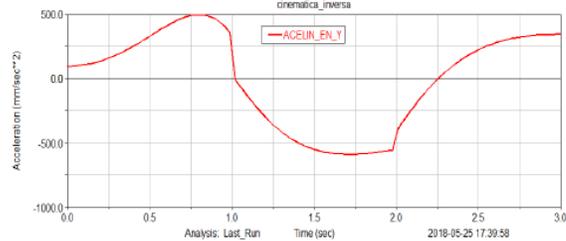
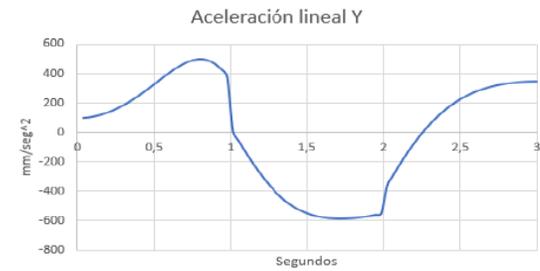
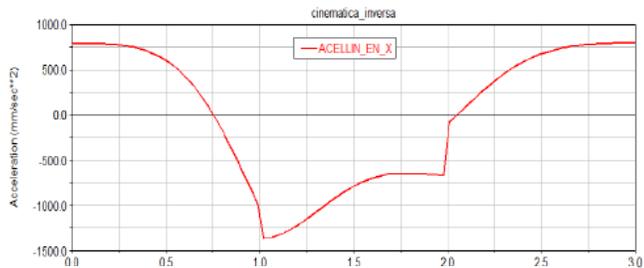
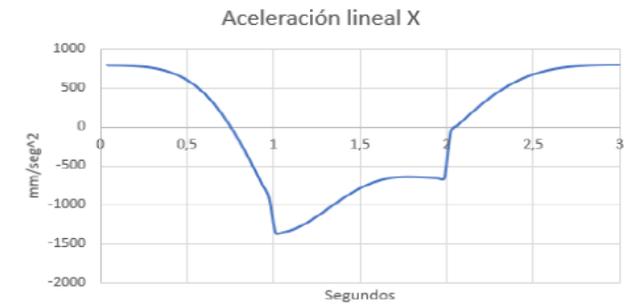
Resultados cinemática inversa



Resultados cinemática inversa



Resultados cinemática inversa



Desarrollo del modelo analítico para la dinámica inversa del robot PUMA 560

- Se ha tomado como referencia los parámetros ofrecidos por el modelo de PAUL81, por ser los más próximos a la realidad

Masa (kg)

Param	Armstrong	Paul81	Tarn
m_1	-	4.43	13.00
m_2	17.40	10.20	22.40
m_3	4.80	4.80	5.00
m_4	0.82	1.18	1.20
m_5	0.35	0.32	0.62
m_6	0.09	0.13	0.16

Centros de masas (mm)

Param	Armstrong	Paul81	Tarn
s_{x1}	-	0	0
s_{y1}	-	80	4
s_{z1}	-	0	-309
s_{x2}	68	216	103
s_{y2}	6	0	5
s_{z2}	-16	-26	-40
s_{x3}	0	0	20
s_{y3}	-70	-216	-4
s_{z3}	14	0	14
s_{x4}	0	0	0
s_{y4}	0	0	-3
s_{z4}	-19	-20	-86
s_{x5}	0	0	0
s_{y5}	0	0	-1
s_{z5}	0	0	-10
s_{x6}	0	0	0
s_{y6}	0	0	0
s_{z6}	32	10	3

Momentos de Inercia

Param	Armstrong	Tarn	Paul81
I_{xx1}	-	1.100	0.195
I_{yy1}	-	1.110	0.026
I_{zz1}	0.350	0.177	0.195
I_{xx2}	0.130	0.403	0.588
I_{yy2}	0.524	0.969	1.886
I_{zz2}	0.539	0.965	1.470
I_{xx3}	66.0 e-3	74.8 e-3	324.0 e-3
I_{yy3}	12.5 e-3	7.3 e-3	17.0 e-3
I_{zz3}	86.0 e-3	75.6 e-3	324.0 e-3
I_{xx4}	1.80 e-3	5.32 e-3	3.83 e-3
I_{yy4}	1.80 e-3	5.20 e-3	3.83 e-3
I_{zz4}	1.30 e-3	3.37 e-3	2.50 e-3
I_{xx5}	300 e-6	487 e-6	216 e-6
I_{yy5}	300 e-6	482 e-6	216 e-6
I_{zz5}	400 e-6	572 e-6	348 e-6
I_{xx6}	150 e-6	123 e-6	437 e-6
I_{yy6}	150 e-6	123 e-6	437 e-6
I_{zz6}	40 e-6	58 e-6	13 e-6

Modelo con ADAMS View para la dinámica inversa

- ▶ Partiremos del modelo ya desarrollado para la cinemática directa y se le añadirán los parámetros másicos e inerciales necesarios

Modify Body

Body: .dinamica.Hombro

Category: Mass Properties

Define Mass By: User Input

Mass: 4.43

Ixx: 0.195 Off-Diagonal Terms

Iyy: 2.6E-02

Izz: 0.195

Center of Mass Marker: .dinamica.Hombro.cm

Inertia Reference Marker:

OK Apply Cancel

Marker Modify

Name: .dinamica.Hombro.cm

Location: 0,0,0

Location Relative To: .dinamica.Hombro.Sistema_1

Curve:

Curve Reference Marker:

Tangent Velocity: X Y Z

Orientation: 0,0,0

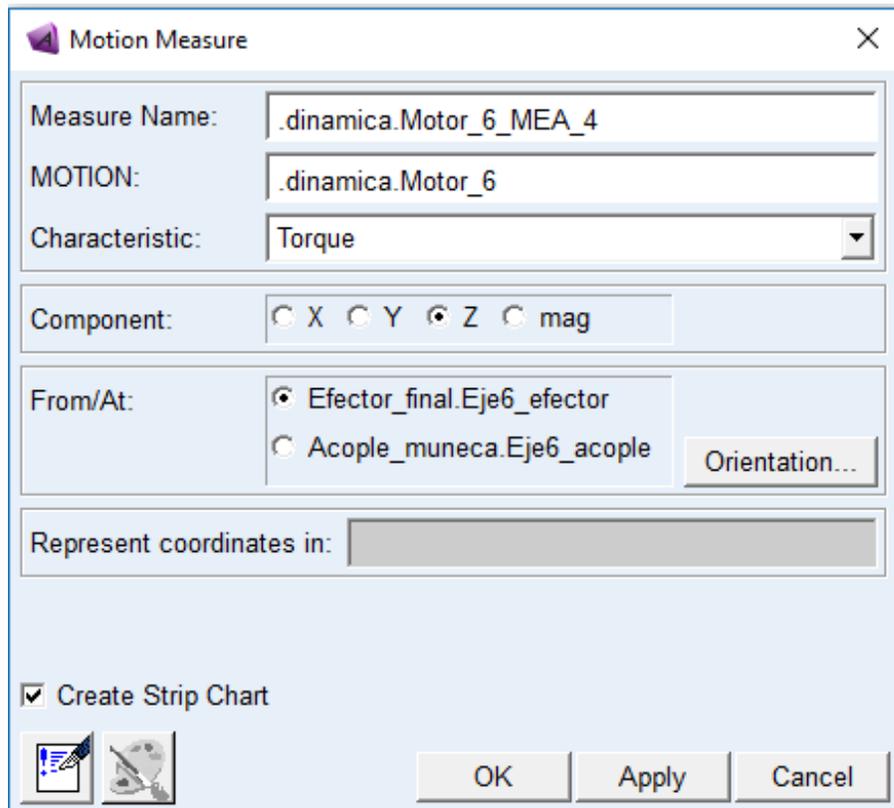
Orientation Relative To: .dinamica.Hombro.Sistema_1

Solver ID: 27

OK Apply Close

Modelo con ADAMS View para la dinámica inversa

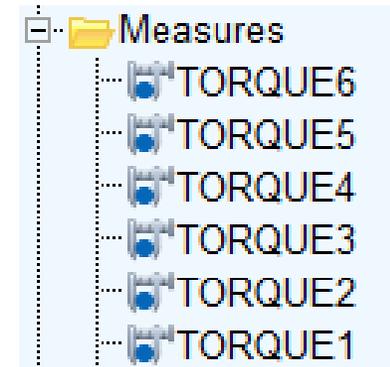
► Mediciones



The screenshot shows the 'Motion Measure' dialog box with the following settings:

- Measure Name: `.dinamica.Motor_6_MEA_4`
- MOTION: `.dinamica.Motor_6`
- Characteristic: Torque
- Component: X Y Z mag
- From/At: Efector_final.Eje6_efector Acople_muneca.Eje6_acople
- Represent coordinates in: (empty field)
- Create Strip Chart

Buttons at the bottom: OK, Apply, Cancel.

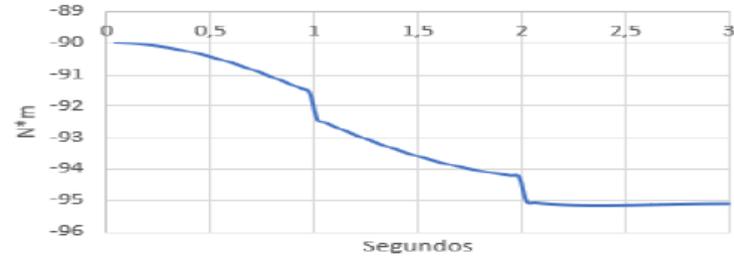


Resultados dinámica inversa

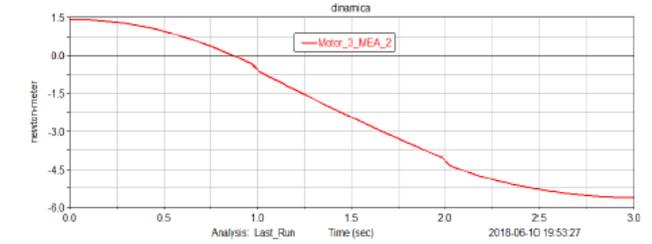
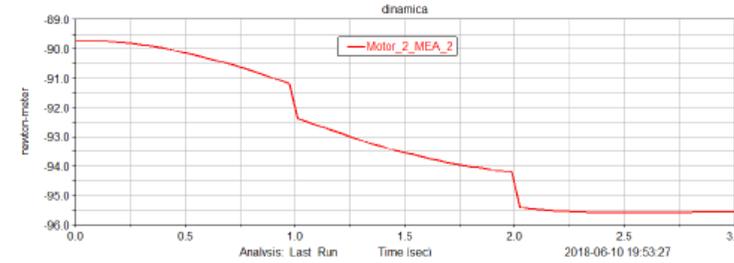
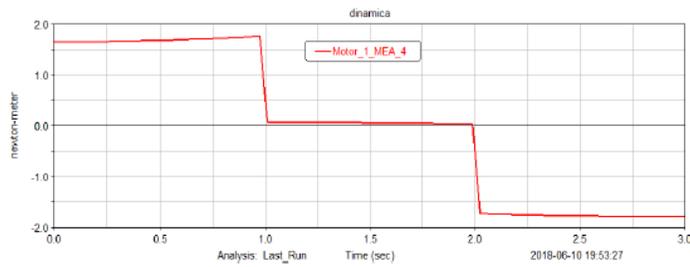
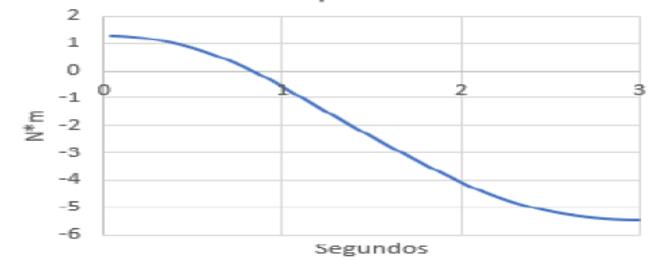
Torque 1



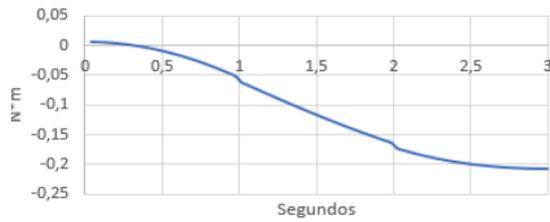
Torque 2



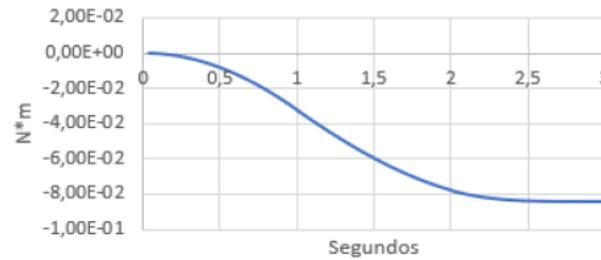
Torque 3



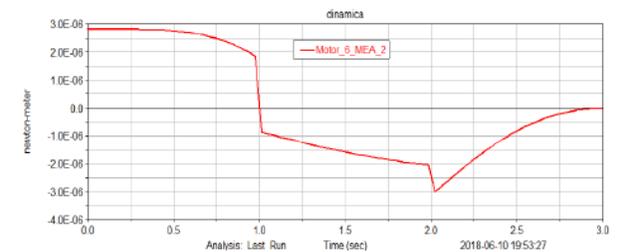
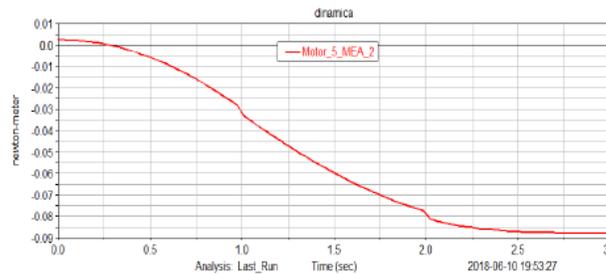
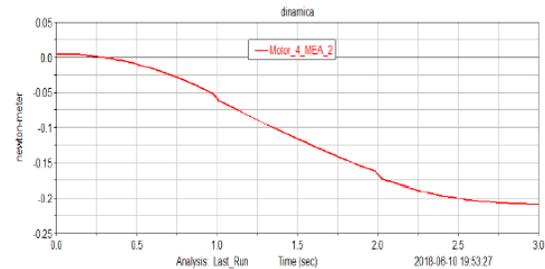
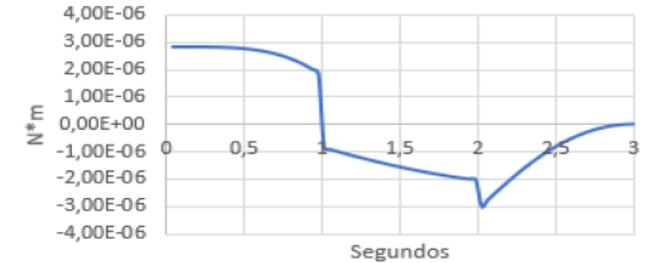
Torque 4



Torque 5



Torque 6



Conclusiones y futuros desarrollos

- Cumplido el objetivo del proyecto con la obtención de los mismos resultados tanto en ADAMS View como en MATLAB
- Reforzado conocimientos de programación, mecánica vectorial y matricial, aprendizaje de softwares del mundo de la robótica
- Se han sentado las bases de programación para aumentar este código para cualquier tipo de robot de seis grados de libertad y muñeca esférica

Presupuesto

- ▶ Costes de mano de obra 9430€
- ▶ Precios de equipos 606.47€
- ▶ **Costes totales 10036.47€**

- ▶ 13% Gastos generales 1304.74€
- ▶ 6% Beneficio Industrial 602.19€
- ▶ **Presupuesto base 11943.4€**

- ▶ 21% IVA 2508.114€
- ▶ **Presupuesto total 14451.514€**

Gracias por su atención