

Design and Control of the Lift Subsystem of a Two-Wheeled Forklift Robot

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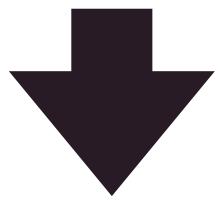


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I. Introduction

In modern industrial environments, humans and robots work together.



- Labor shortage in industrialized countries.
- High-risk tasks executed by robots.



[A]

Mobile robots should have a small footprint for safety and space optimization reasons.



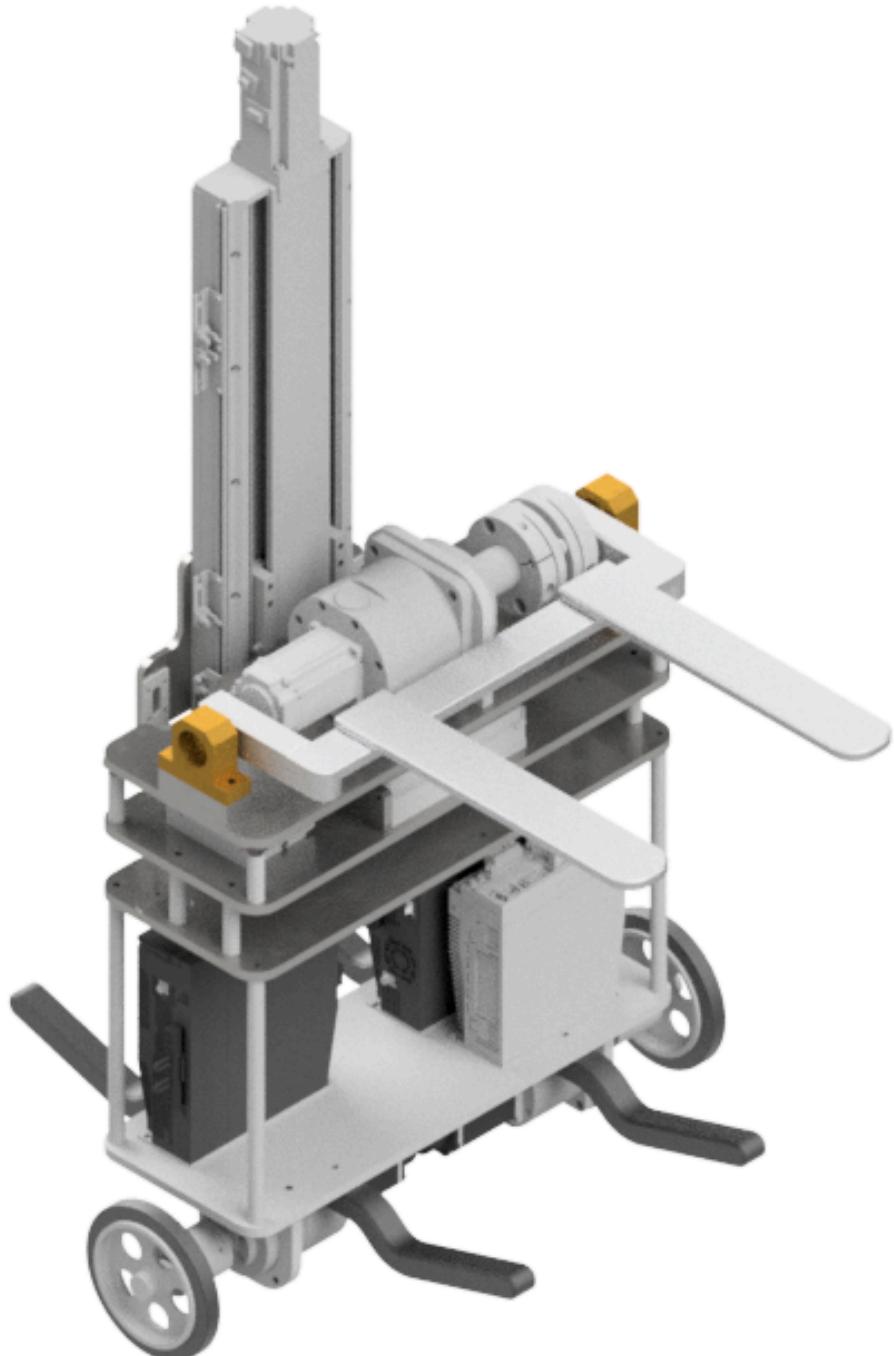
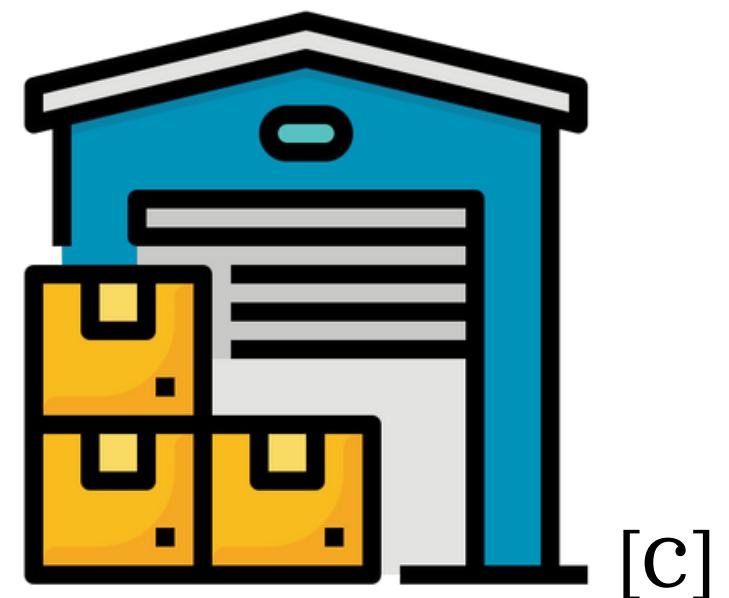
[B]



I. Introduction

Two-Wheeled Forklift Robot:

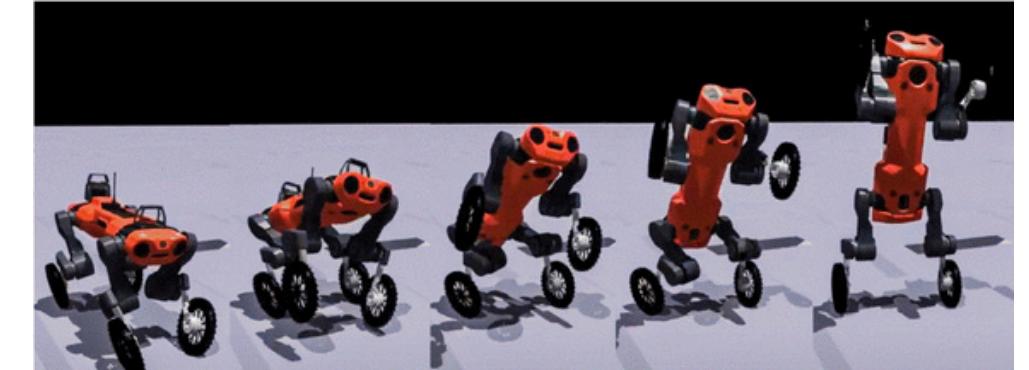
- Aimed for load movement in warehouses.
- Self-balanced mobile robot.
- Small footprint.





I. Introduction

- Literature review





II. Lift mechanical design

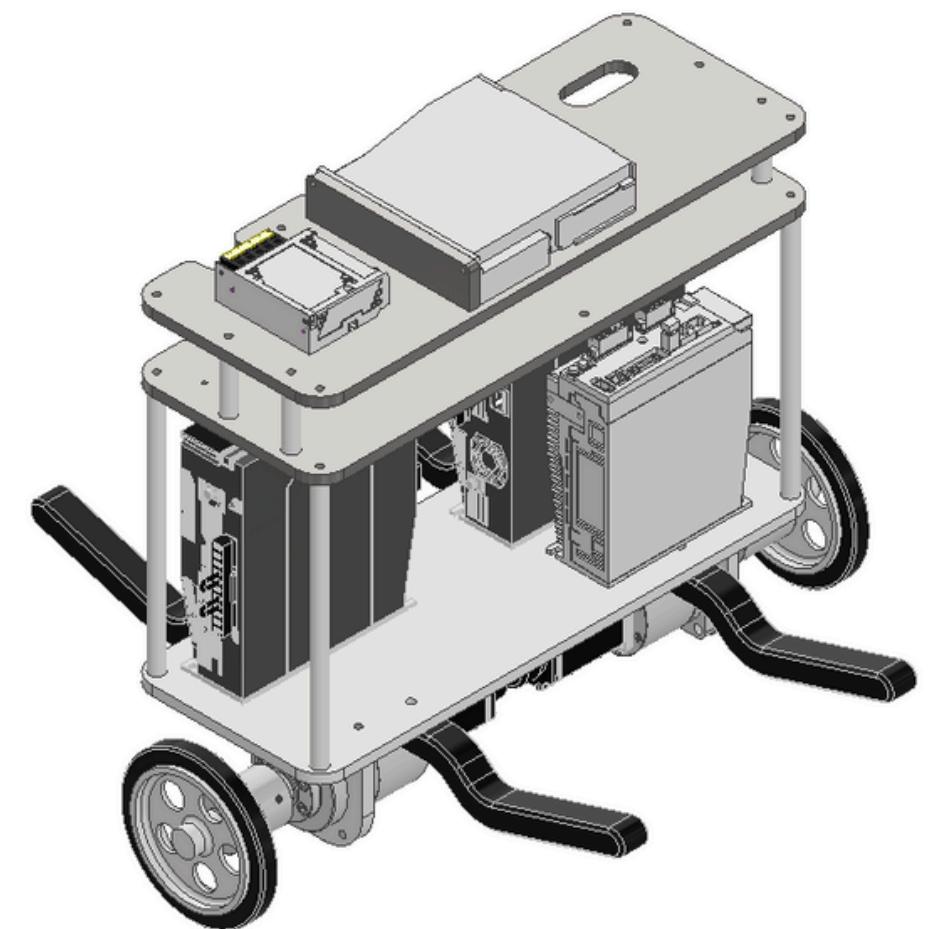
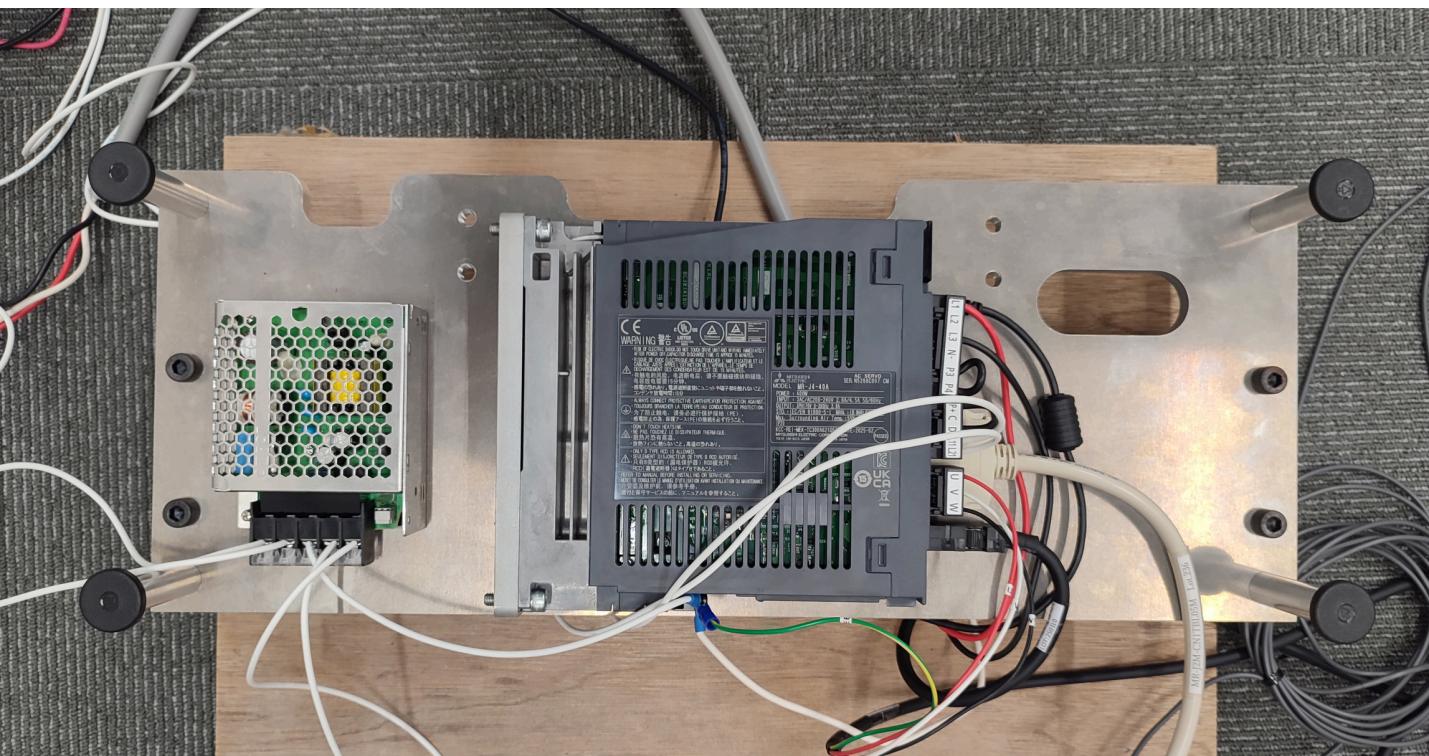
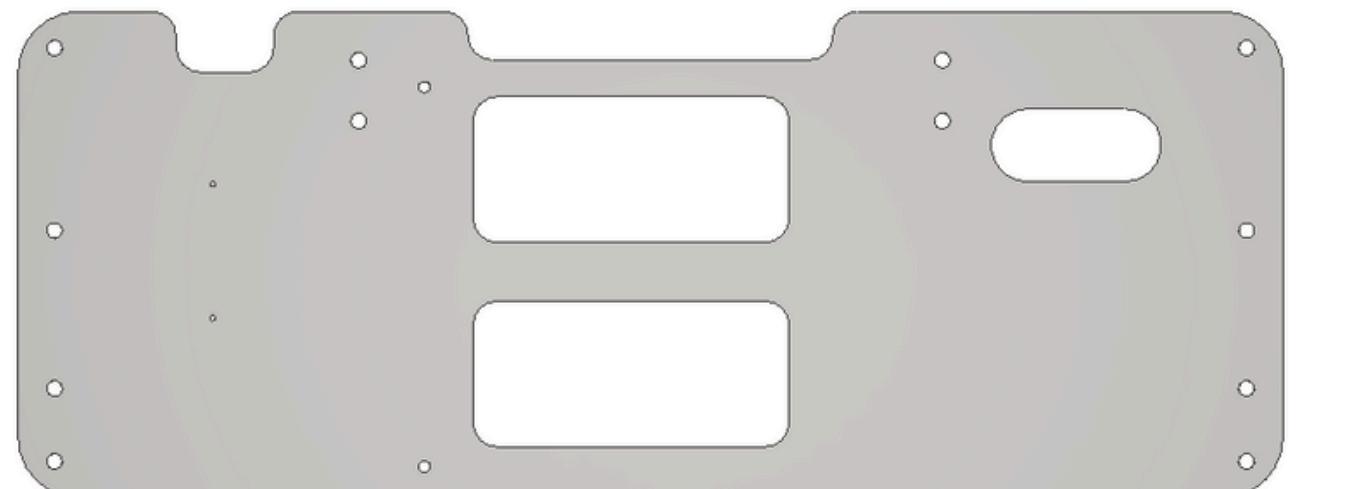
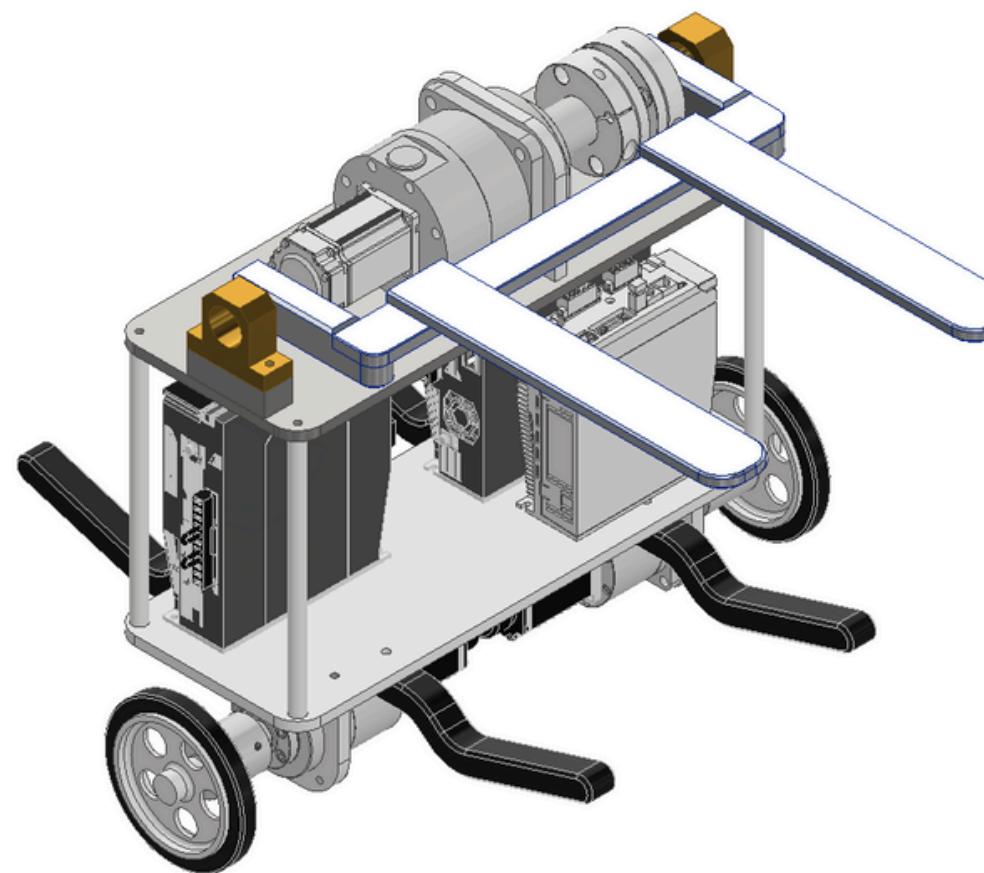
Ball screw linear actuator ETH2-17-L5-350-BC-M40B-E5N5L

Repeatability		mm	(+/-0.005)							
Lead	mm	5	10	20	40					
Maximum Rotating Speed(mm/s)	rpm	3600	3600	3600	3600					
Maximum Linear Speed	mm/s	300	600	1200	2400					
Maximum Payload	Horizontal	kg	120	110	75	16				
	Vertical (For Non-generative power)	kg	40	25	11	9				
	Vertical(external 50W regenerative register)	Kg	50	30	18	15				
Rated Thrust	N	1389	694	347	174					
Stroke Pitch	mm	50-1200mm/50 intervals(50mm pitch)								
Maximum Acceleration	G	0.15	0.31	0.61	1.22					
Ball Screw	Basic Dynamic load rating Ca	N	13428	11223	5667	9656				
	Basic Static load rating Coa	N	29671	24456	11182	20274				
Linear Guide	Dynamic Horizontal	N	7866							
	Static Horizontal	N	78400							
Fixed Bearing	Bsic Dynamic load rating Cr	N	9666							
	Static Load rating Cor	N	6400							
AC Actuator with Motor Output	W	400								
Ball Screw	mm	C7 X ø20								
Linear Guide	mm	W15XH12.5								
Ball Screw	mm	14 X 12								
Home Sensor	Outside	T64N2(NPN)								

[19]

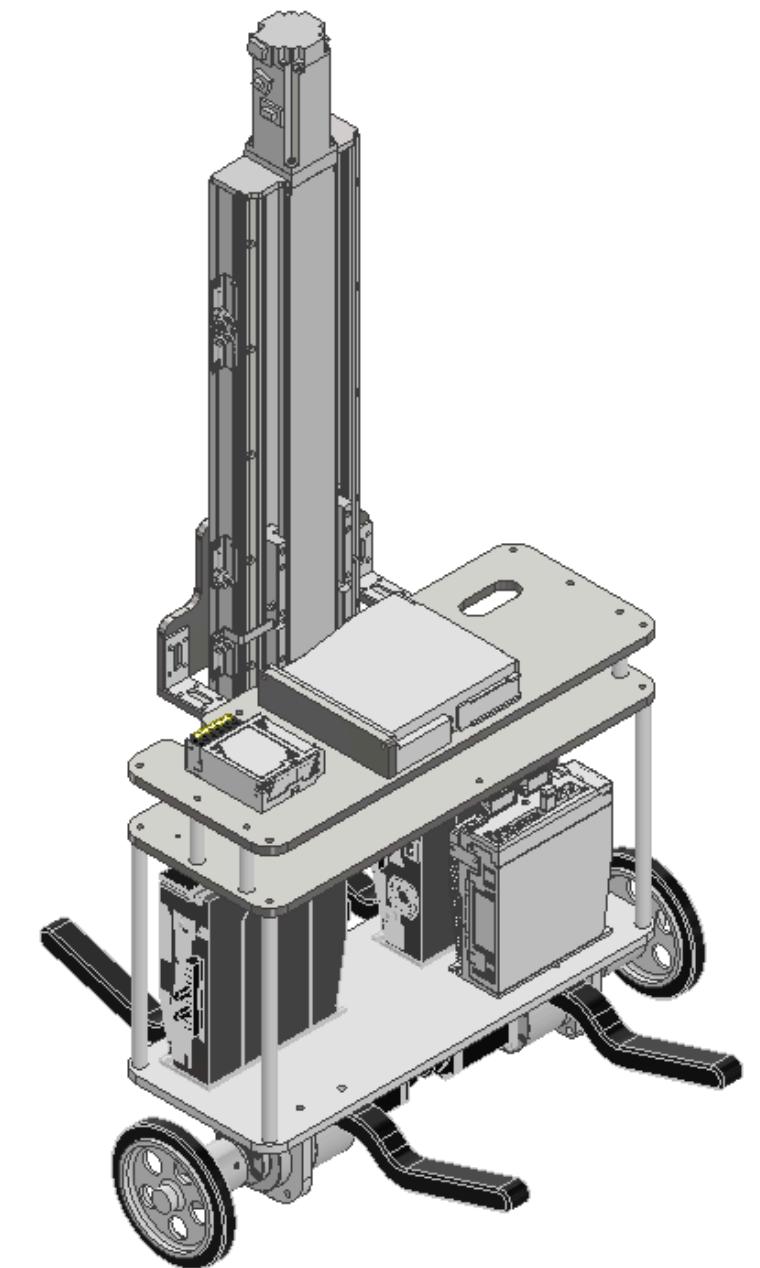
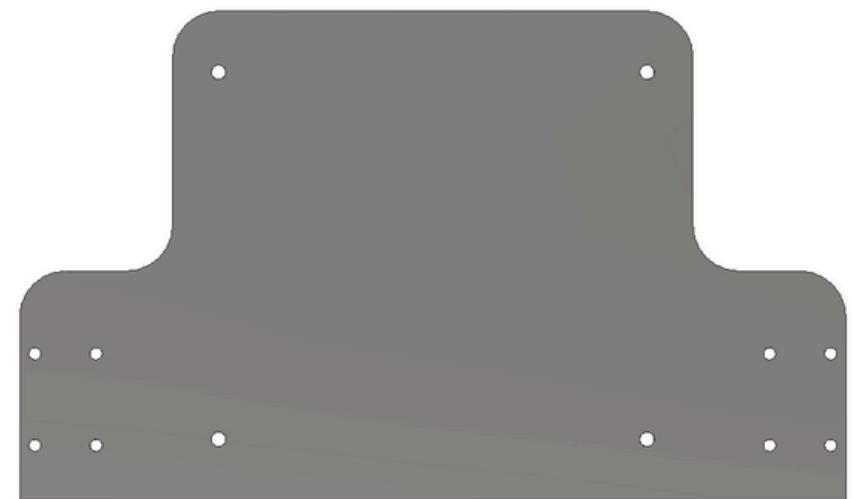
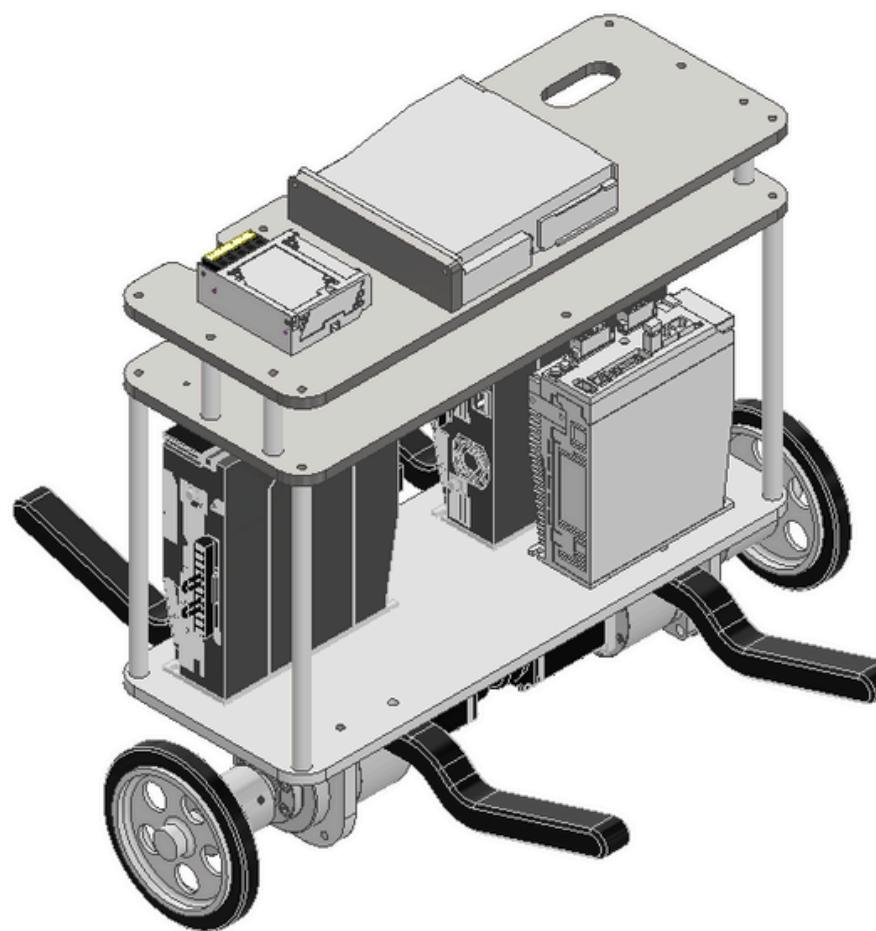


II. Lift mechanical design



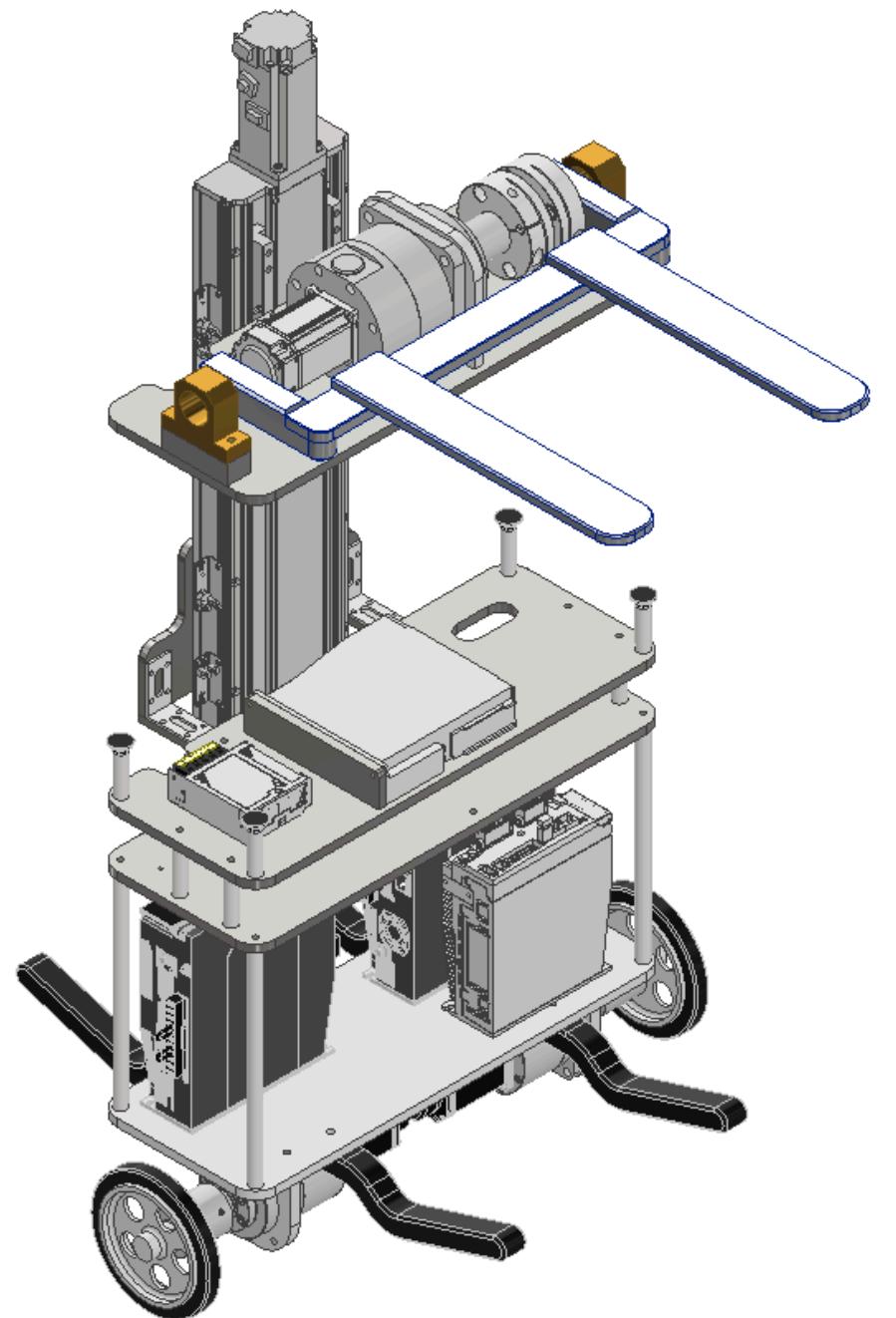
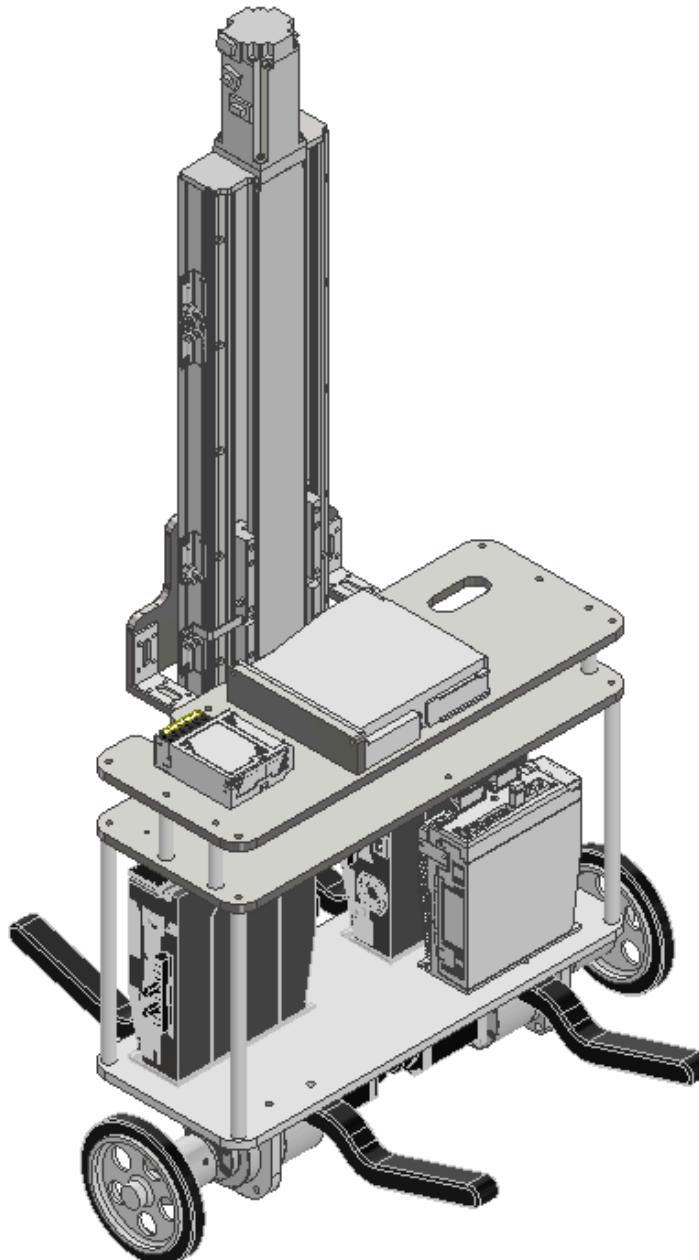


II. Lift mechanical design





II. Lift mechanical design



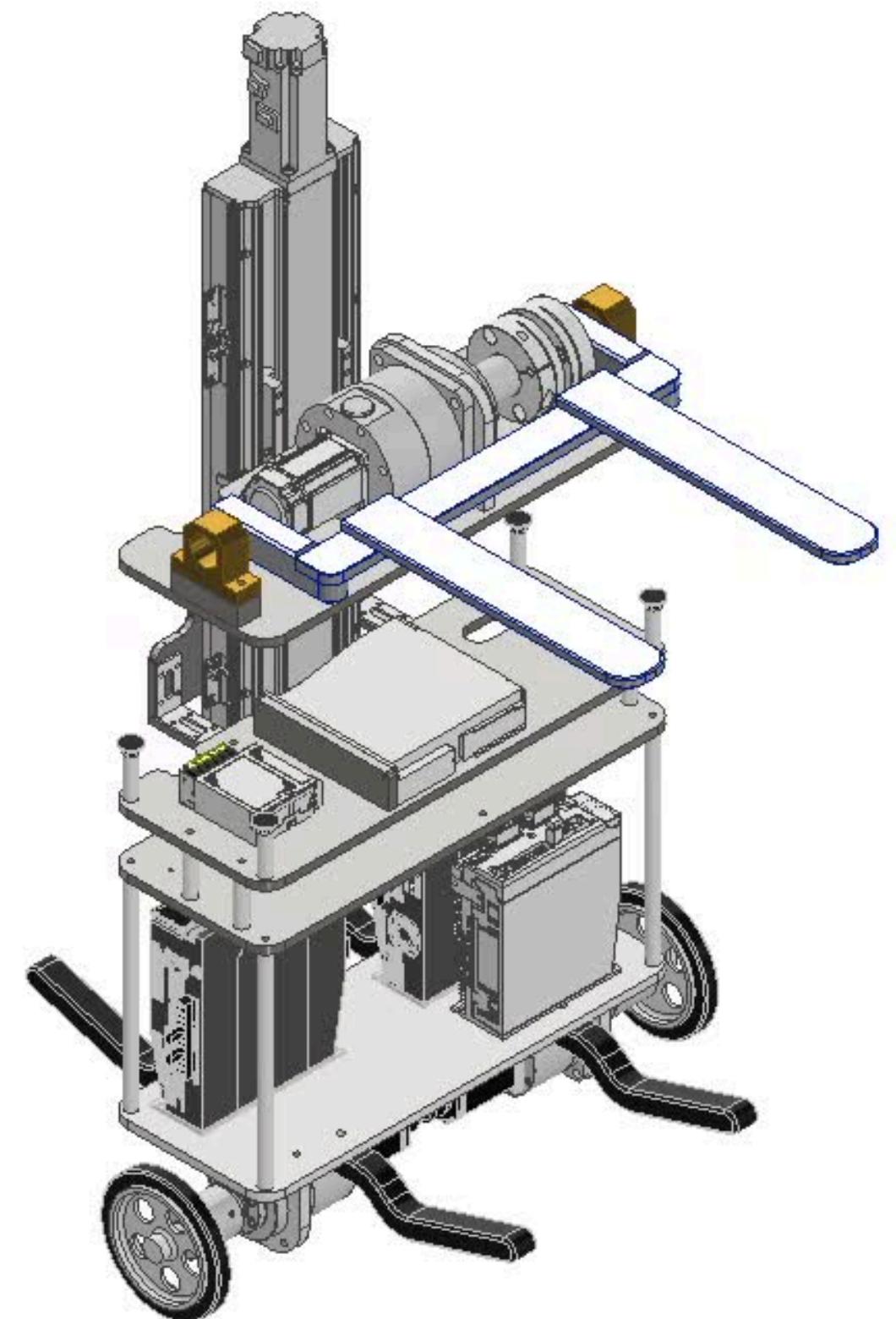


II. Lift mechanical design

Element	Reference	Manufacturer
Wheel motors	R88M-1M40030S-S2	OMRON
Wheel reduction drives	HPG-20A-11-J6GDK	HARMONIC DRIVE
Wheels motor drivers	R88D-1SN04L-ECT	OMRON
Fork motor	R88M-K40030S	OMRON
Fork reduction drive	HPG-32A-33-J2NELA	HARMONIC DRIVE
Fork motor driver	R88D-KN04L-ECT	OMRON
Lift motor	HG-KR43B	MITSUBISHI
Lift mechanism	ETH2-17-L5-350	TOYO ROBOTICS
Lift motor driver	MR-J4-40TM-ECT	MITSUBISHI

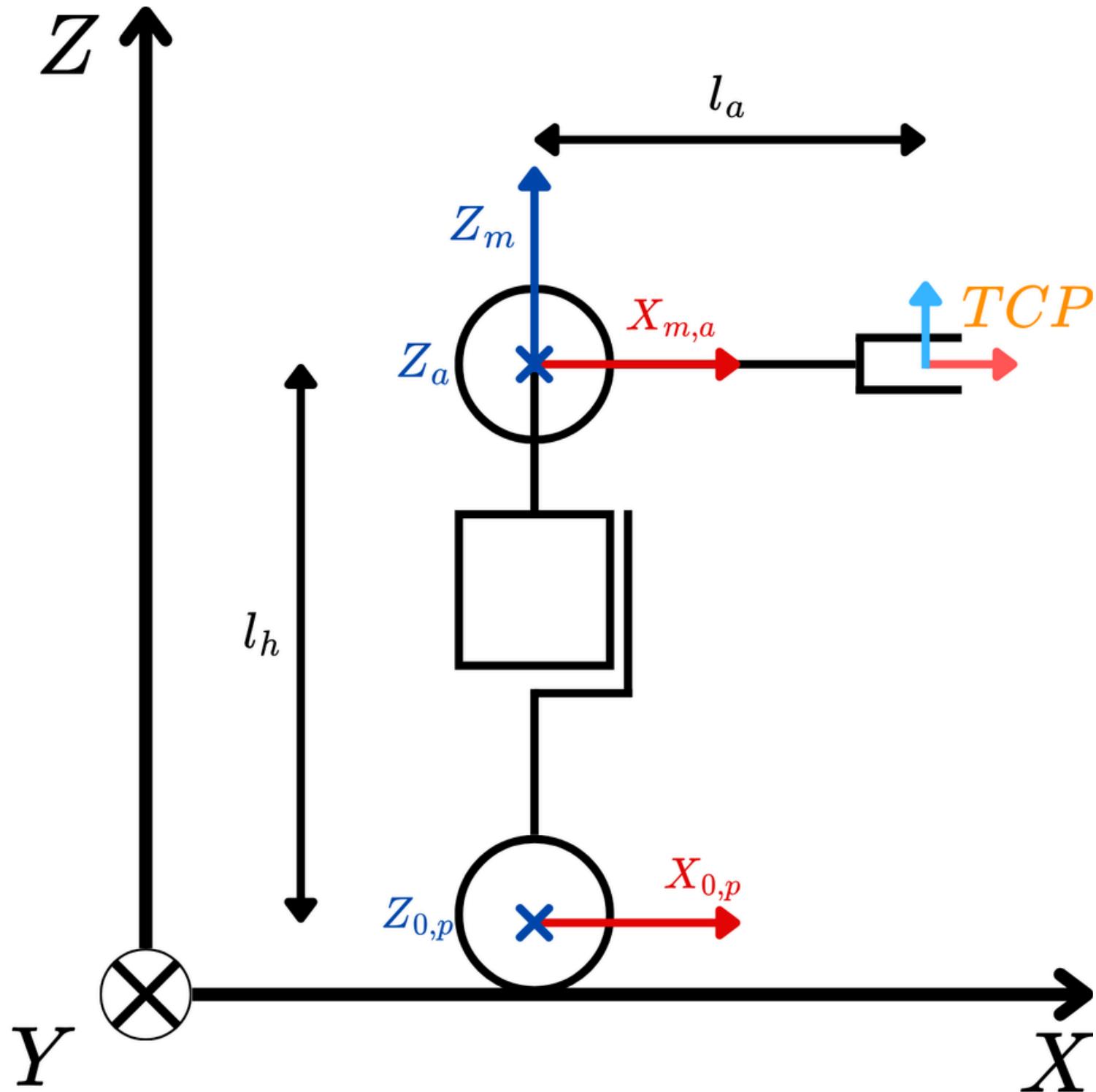


II. Lift mechanical design





III. Modeling



Kinematics:

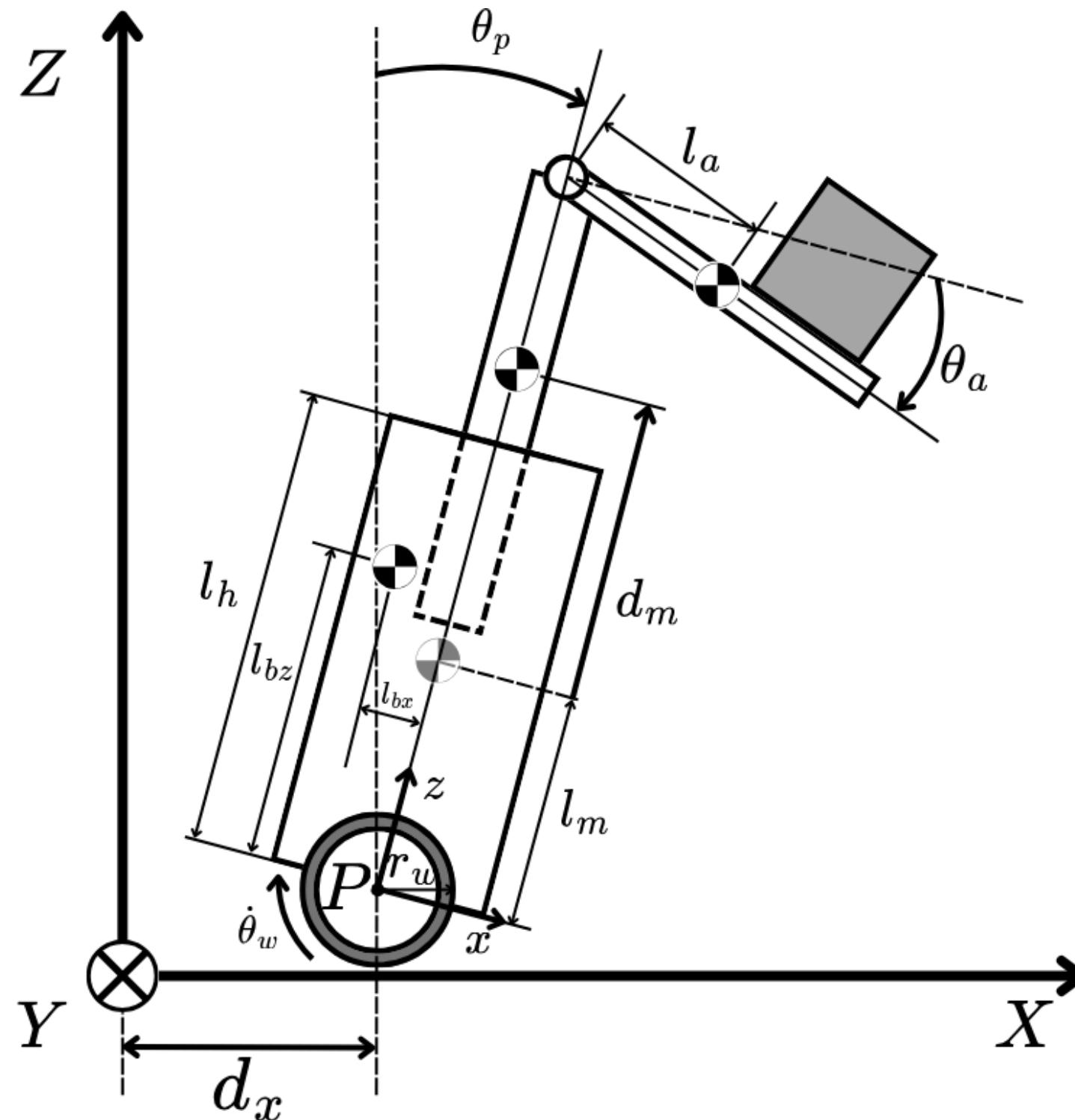
θ_w : Wheel angle, θ_p : Pitch angle,
 d_m : Lift displacement, θ_a : Arm angle

$$\theta_p + \theta_a = 0$$

$$H_T^B = \begin{pmatrix} 1 & 0 & 0 & s_p(l_h + d_m) + l_a \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & r_w + c_p(l_h + d_m) \\ 0 & 0 & 0 & 1 \end{pmatrix}$$



III. Modeling



Kinematics:

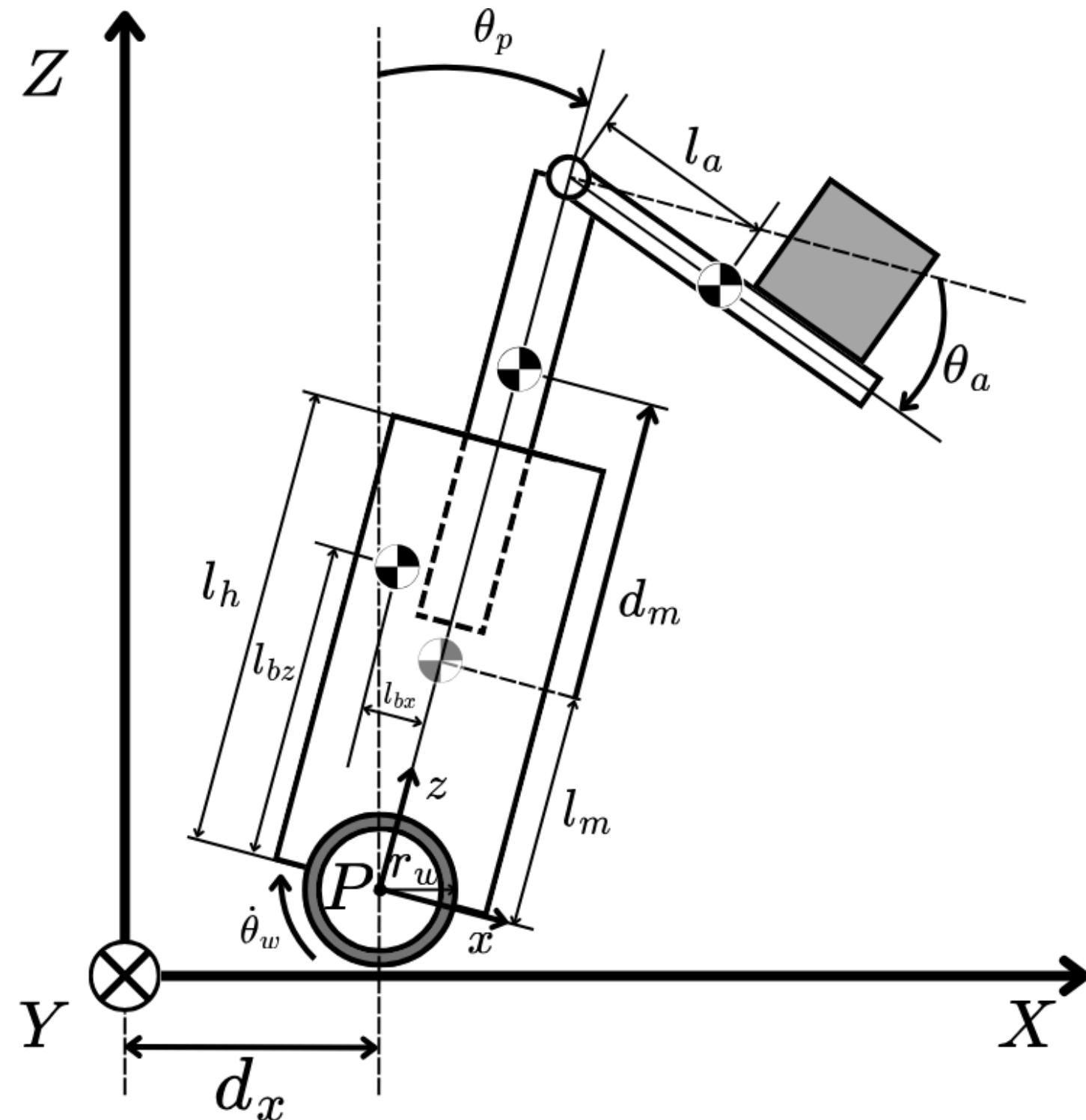
$$CoG = \left(\begin{array}{c} \frac{m_l \left(d_m s_p + l_h s_p + \frac{t_1}{g m_l} \right) + m_a (l_a + d_m s_p + l_h s_p) + m_b (l_{bz} s_p - l_{bx} c_p) + m_m (d_m + l_m) s_p}{m_a + m_b + m_l + m_m} \\ \frac{(m_a + m_l) (d_m c_p + l_h c_p) + m_b (l_{bz} c_p + l_{bx} s_p) + m_m (d_m + l_m) c_p}{m_a + m_b + m_l + m_m} \end{array} \right)$$

❖

$$\begin{cases} r_w + c_p(l_h + d_m) = z \\ c_p \dot{d}_m - s_p(l_h + d_m) \dot{\theta}_p = \dot{z} \\ CoG_x(\theta_p, d_m, m_l, t_1) = \sin(\theta_t) l_t \\ \dot{\theta}_p = 0 \end{cases}$$



III. Modeling



Dynamics:

$$M(q)\ddot{q} + H(\dot{q}, q) + G(q) = \tau$$

Generalized coordinates:

$$q = [\theta_w \quad \theta_p \quad d_m \quad \theta_a]^T$$

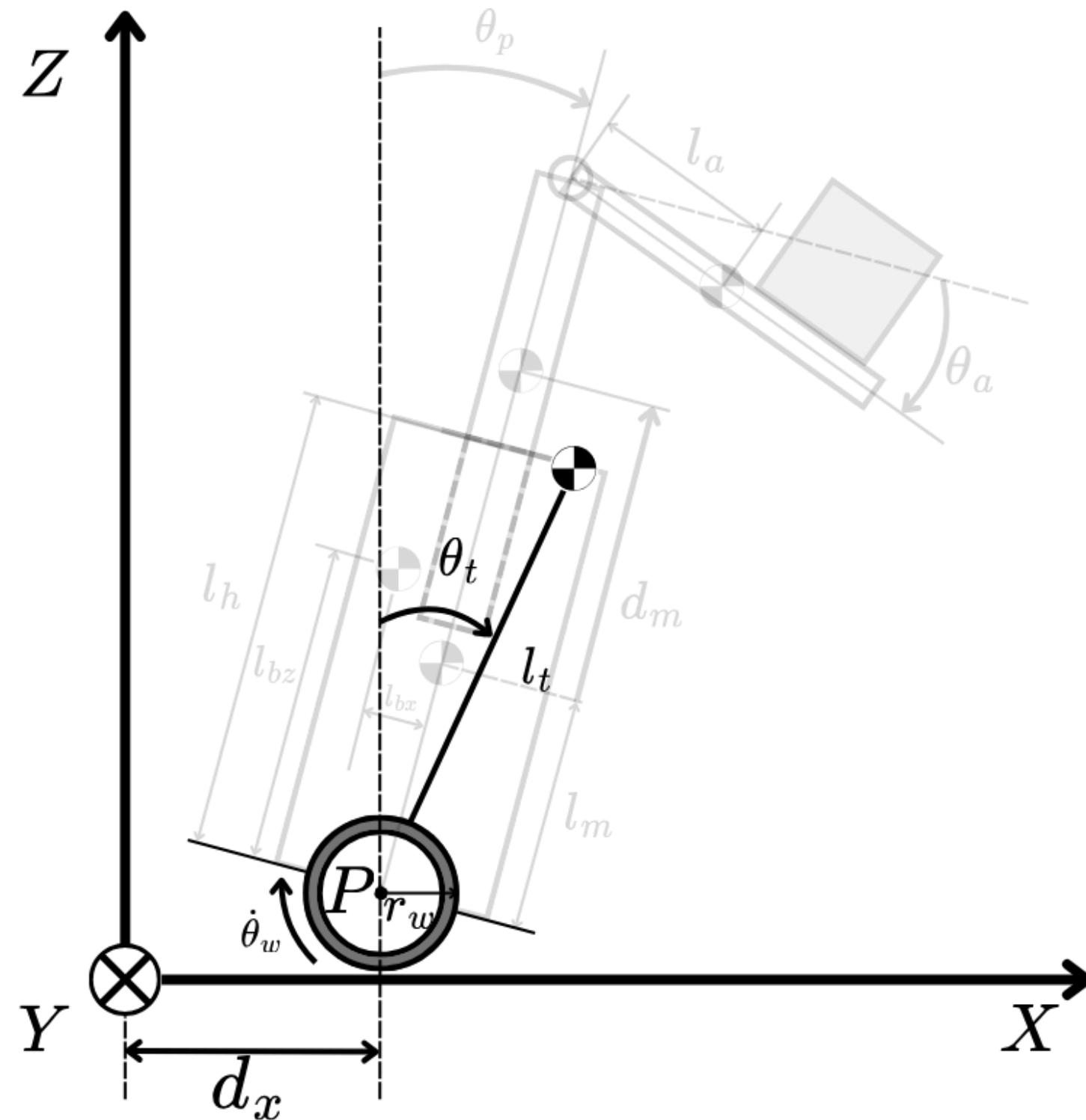
$$\tau = [n_w\tau_w \quad -n_w\tau_w \quad f_m \quad n_a\tau_a]^T$$

τ_w : Wheel torque, f_m : Lift force,

τ_a : Arm torque



III. Modeling



Simplified dynamics:

❖ $M^*(q')\ddot{q}' + H^*(\dot{q}', q') + G^*(q') = \tau^*(\ddot{x})$

Generalized coordinates:

$$q' = [\theta_w \quad \theta_t]^T$$

$$\tau^*(\ddot{x}) = [n_w \tau_w(\ddot{x}) \quad -n_w \tau_w(\ddot{x})]^T$$

$$\tau_w(\ddot{x}) = r_w m_t \ddot{x}^{ref}$$



$$\theta_t = \text{atan}\left(\frac{CoG_x}{CoG_z}\right), \quad l_t = \|CoG\|$$



IV. Control

Synthesized Pitch Angle Disturbance Observer (SPADO):

$$m_{11}\ddot{\theta}_w + m_{12}\ddot{\theta}_p + m_{13}\ddot{d}_m + m_{14}\ddot{\theta}_a + h_1 = n_w\tau_w - T_{lw}$$

$$m_{n11}\ddot{\theta}_w^{res} = n_w\tau_w^{ref} - \tilde{\tau}_w^{dist}$$

$$\tilde{\tau}_w^{dist} = (m_{11} - m_{n11})\ddot{\theta}_w + m_{12}\ddot{\theta}_p + m_{13}\ddot{d}_m + m_{14}\ddot{\theta}_a + h_1 + T_{lw}$$

$$m_{21}\ddot{\theta}_w + m_{22}\ddot{\theta}_p + m_{23}\ddot{d}_m + m_{24}\ddot{\theta}_a + h_2 + g_2 = -n_w\tau_w - T_{lp}$$

$$m_{n21}\ddot{\theta}_w^{res} + m_{n22}\ddot{\theta}_p^{res} = -n_w\tau_w^{ref} - \tilde{\tau}_p^{dist}$$

$$\tilde{\tau}_p^{dist} = (m_{21} - m_{n21})\ddot{\theta}_w + (m_{22} - m_{n22})\ddot{\theta}_p + m_{23}\ddot{d}_m + m_{24}\ddot{\theta}_a + h_2 + g_2 + T_{lp}$$



IV. Control

SPADO:

$$m_{n22}\ddot{\theta}_p^{res} + \frac{m_{n21} + m_{n11}}{m_{n11}}n_w\tau_w^{ref} = \frac{m_{n21}}{m_{n11}}\tilde{\tau}_w^{dis} - \tilde{\tau}_p^{dist}$$

$$\tilde{\tau}_s^{dist} = \tilde{\tau}_p^{dist} - \frac{m_{n21}}{m_{n11}}\tilde{\tau}_w^{dis}$$

$$m_{n22}\ddot{\theta}_p^{res} + \frac{m_{n21} + m_{n11}}{m_{n11}}n_w\tau_w^{ref} = -\tilde{\tau}_s^{dist}$$

$$\hat{\tau}_s^{dist} = \frac{g_s}{s + g_s}(g_s m_{n22}\dot{\theta}_p^{res} - \frac{m_{n21} + m_{n11}}{m_{n11}}n_w\tau_w^{ref}) - g_s m_{n22}\dot{\theta}_p^{res}$$

Pseudo differentiation



IV. Control

PD controller pitch angle:

$$V = \frac{1}{2}K_1(\theta_p^{cmd} - \theta_p^{res})^2 + \frac{1}{2}K_2(\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})^2$$

$$\dot{V} = (\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})(K_1(\theta_p^{cmd} - \theta_p^{res}) + K_2(\ddot{\theta}_p^{cmd} - \boxed{\ddot{\theta}_p^{res}}))$$

$$\dot{V} = -K_3(\dot{\theta}_p^{cmd} - \dot{\theta}_p^{res})^2$$

$$\tau_w^{ref} = -\frac{m_{n11}m_{n22}}{n_w(m_{n21} + m_{n11})} \left(K_{pp}(\boxed{\theta_p^{cmd}} - \theta_p^{res}) + K_{dp}(\boxed{\dot{\theta}_p^{cmd}} - \dot{\theta}_p^{res}) + \boxed{\ddot{\theta}_p^{cmd}} \right) - \frac{m_{n11}}{n_w(m_{n21} + m_{n11})} \boxed{\hat{\tau}_s^{dist}}$$

$$K_{pp} = \frac{K_1}{K_2}, \quad K_{dp} = \frac{K_3}{K_2}$$



IV. Control

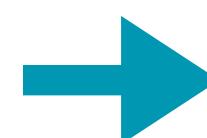
Fork Disturbance Observer (FDOB):

$$m_{41}\ddot{\theta}_w + m_{42}\ddot{\theta}_p + m_{43}\ddot{d}_m + m_{44}\ddot{\theta}_a + h_4 + g_4 = n_a\tau_a - T_{la}$$

$$m_{n44}\ddot{\theta}_a^{res} = n_a\tau_a^{ref} - \tilde{\tau}_a^{dist}$$

$$\tilde{\tau}_a^{dist} = m_{41}\ddot{\theta}_w^{res} + m_{42}\ddot{\theta}_p^{res} + m_{43}\ddot{d}_m^{res} + (m_{44} - m_{n44})\ddot{\theta}_a^{res} + h_4 + g_4 + T_{la}$$

$$\hat{\tau}_a^{dist} = \frac{g_a}{s + g_a}(n_a\tau_a^{ref} + g_a m_{n44}\dot{\theta}_a^{res}) - g_a m_{n44}\dot{\theta}_a^{res}$$



Pseudo differentiation

PD controller fork angle:

$$\tau_a^{ref} = K_{pa}(\theta_a^{cmd} - \theta_a^{res}) + K_{da}(\dot{\theta}_a^{cmd} - \dot{\theta}_a^{res}) + \hat{\tau}_a^{dist}$$



IV. Control

Fork Reaction Torque Observer (FRTOB):

$$T_{la} = \tilde{\tau}_a^{ext} + \tilde{\tau}_a^{fric}$$

$$\tilde{\tau}_a^{reac} = m_{41}\ddot{\theta}_w^{res} + m_{42}\ddot{\theta}_p^{res} + m_{43}\ddot{d}_m^{res} + (m_{44} - m_{n44})\ddot{\theta}_a^{res} + h_4 + \tilde{\tau}_a^{ext}$$

$$m_{n44}\ddot{\theta}_a^{res} = n_a \tau_a^{ref} - g_4 - \tilde{\tau}_a^{fric} - \tilde{\tau}_a^{reac}$$

$$\hat{\tau}_a^{reac} = \frac{g_r}{s + g_r} (n_a \tau_a^{ref} + g_r m_{n44} \dot{\theta}_a^{res} - g_4 - \tilde{\tau}_a^{fric}) - g_r m_{n44} \dot{\theta}_a^{res}$$

Pseudo differentiation

$$t_1 = -\hat{\tau}_a^{reac}$$



IV. Control

Lift Disturbance Observer (LDOB):

$$m_{31}\ddot{\theta}_w + m_{32}\ddot{\theta}_p + m_{33}\ddot{d}_m + m_{34}\ddot{\theta}_a + h_3 + g_3 = f_m - F_{lm}$$

$$m_{n33}\ddot{d}_m^{res} = f_m^{ref} - \tilde{f}_m^{dist}$$

$$\tilde{f}_m^{dist} = m_{31}\ddot{\theta}_w^{res} + m_{32}\ddot{\theta}_p^{res} + (m_{33} - m_{n33})\ddot{d}_m^{res} + m_{34}\ddot{\theta}_a^{res} + h_3 + g_3 + F_{lm}$$

$$\hat{f}_m^{dist} = \frac{g_m}{s + g_m}(f_m^{ref} + g_m m_{n33} \dot{d}_m^{res}) - g_m m_{n33} \dot{d}_m^{res} \rightarrow \text{Pseudo differentiation}$$

PD controller lift displacement:

$$f_m^{ref} = K_{pm}(d_m^{cmd} - d_m^{res}) + K_{dm}(\dot{d}_m^{cmd} - \dot{d}_m^{res}) + \hat{f}_m^{dist}$$



IV. Control

Lift Reaction Force Observer (LRFOB):

$$F_{lm} = \tilde{f}_m^{ext} + \tilde{f}_m^{fric}$$

$$\tilde{f}_m^{reac} = m_{31}\ddot{\theta}_w^{res} + m_{32}\ddot{\theta}_p^{res} + (m_{33} - m_{n33})\ddot{d}_m^{res} + m_{34}\ddot{\theta}_a^{res} + h_3 + \tilde{f}_m^{ext}$$

$$m_{n44}\ddot{d}_m^{res} = f_m^{ref} - g_3 - \tilde{f}_m^{fric} - \tilde{f}_m^{reac}$$

$$\hat{f}_m^{reac} = \frac{g_r}{s + g_r} (f_m^{ref} + g_r m_{n33} \dot{d}_m^{res} - g_3 - \tilde{f}_m^{fric}) - g_r m_{n33} \dot{d}_m^{res}$$

Pseudo differentiation

$$m_l = \frac{\hat{f}_m^{reac}}{g \cos(\theta_p)}$$



IV. Control

Wheel Position Control:

$$\theta_p^{cmd-PD} = K_{pw}(\theta_w^{cmd} - \theta_w^{res}) + K_{dw}(\dot{\theta}_w^{cmd} - \dot{\theta}_w^{res})$$

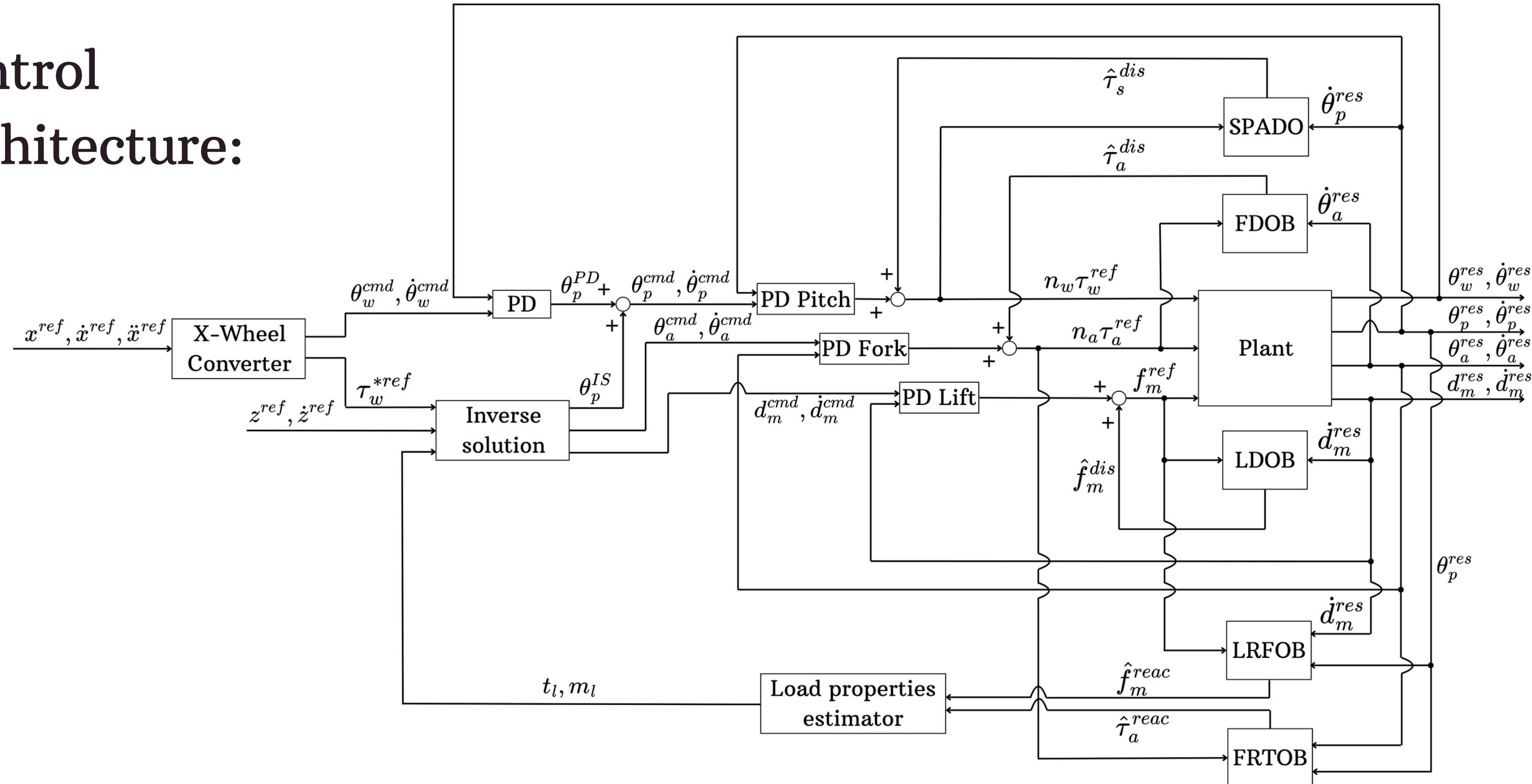
Total pitch command:

$$\theta_p^{cmd} = \theta_p^{cmd-IS} + \theta_p^{cmd-PD}$$



IV. Control

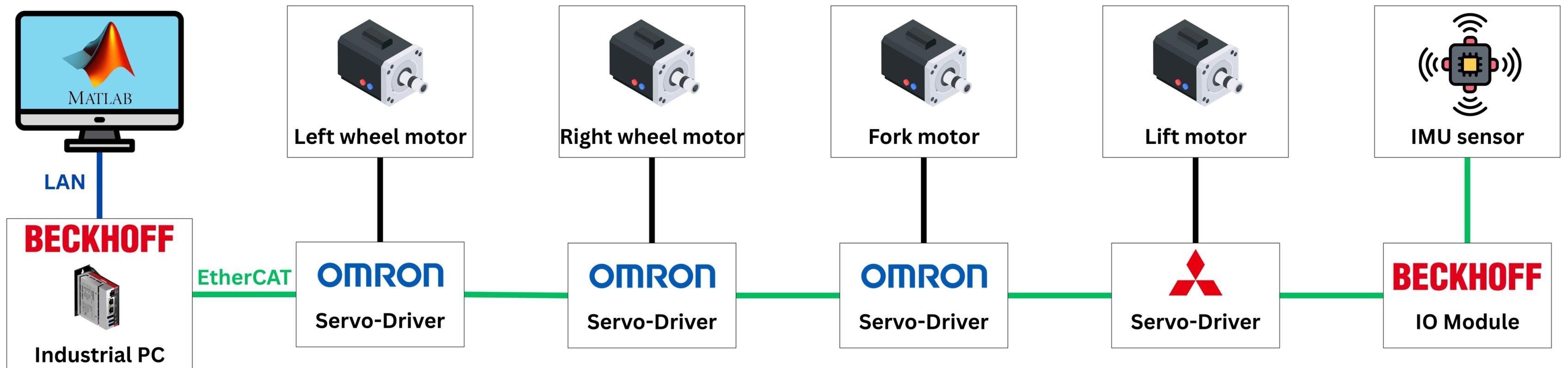
Control Architecture:





IV. Control

Physical implementation:





V. Results

Parameter	Explanation	Value
K_{pp}	P-gain of pitch angle control	200
K_{pd}	D-gain of pitch angle control	50
K_{pa}	P-gain of arm position control	200
K_{da}	D-gain of arm position control	50
K_{pm}	P-gain of lift position control	200
K_{dm}	D-gain of lift position control	50
K_{pw}	P-gain of wheel position control	0.07
K_{dw}	D-gain of wheel position control	0.09
g_s (rad/s)	Cutoff angular frequency of SPADO	$2\pi 6$
g_a (rad/s)	Cutoff angular frequency of arm FDOB	$2\pi 5$
g_r (rad/s)	Cutoff angular frequency of FRTOB, LRFOB	$2\pi 1$
g_m (rad/s)	Cutoff angular frequency of LDOB	$2\pi 4$
N_w	Wheel gear ratio	11
N_a	Arm gear ratio	33

Parameter	Explanation	Value
I_{wy} (kg m^2)	Wheel inertia	0.0052
I_{by} (kg m^2)	Body inertia	4.0590
I_{my} (kg m^2)	Lift inertia	0.0482
I_{ay} (kg m^2)	Arm inertia	0.0890
l_{bz} (m)	Body CoG z coordinate	0.3206
l_{bx} (m)	Body CoG x coordinate	0.0246
l_m (m)	Lift CoG distance	0.3975
l_a (m)	Arm CoG distance	0.2200
m_w (kg)	Wheel mass	1.21
m_b (kg)	Body mass	64.1
m_m (kg)	Lift mass	21.5
m_a (kg)	Arm mass	3.5
m_l (kg)	Load mass	5



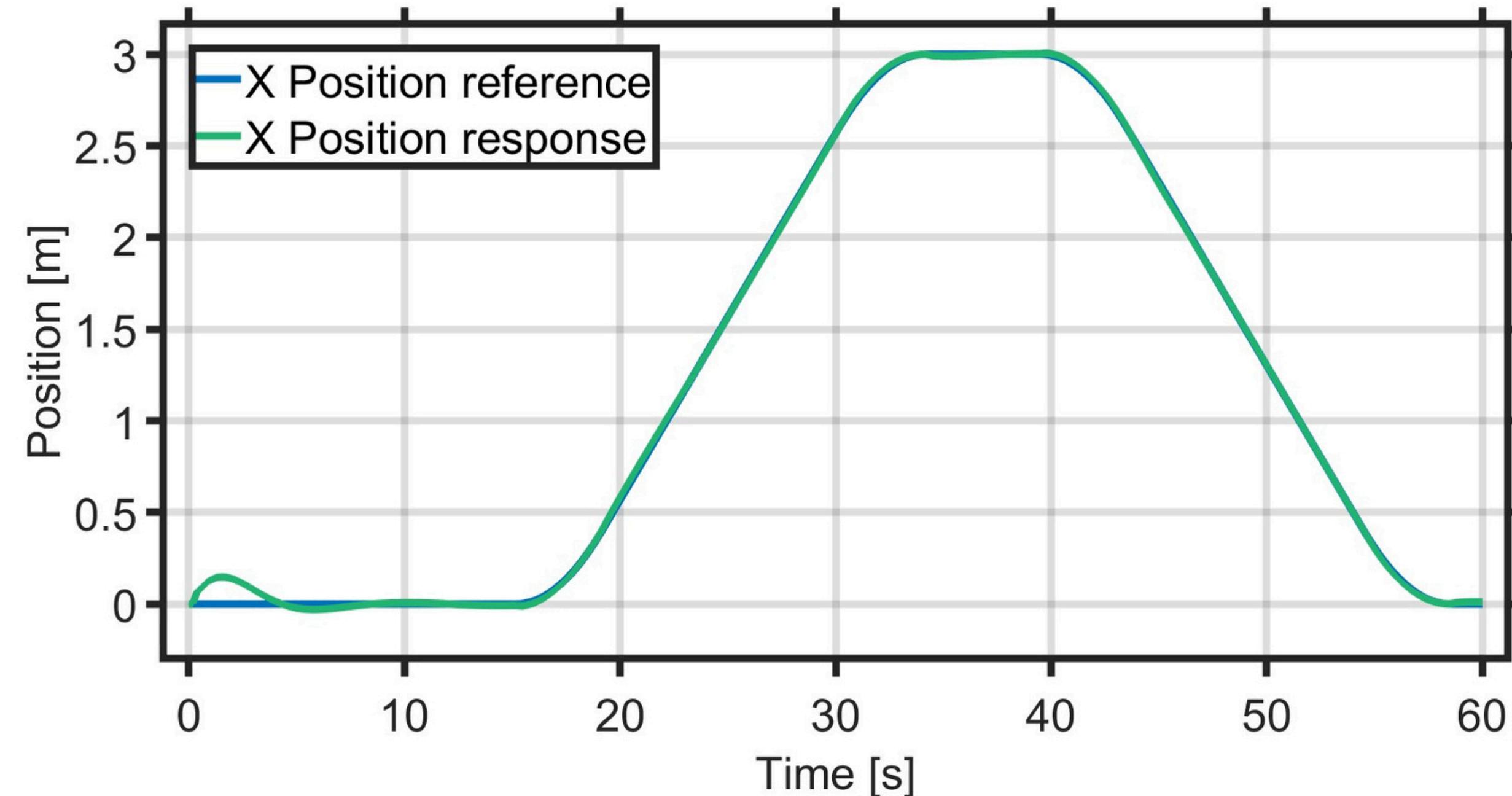
V. Simulation





V. Simulation

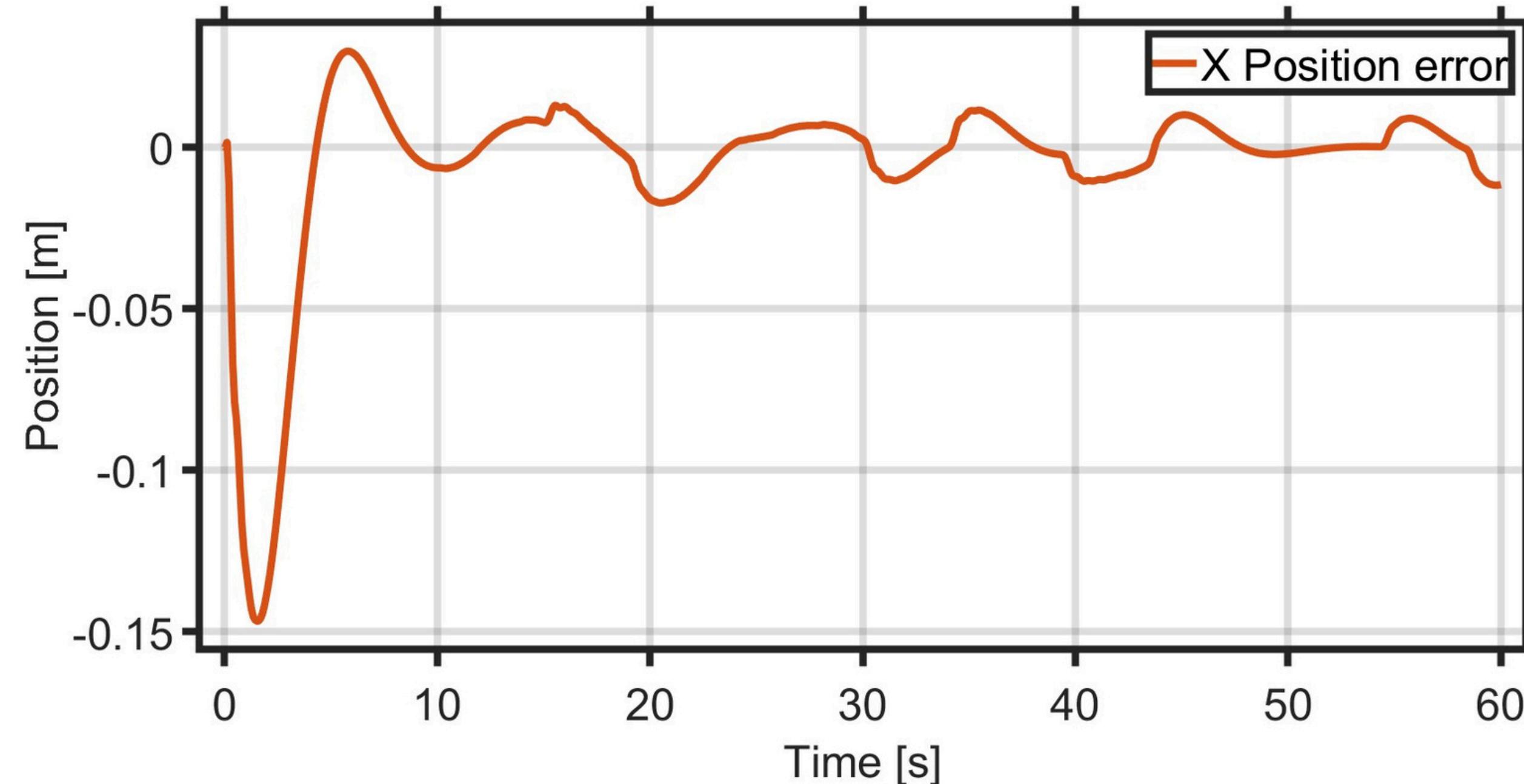
Horizontal displacement of the robot





V. Simulation

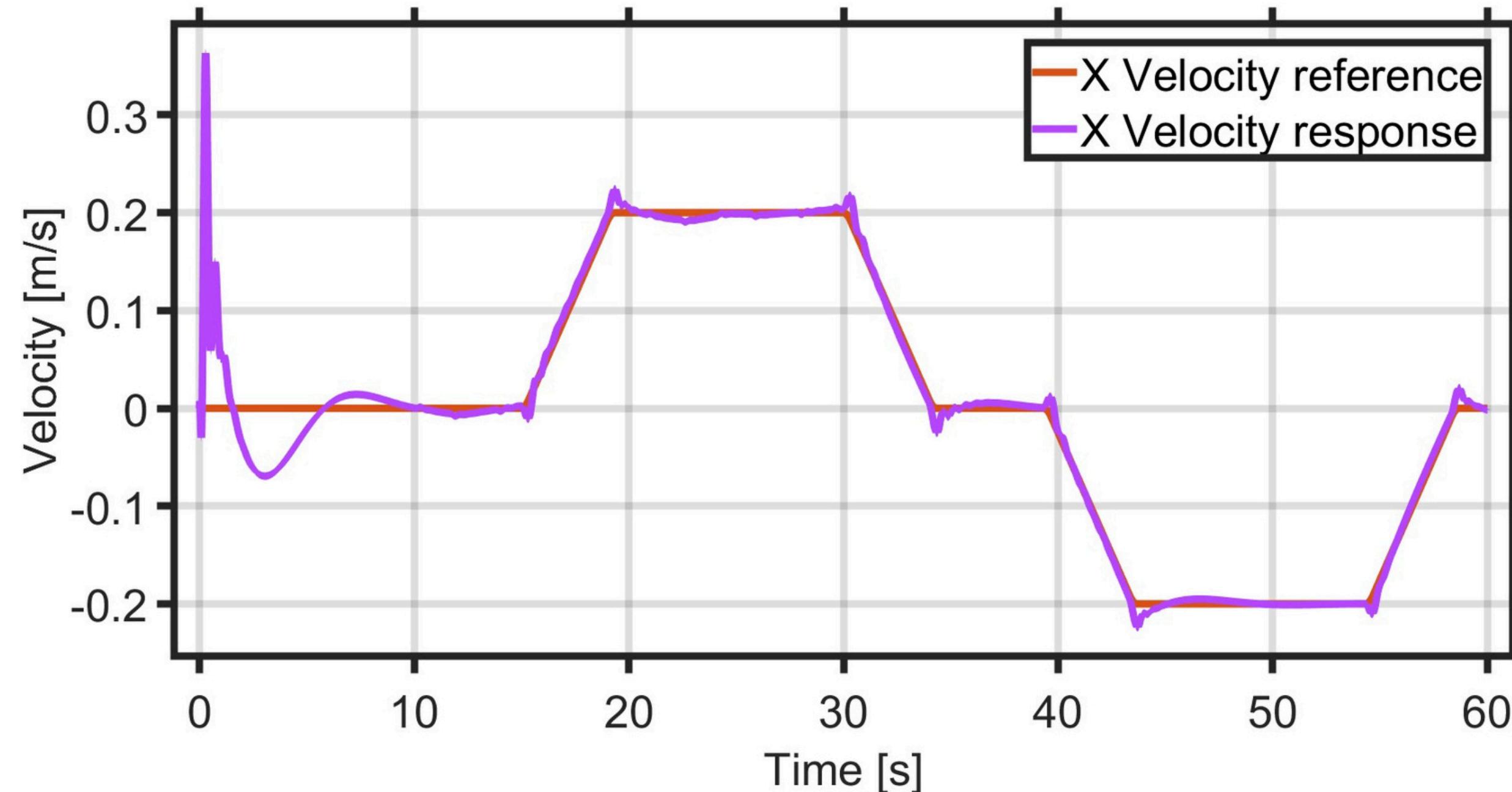
Position error of the robot





V. Simulation

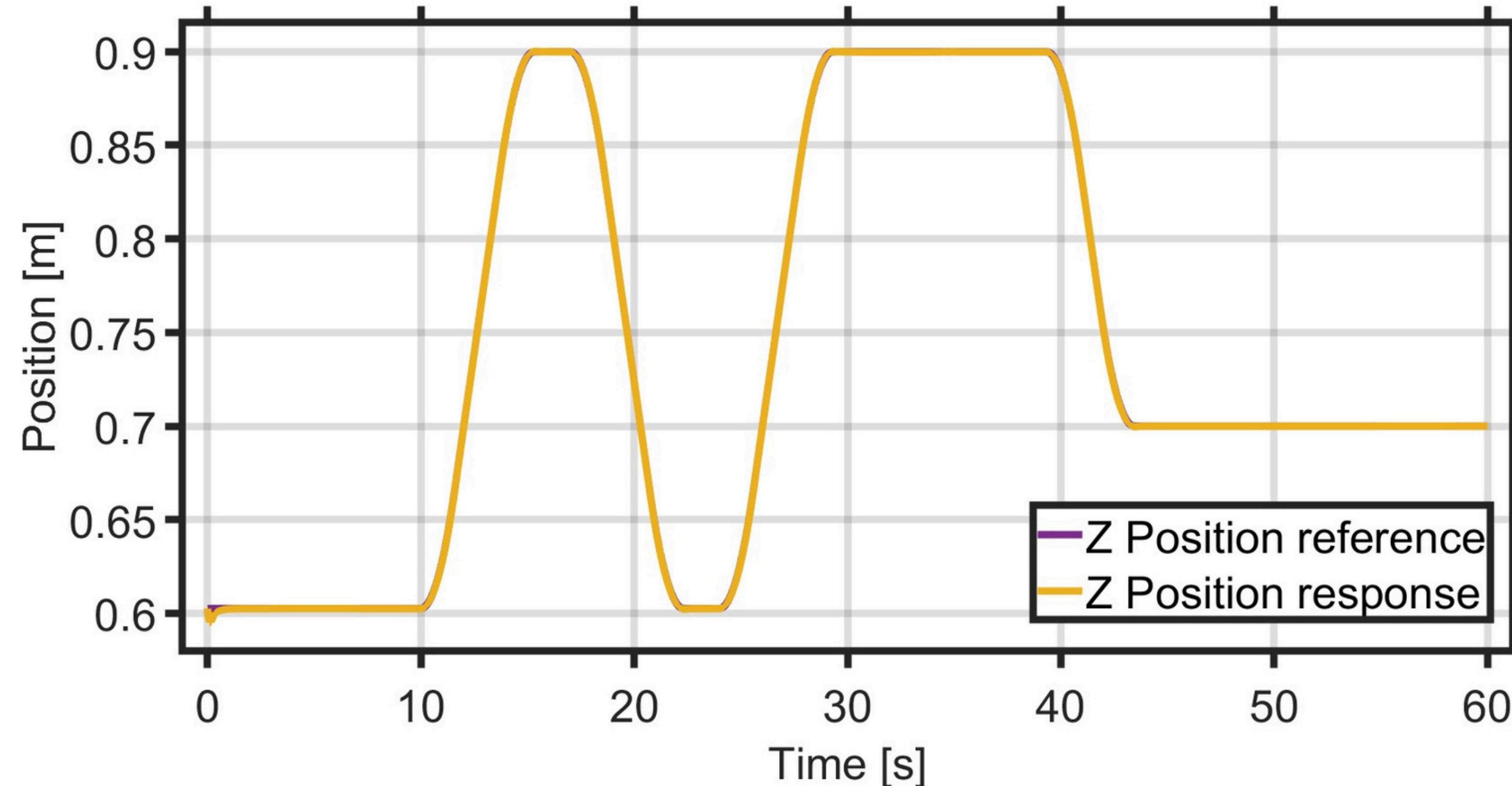
Horizontal velocity of the robot





V. Simulation

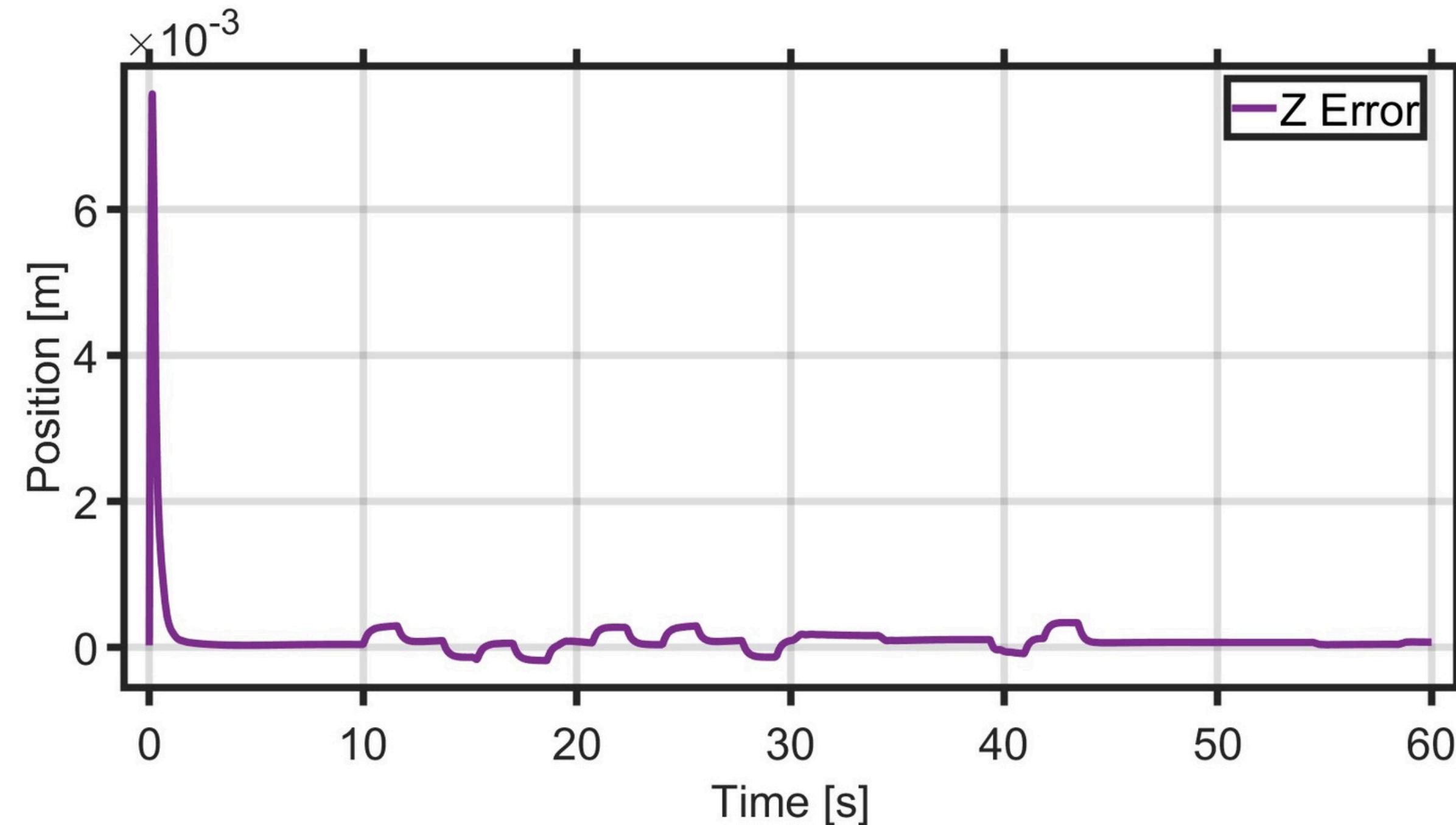
Vertical position of the fork





V. Simulation

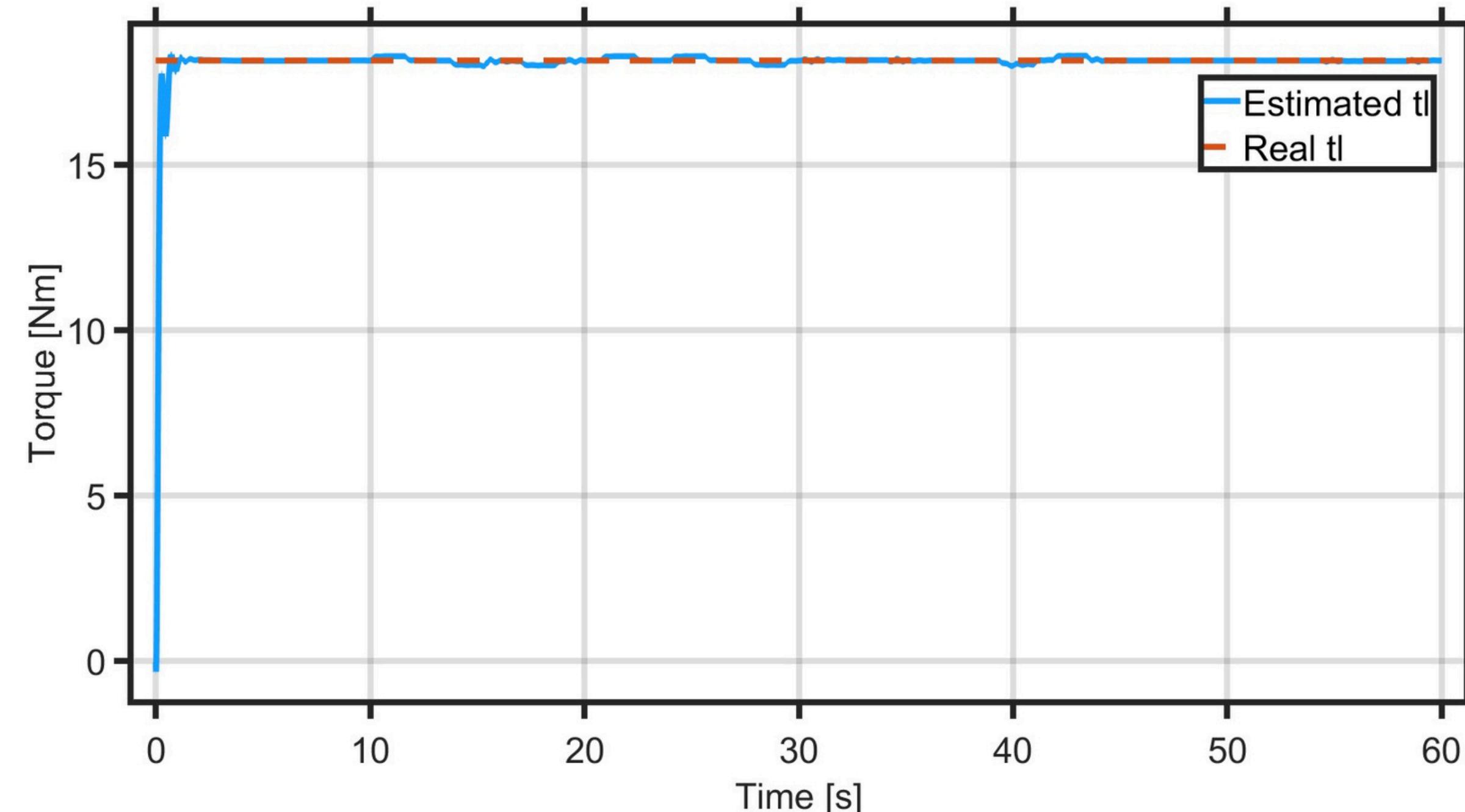
Position error of the fork





V. Simulation

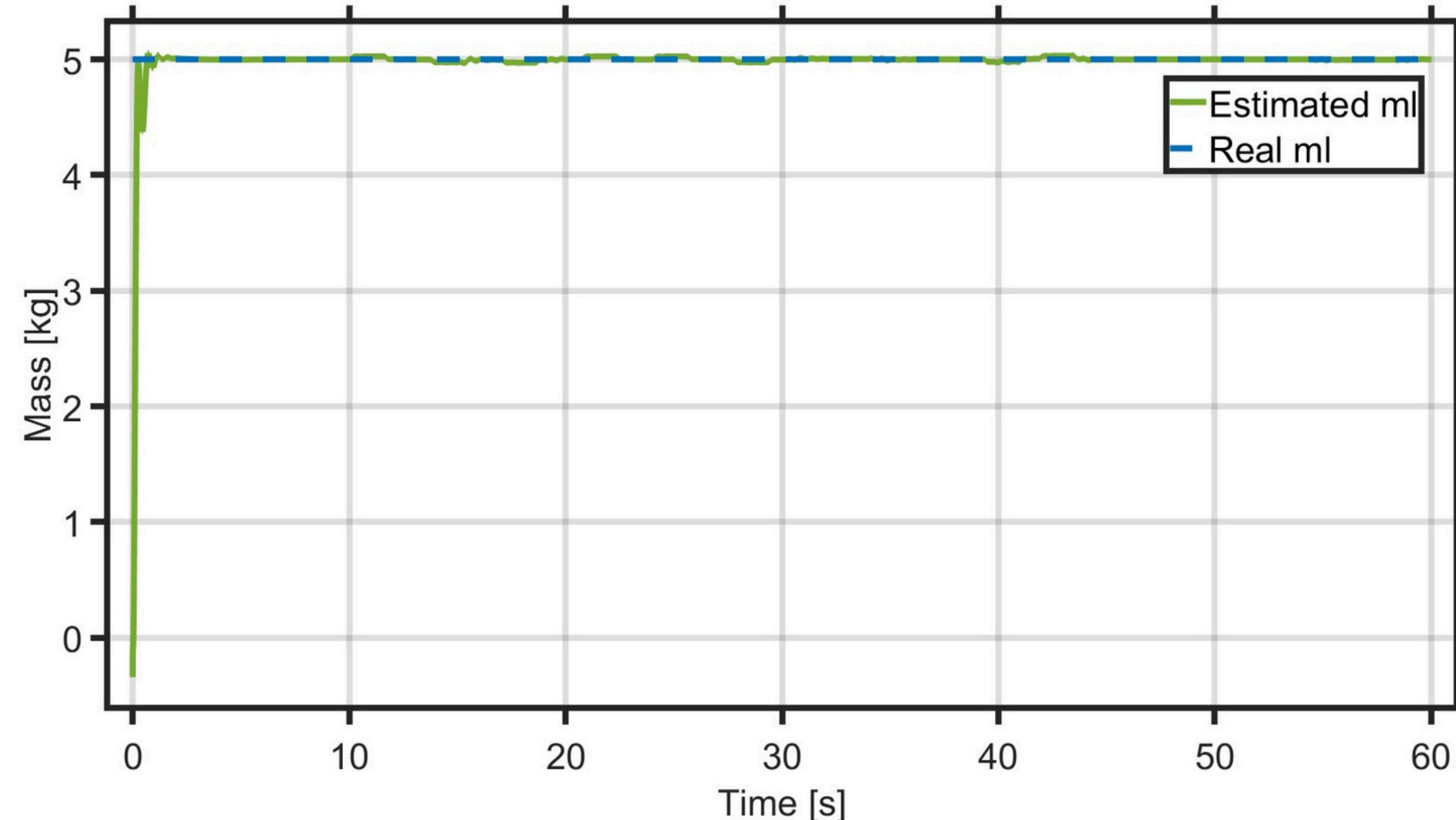
Estimated external torque over the fork (18.142Nm)





V. Simulation

Estimated mass of the external load (5kg)





VI. Conclusions and Future work

- The proposed motion planning and control strategies allow the TWFR to execute trajectories in the X and Z coordinate axes simultaneously with an admissible position error.
- The implementation of adaptive IK and ID solutions that depend on the estimation of physical properties of the external load provides great flexibility in industrial environments where it is not possible to control the variables of the load that will be manipulated.
- The next steps for this work are the construction of the lift subsystem and the physical implementation of the presented motion planning and control algorithms.

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