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# Modeling and simulation for heavy-duty mecanum wheel platform using model predictive control

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**Abstract.** This paper presents a study on a control system for a heavy-duty four Mecanum wheel platform. A mathematical model for the system is synthesized for the purpose of examining system behavior, including Mecanum wheel kinematics, AC servo motor, gearbox, and heavy duty load. The system is tested for velocity control, using model predictive control (MPC), and compared with a traditional PID setup. The parameters for the controllers are determined by manual tuning. Model predictive control was found to be more effective with reference to a linear velocity.

## 1. Introduction

The Mecanum wheel is an omni-directional wheel type, invented in 1973 by Bengt Illon with the Swedish company, Mecanum A.B. [1] The Mecanum wheel design incorporates passive rollers mounted at 45 degrees to the wheel plane around a solid axis. The roller design allows for free movement in any direction without changing orientation. In addition, the Mecanum wheel design also allows for free rotation around its central axis with a relatively low driving torque, as well as minimal friction.

Both of these features allow for good maneuverability in areas that are very constrained and do not allow traditional wheels to navigate. [2] They also have the same torque requirements as a traditional wheel setup. However, they do come at a tradeoff, which is less traction with the floor surface, causing them to slip at lower torque levels compared to traditional wheels. [3] They are also very susceptible to rough floors, which may affect their ability to travel in the desired direction.

Mecanum wheels have been used in a variety of applications. Recent uses have seen it in space exploration, where NASA has explored hazardous terrain exploration options with Mecanum robots. Driven by brushless servomotors, NASA's OmniBot allowed agile movements in 2 degrees of freedom. In areas where human personnel are unable to be deployed, the OmniBot's ability to navigate areas freely without being limited by conventional wheel limitations is very powerful. [4,5]



Commercial applications towards the usage of Mecanum wheels also exist. Airtrax Sidewinder ATX-3000 forklifts are a good example, where the forklift's usage of Mecanum omnidirectional wheels allows it to travel freely in tight spaces such as warehouses, though it has since halted production in 2013. [6]

The Mecanum wheels' usage in tight spaces allow for very specific uses in research environments as well. Malaysia's space agency, ANGKASA, has been exploring its usage in developing a satellite testing lifter platform. With total loads of up to 5 tons, the lifter platform is able to transport heavy satellite testing loads in a sterile clean room environment. With the application of Mecanum wheels, they were also able to achieve this in a very small area while minimizing shock with respect to the satellite's sensitive nature, which would have been normally very difficult with regular wheels. [13]

There have been many control schemes that have been presented for the Mecanum wheel platform. First, kinematics and dynamics are derived for a four-wheel setup, as in Tlale and de Villiers [7], and from there, we can use several methods. On the basic level, Viboonchaicheep et al. [8] have presented a position rectification control using Symptomatic Rectification (correction after inputs) and Preventive Rectification (indirect control parameter correction). More complete methods, which increase the effective maximum speed, include Lin and Shih, with nonlinear adaptive control with Lyapunov stability theory [9], as well as Tsai and Wu, with fuzzy control, through kinematic and joint-space dynamic modeling. [10]

This work focuses on proposing a simpler method, which will use a single Model Predictive Controller that reads a single velocity input and drives four servo outputs. The input is derived from the angular velocity of each of the four outputs. From the derivation of kinematics from the Mecanum wheel system as well as a simulation of an AC servo system, we can obtain a Mecanum wheel platform with linear and rotational velocity control using Model Predictive Control.

## 2. Modeling of Mobility System

### 2.1. AC Servomotor Equations.

From [11] and [12], we obtain the AC servomotor system, which consists of an AC motor coupled to a gearbox, as well as a load rigidly fixed to the output shaft.

Consider a motor, gearbox, and load with moments of inertia  $J_m$ ,  $J_g$  and  $J_l$ . The motor is driven by a input control field voltage in its stator, denoted by  $V_s$ , and has two electrical constants  $K_1$  and  $K_2$ .  $K_1$  is calculated from the motor's stall torque, in N.m., divided by its rated voltage, and  $K_2$  is calculated by its stall torque, in N.m., divided by its no-load speed at rated voltage in radians. The gearbox has a reduction ratio of  $N$  between the motor and the load. The load has a damping coefficient of  $c$ , in N.m.s/rad, and its angular displacement output is denoted as  $\theta_m$ .

The motor's rotational motion can then be described by the following nonlinear differential equation:

$$(J_m + J_g + \frac{1}{N^2} J_l) \frac{d^2 \theta_m}{dt^2} + c \frac{d \theta_m}{dt} = K_1 V_s - K_2 \frac{d \theta_m}{dt} \quad (1)$$

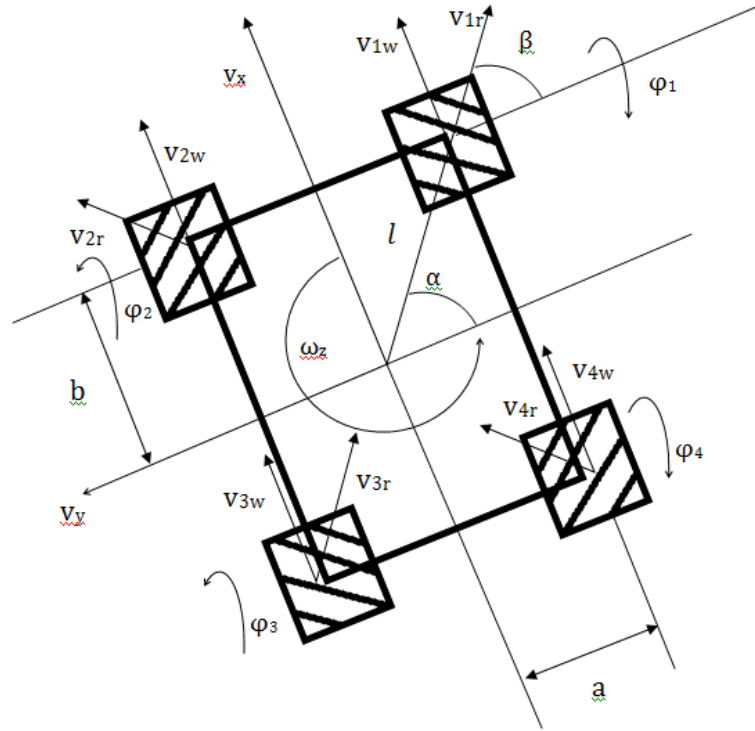


Figure 1. Configuration of Mecanum platform.

## 2.2. Mecanum Platform Equation.

Taking from [9], let the velocity in Cartesian coordinates be described as  $v_c = [v_x \ v_y \ \omega_z]^T \in \mathbb{R}^{3 \times 1}$  where  $v_x$  and  $v_y$  are the linear velocities and  $\omega_z$  is rotation about z-axis. The wheel angular velocities are described as  $\omega_w = [\phi_1 \ \phi_2 \ \phi_3 \ \phi_4]^T \in \mathbb{R}^{4 \times 1}$ , with rollers angled at  $\gamma = 45^\circ$  to the wheel axis, taken as clockwise looking outwards from the mounted frame as shown in Figure 1.

The wheels' linear velocities can be computed as  $v_w = r\omega_w \cos \gamma$ . Taking into consideration the Cartesian velocity vector,  $v_w$  can also be written as the following:

$$v_{wi} = r\omega_w \cos \gamma = [\sin(\alpha + \beta + \gamma) \quad -\cos(\alpha + \beta + \gamma) \quad -l \cos(\beta + \gamma)] [v_x \quad v_y \quad \omega_z]^T \quad (2)$$

Where  $\alpha$  is the angle between the geometric center of the platform and the wheel center,  $l$  is the distance between these positions, and  $\beta$  is the angle between the wheel axis and the line denoted by  $l$ . Main wheel radius is  $r$ . Let  $v_{ci} = [v_{xi} \ v_{yi} \ \omega_{zi}]^T \in \mathbb{R}^{3 \times 1}$ , where  $v_{ci}$  is the velocity in terms of inertial frame. The rotation matrix of the robot frame in terms of the inertia frame,  ${}^R R_i(\theta)$ , is as follows:

$${}^R R_i(\theta) = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (3)$$

Where  $\theta$  is the angle between the robot frame and inertial frame.  $v_c = {}^R R_i(\theta) v_{ci}$ . Assuming  $l$  and  $r$  are equal across all wheels, we can substitute the  $v_c$  term in  $v_w$  with  ${}^R R_i(\theta) v_{ci}$ . The  $\alpha$ ,  $\beta$  and  $\gamma$  values can be substituted for the following. Note that  $\tan^{-1}(\frac{b}{a}) = \alpha$ . Note that the derivation from [9] of the values in Table 1 is slightly different from this derivation, due to the modified configuration of the wheels, where this paper uses a diamond-like shape formation, and Lin and Shih use an X-shaped formation. All other derivations are the same.

Table 1. Wheel angular parameters.

Wheel	$\alpha$	$\beta$	$\gamma$
1	$\tan^{-1}(\frac{b}{a})$	$-\tan^{-1}(\frac{b}{a})$	$-(\pi/2 + \pi/4)$
2	$\pi - \tan^{-1}(\frac{b}{a})$	$\tan^{-1}(\frac{b}{a})$	$(\pi/2 + \pi/4)$
3	$\pi + \tan^{-1}(\frac{b}{a})$	$-\tan^{-1}(\frac{b}{a})$	$-(\pi/2 + \pi/4)$
4	$2\pi - \tan^{-1}(\frac{b}{a})$	$\tan^{-1}(\frac{b}{a})$	$(\pi/2 + \pi/4)$

The substitution allows us to find the inverse kinematics equation,

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{bmatrix} = -(\sqrt{2}/r) \begin{bmatrix} -\sqrt{2}/2 & \sqrt{2}/2 & l \sin(\pi/4 + \alpha) \\ -\sqrt{2}/2 & -\sqrt{2}/2 & l \sin(\pi/4 + \alpha) \\ \sqrt{2}/2 & -\sqrt{2}/2 & l \sin(\pi/4 + \alpha) \\ \sqrt{2}/2 & \sqrt{2}/2 & l \sin(\pi/4 + \alpha) \end{bmatrix} \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix}, \quad (4)$$

with the Jacobian defined as

$$J_0 = \begin{bmatrix} -\sqrt{2}/2 & \sqrt{2}/2 & l \sin(\pi/4 + \alpha) \\ -\sqrt{2}/2 & -\sqrt{2}/2 & l \sin(\pi/4 + \alpha) \\ \sqrt{2}/2 & -\sqrt{2}/2 & l \sin(\pi/4 + \alpha) \\ \sqrt{2}/2 & \sqrt{2}/2 & l \sin(\pi/4 + \alpha) \end{bmatrix} \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (5)$$

Obtaining the pseudoinverse of  $J_0$ , which is  $J_0^+$ , we can find the forward kinematics equation to put into the final model.

$$J_0^+ = (J_0^T J_0)^{-1} J_0^T. \quad (6)$$

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = -(\sqrt{2}/2)(r) J_0^+ \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{bmatrix}. \quad (7)$$

### 3. Simulation Performance Analysis between Model Predictive Control (MPC) and Proportional-Integral-Derivative (PID)

Model predictive control (MPC) is an advanced control method that uses a set of plant outputs, state variables, model functions and process variable references and restrictions in order to form a “current model” of the system. It uses the current model to form future predictions of a finite prediction horizon. Because of this, MPC is also termed as “receding horizon control”.

With this model, we have used Mathworks’ MPC Controller Simulink block in order to form a linearized model of the plant. From there, the operating points of the system are extracted and the plant is sampled discretely with a period of 0.1s, prediction horizon of 1s, and a total run length of 10s. In addition, the MPC is compared against a PID model using PI controller. Both control methods were tuned to have almost zero overshoot and as low of a response time as possible. The reference value was a set linear velocity of 0.083m/s, or 5m/min.

Final value of PI controller are  $P = 5.28$  and  $I = 19.5013$ . Table 2 shows the reference values used in simulating the model, taken from actual servos and figures from a proposed heavy-duty Mecanum wheel platform. The values are taken from servomotor SANYODENKI R2AAB8100FXP11, and gearbox SEW-EURODRIVE K87AQA115/1.

Table 2. Reference values in simulation.

<b>Servo Rotor Moment (kg.m<sup>2</sup>)</b>	$6.7 \cdot 10^{-4}$	<b>Gearbox Ratio</b>	197.37
<b>Gearbox Moment (kg.m<sup>2</sup>)</b>	$1.4 \cdot 10^{-4}$	<b>Stall Torque over Rated Voltage (Nm/V)</b>	$1.736 \cdot 10^{-2}$
<b>Wheel Moment (kg.m<sup>2</sup>)</b>	3.987	<b>Stall Torque over No-Load Speed (Nm/rad)</b>	$1.216 \cdot 10^{-2}$
<b>Platform Moment (kg.m<sup>2</sup>)</b>	61.935	<b>Wheel Radius (m)</b>	0.2032
<b>Mass of Platform without Wheels (kg)</b>	6000	<b>Mass of Wheel (kg)</b>	165.283
<b>Wheel Axle Width (m)</b>	1.5	<b>Wheel Axle Spacing (m)</b>	3.15

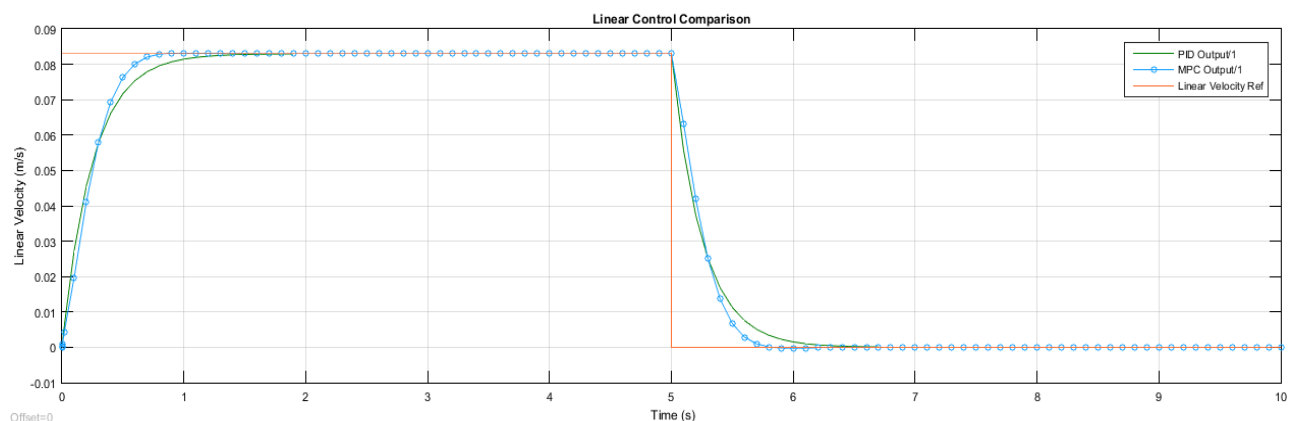


Figure 2. Linear velocity comparison between MPC and PID controller.

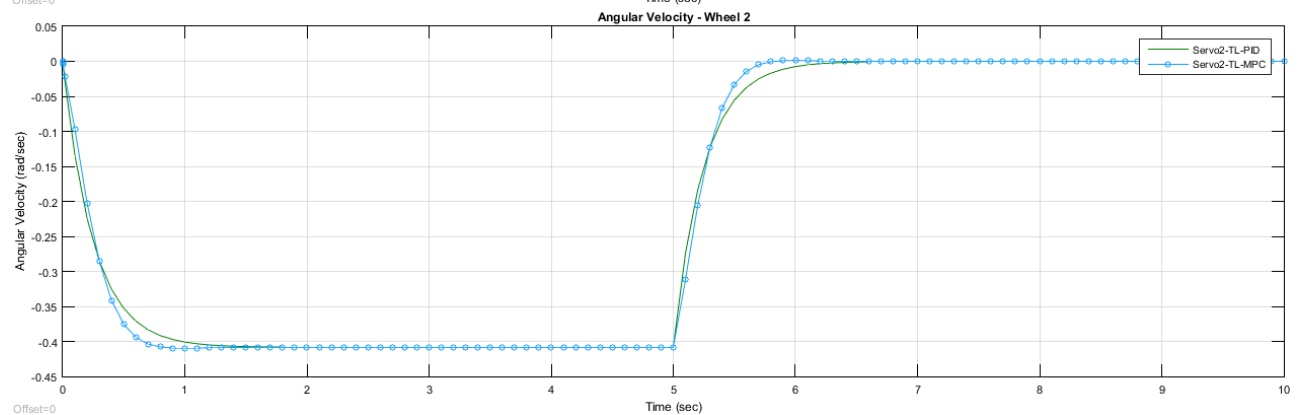
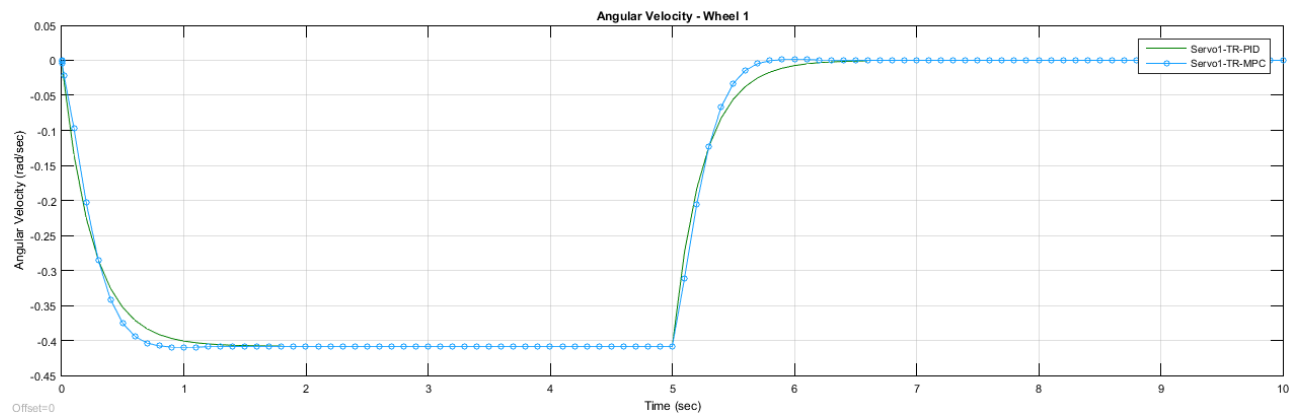


Figure 3(a) and (b). Angular velocity comparison between MPC and PID controller for front wheels on the right and left respectively.

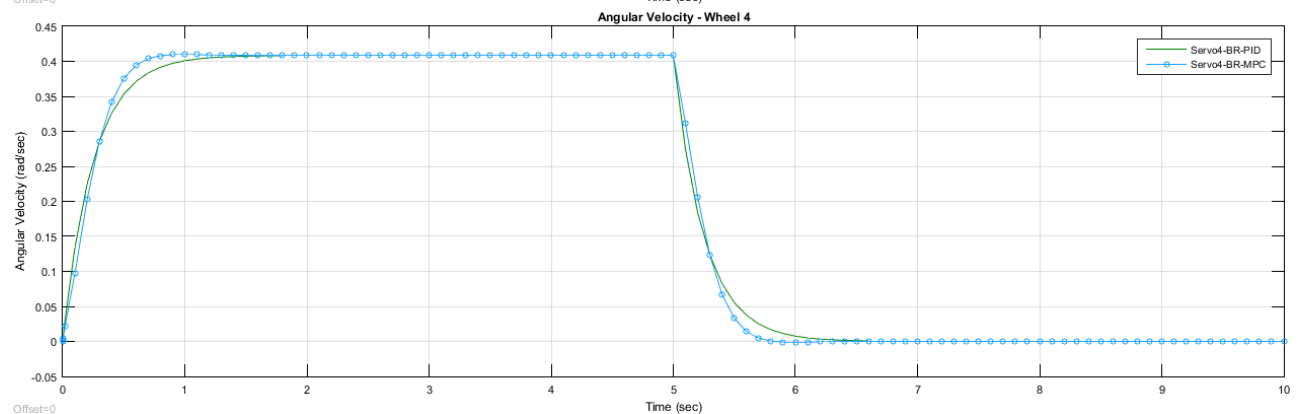
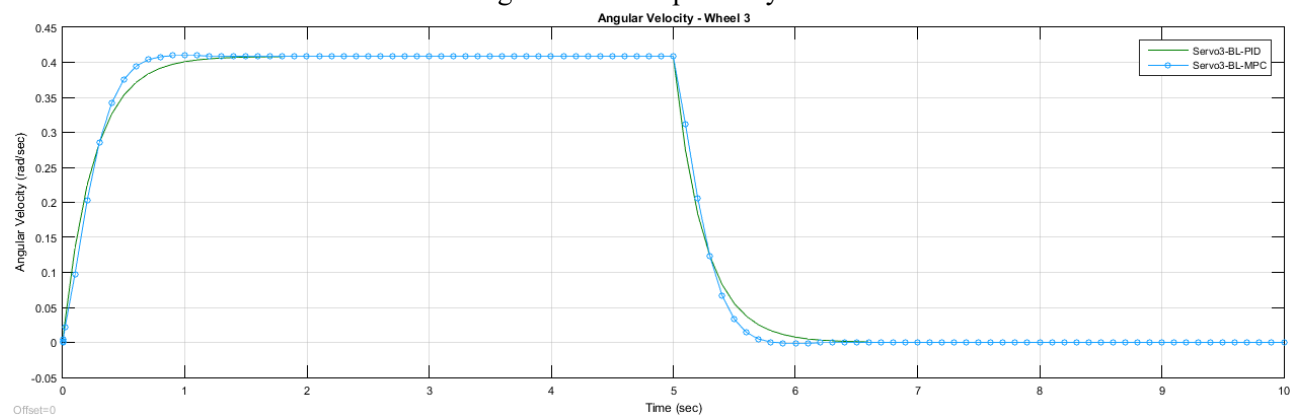




Figure 3(c) and (d). Angular velocity comparison between MPC and PID controller for rear wheels on the left and right respectively.

Figure 2 and Figure 3 shows the method in which the simulation was tested, where the controller simulated a desired velocity in the X-direction for the reference value of 0.083m/s for 5 seconds, and 0m/s for 5 seconds thereafter. As seen in the figures, the MPC control reaches the target velocity faster than the PID control by roughly 1 second. The limitation of this study is that there is no dynamics analysis, due to the very low speed tested for the platform. Factors such as frictional force reducing the speed were not taken into account.

#### 4. Conclusion

In this paper, a mathematical model was derived for the kinematics of a Mecanum wheel platform driven by AC servomotors coupled to a gearbox and load. Two controller methods are tested: Model Predictive Control (MPC) and PID control.

Tuning was done automatically using computer simulation, and a test with velocity tracking was used to illustrate the difference between MPC and PID control. MPC controller was shown to have a more robust response compared to PID controller. In coming studies, more controller types can be tested, including Non-Linear Model Predictive Control (NMPC).

Finally, we would like to thank Mr. Dan Fisher, University of St. Thomas, Minnesota, USA, for helping us with the basic Mecanum wheel structure simulations.

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