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DESIGN PROCESS OF A MASTER CONTROLLER FOR ELECTRIC OMNIDIRECTIONAL PLATFORMS

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Abstract. The need vehicles able to move or park easily in narrow or cluttered halls, along with the progress in matter of motors, batteries and controllers applied to electric vehicles has supported the development of electric omnidirectional vehicles, in robotics, industrial and health fields.
The solutions currently found in the market generally integrate all the electrical/mechanical components and do not offer an option of a master controller compatible with different omnidirectional platforms.
A master controller for electric omnidirectional platforms adaptable to a wide range of usage conditions and mechanical power requirements, would be an interesting component for design purposes at academic level, where engineering students could understand how design variables are related to the component selection.
This article presents the design process of a master controller for this kind of vehicles and the procedure for determining its parameters and the specifications for electric motors required on different platforms that will have different mechanical power requirements and use conditions. First, specific characteristic for a general platform have been defined, the kinematic behavior has been characterized and next, a simulation model has been configured and tested with a real platform in order to identify the real behavior or the master controller.

Introduction

The need of emission-free and quiet vehicles, along with the progress in matter of electric motors, batteries and controllers have supported the development of electric vehicles. Since 2009, students of the Product Design Engineering Program, at EAFIT University, Medellín, Colombia; have been involved in a course to develop an electric vehicle prototype, in order to understand how the design features determine the selection of the used components. Besides, the need of a vehicle able to dodge obstacles, and park easily in narrow or cluttered halls is a challenge for mobility products designers who are looking for reliable, user friendly and low cost products. There are commercial and academic products that use holonomic wheels such as forklifts, wheelchairs and small autonomous robots, but these solutions integrate all electrical and mechanical components, are very expensive and do not offer an option of a master controller compatible with different omnidirectional platforms.

This motivates the development of a master controller, determining its parameters and also the specifications for electric motors, required on different platforms that will have different mechanical power requirements and use conditions. All platforms use four Mecanum wheels and four electric BLDC motors. On chapter 2 the design process for vehicle configuration and its principal components is presented. Mathematic models for kinematic behavior using differential equations, space state representation, and a brief dynamic behavior analysis and motor selection process is presented on chapter 3. Master controller function and the simulation results are stated on chapter 4. Finally chapter 5 states the conclusions.

Design Process for Vehicle Configuration

The design process started looking for state of the art. The information found about omnidirectional products with three, four or more Mecanum, universal omnidirectional, spherical or omni-disc wheels [1], [2], [3], [4], [5] was used.

Omnidirectional Platform. The designed platforms have four Mecanum type wheels arranged in mirrored pairs. Greater stability and payload is achieved in this way and although being an over-determined system. The platforms supports the bodywork of the vehicle which can be changed depending on the application and context of use. All platforms use the following components, whose specifications change depending on power mechanics requirements.

Mecanum wheels

These wheels were chosen because it is possible to make omnidirectional movements without complex direction systems in specific arrangements by controlling speed and rotation direction of each wheel independently. When defining the context where the platform will be used, it must be considered that these wheels have little tolerance to not uniform surfaces, because the diameter of the rollers defines the maximum tread that the vehicle can overcome. Besides, the contact point with the ground is in the roller, which means that the entire load applies pressure to that point, causing slide due to low friction. It is of utmost importance to make sure that all the wheels keep on contact with the surface, this involves the use of suspension in vehicles with more than three wheels and distributing the load trying to match the center of mass with the geometric center and also trying to make the center of mass as low as possible.

BLDC motors (Brushless DC)

For mechanical power between 200 and 2000 watts, the BLDC motors were chosen because they offered a good velocity-torque ratio (almost flat within the operation range), great dynamic response, high efficiency, superior durability, low noise. They are able to functionality in a wide range of velocity and the low cost compared to other types of electric motors with less than 2 KW of power. The selected range meets the power requirement used in prototypes of academic projects.

Velocity controllers for each BLDC motor

When selecting the controller, were considered: input for the signal of both clockwise and counter-clockwise, and for the reference speed signal, which can be in RS232, and/or analog voltage, and/or CANbus. Besides it is necessary allow closed loop control of the motor's torque at the desired velocity within its operation range [9].

Batteries

Chosen batteries are Lithium iron phosphate battery ($LiFePO_4$), because of their power density, price, reliability and high battery life.

Kinematic Behavior.

Differential equations

The coordinate system are illustrated on Figure 1. The equations of kinematic behavior [3], [5], [6], [7], [8], were used to obtain mathematic representation models. The velocity of each wheel is expressed in terms of the velocity of the vehicle (1) and the velocity of the vehicle can be determined knowing the velocity of the wheels (2):

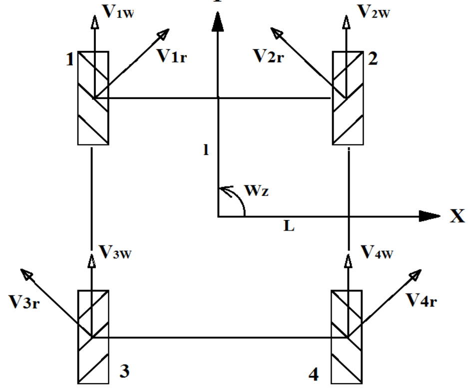

Figure 1

$$\begin{bmatrix} V_{1W} \\ V_{2W} \\ V_{3W} \\ V_{4W} \end{bmatrix} = \begin{bmatrix} 1 & 1 & -(L+l) \\ -1 & 1 & (L+l) \\ -1 & 1 & -(L+l) \\ 1 & 1 & (L+l) \end{bmatrix} * \begin{bmatrix} V_X \\ V_Y \\ \omega_Z \end{bmatrix} \quad (1) \qquad \begin{bmatrix} V_X \\ V_Y \\ \omega_Z \end{bmatrix} = \frac{1}{4} \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 \\ \frac{-1}{L+l} & \frac{1}{L+l} & \frac{-1}{L+l} & \frac{1}{L+l} \end{bmatrix} * \begin{bmatrix} R\omega_1 \\ R\omega_2 \\ R\omega_3 \\ R\omega_4 \end{bmatrix} \quad (2)$$

where V_{iW} (m/s) is the tangential velocity on each wheel, being *i* the wheel number; defined by the equation $V_{iw}=\omega_{iw}*R_w$, R_W= R (m) is the radius of each of the four wheels, ω_{iw} (rad/s) is the angular velocity of each wheel, V_{ir} (m/s) is the tangential velocity of the roller in contact with the surface in each wheel, L and l (m) are the X and Y components of the distance from the center of the wheel to the center of the vehicle respectively. V_X (m/s), V_Y (m/s) and ω_Z (rad/s) are the X, Y and Z component of the vehicle's velocity.

Space State representation

Using time derivates of equations (2), the space state representation for the vehicle are obtained:

$$\dot{X} = AX + BU$$
$$Y = CX + DU$$

$$\dot{X} = \begin{bmatrix} a_X \\ a_Y \\ a_Z \end{bmatrix} \quad X = \begin{bmatrix} V_X \\ V_Y \\ \omega_Z \end{bmatrix} \quad Y = \begin{bmatrix} V_X \\ V_Y \\ \omega_Z \end{bmatrix} \quad U = \begin{bmatrix} \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\omega}_3 \\ \dot{\omega}_4 \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad B = \frac{R}{4} \begin{bmatrix} 1 & -1 & -1 & 1 \\ 1 & 1 & 1 & 1 \\ \frac{-1}{(L+l)} & \frac{1}{(L+l)} & \frac{-1}{(L+l)} & \frac{1}{(L+l)} \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (3)$$

Where, a_X (m/s^2), a_Y (m/s^2), a_Z (rad/s^2) are X, Y, Z component of the vehicle's acceleration.

Dynamic Behavior. The dynamic behavior model [3], [6] and the electric motor's fundamentals [9], were used to determine electric motors specifications.

Force analysys

The force analysys of the Mecanum wheel vehicle [1], shows that: a) If the vehicle moves in ±X or ±Y direction and the vehicle's velocity is equal to the wheel's tangential velocity (speed is equal for all wheels), due to the roller´s tilted angle, wheel force must be total force divided by 4 and multiplied by √2. If the wheels are not Mecanum, and if the vehicle tries to move in ±Y direction, force in each wheel is total force divided by 4. b) If the vehicle moves diagonally in direction X, Y and the vehicle's velocity is equal to half wheel tangential velocity (speed is equal for two wheels and is zero for the others two wheels), force in each active wheel will be the total force divided by 2 and multiplied by √2

Motor selection process

This selection considers: Total weight to move, maximum velocity, minimum time to accelerate, Mecanum wheels' coefficient of friction and maximum slope to be transited.

Four different motors for total weight to be moved are considered: 200, 400, 1000 and 1200 Kg. All platforms must be able to climb a 4.8° ramp at 2.22 m/s with maximum and they must also be able to move in a horizontal ground at 2.78 m/s with a maximum time of 3 s to accelerate. All platforms use 8" diameter Mecanum wheels with 12 rollers, made of urethane exterior. With these data, required torque and angular speed in each wheel are calculated and the motor's manufacturer specifications are used to define each motor and its gear transmission system.

This analysis is about movements of translation and does not spin movements, therefore it does not consider moment of inertia around Z axis, neither the distances to geometer and mass center of the platform.

Master controller

Information about controllers for ominidirectional robots or platforms [3], [7], [10], [11] was considered, and based on this information and on the simulation analysis it was decided to develop the master controller.

The Master controller delivers the reference speed signals and the clockwise and counter-clockwise spin signals for the controllers of each one of the BLDC motors. The purpose of this controller is to assure the absence of errors on the stationary state of the velocity V_X, V_Y, ω_z, making the controller effort doable and minimizing settling time (therefore the error in directions X, Y, Z during transitory state) even if there are perturbations.

If ω1=ω2=ω3=ω4=ω, just eleven operation modes will be defined, depending on the angular velocities of the four motors. Each operation mode corresponds to the combination of the angular velocities of the four motors and according to the results in 0, the whole vehicle's behavior for each operation mode is presented in Table 1.

Table 1

	ω_1 [rad/s]	ω_2 [rad/s]	ω_3 [rad/s]	ω_4 [rad/s]	V_X [m/s]	V_Y [m/s]	ω_z [rad/s]
1. Stopped	0	0	0	0	0	0	0
2. Moves north	ω	ω	ω	ω	0	ω*R	0
3. Moves south	-ω	-ω	-ω	-ω	0	-ω*R	0
4. Moves east	ω	-ω	-ω	ω	ω*R	0	0
5. Moves west	-ω	ω	ω	-ω	-ω*R	0	0
6. Moves north-east	ω	0	0	ω	ω*R/2	ω*R/2	0
7. Moves south-east	0	-ω	-ω	0	ω*R/2	ω*R/2	0
8. Moves north-west	0	ω	ω	0	ω*R/2	ω*R/2	0
9. Moves south-west	-ω	0	0	-ω	ω*R/2	ω*R/2	0
10. Clockwise	ω	-ω	ω	-ω	0	0	ω*R/(L+l)
11. Counter clockwise spin	-ω	ω	-ω	ω	0	0	ω*R/(L+l)

Maximum translation velocity of the platform is different if it moves in X, Y or diagonally which results in an anisotropic movement. For the cases where the speed magnitude is equal for all wheels, $|V_X|$ or $|V_Y|$ are equal to $|V_W|$ if the platform moves north, south, east or west. For the cases where only two wheels are active and have the same speed magnitude, $|V_X|$ and $|V_Y|$ are equal to $|V_W/2|$ if the platform moves north-east, north-west, south-east or south-west.

System Simulation

On the basis of the kinematic behavior and using Simulink (graphical programming language tool of Matlab), the system was simulated in order to determine the master controller.

Differential Equations Representation. According to the kinematic model, the system is linear with multiple inputs and multiple outputs (MIMO) and the subsystem of the BLDC motor and its controller approximate to be linear. It is observed in the simulations that for step type perturbations on the angular velocity of the motors, the error in stationary state of the outputs V_X, V_Y, ω_Z, remains constant, and for ramp type perturbations the error in the stationary state tends to infinite, which means that the system is type 0.

Sensitivity analysis to perturbations

The sensitivity analysis to perturbations is made for the outputs (V_X, V_Y, ω_Z), during a simulation of 100 seconds in various of the possible states with step type perturbations of ±5% in amplitude of the angular velocity of the motors.

This analysis does not consider dynamic conditions such as friction, wheel sliding or inadequate distribution of the load which leads to a different mass center that does not match the geometric center of the vehicle or variation in the parameters of the system (for example different radius of the wheels or variation in the distances from the center of the wheels to the center of the coordinate system).

In order to improve the response of the vehicle and decrease the sensitivity to this type of perturbations, a PID controller will be used for each of the motor's velocity signal.

PID Controller tuning

For the PID controller tuning the sensitivity model of Ziegler-Nichols [8] is used, finding that the V_X, V_Y, ω_Z does not oscillate even with a gain of K=50000, and K=100 is the minimum gain in which the stationary error for V_X, V_Y, ω_Z is equal a 1%.
Using Simulink PID Tuner tool, many combinations of the Kp, Ti and Td values were tested for combined perturbations of ±5% in the angular velocities of the motors. With the controller parameters Kp=0.330, Ti=2.444, Td=0 the error on V_X, V_Y and ω_Z is zero for stationary state and the settling time is 2s. Table 2 shows for stationary state, the error in V_X, V_Y and ω_Z and control effort in reference speed signal for motors, when this PID Master controller was used.

Master controller configuration

In order to control the vehicle it is necessary to have closed loop control of the angular velocities of each motor, so the Master controller must have the angular velocities of each motor as input. Optic rotatory encoders are used for these signals.

This control is designed to be integrated with the motor controllers.

The inputs of the Master controller are: a) Joystick signal for X,Y direction vehicle´s movement. b) Joystick signal for Z spin direction. c) Vehicle reference speed signal. d) Sensor signals to determine angular velocity of all wheels. The outputs are: a) Speed signal for the controllers of all motors. b) Rotation direction signal for the controllers of all motors.

Space State Representation. According with the model, the system is linear with MIMO and time-invariant.

Stability analysis, controllability and observability

With eigenvalues of matrix A it is possible to know the system´s stability. The following eigenvalues were obtained: eig(A)= [0;0;0]. That confirms that vehicle is not stable (asymptotically stable).

Rank of the matrix mc=[B A*B A^2*B] shows system´s controllability. In this case, the value obtained is: rank(mc)=3, then vehicle is controllable.
Rank of matrix mo=[C; CA; CA^2] shows system´s observability. In this case, the value obtained is: rank(mo)=3, then the vehicle is observable.

Feedback control

Simulations with poles placement shows that response time in V_X, V_Y, ω_Z, for variations of ±5% on V_X, V_Y, ω_Z are reduced when poles moves towards the left half plane. It also shows that only proportional action is not possible due to singularity in the kinematic model. But, proportional integral action in state feedback is possible. Matrix K and L are determined using Matlab´s place function, using matrices AA, BB and PP.

$$AA = \begin{bmatrix} A & 0 \\ -C & I \end{bmatrix}, BB = \begin{bmatrix} B \\ 0 \end{bmatrix}, PP = \begin{bmatrix} -0{,}5 \\ -0{,}5001 \\ -0{,}5002 \\ -0{,}5003 \\ -0{,}5004 \\ -0{,}5005 \end{bmatrix}, \quad L = 2.2514 \begin{bmatrix} -1 & -1 & 1 \\ 1 & -1 & -1 \\ 1 & -1 & 1 \\ -1 & -1 & -1 \end{bmatrix}, K = 2{,}0003 \begin{bmatrix} 1{,}0003 & 1 & -1 \\ -1{,}0003 & 1 & 1 \\ -1{,}0003 & 1 & -1 \\ 1{,}0003 & 1 & 1 \end{bmatrix} \quad (4)$$

Many poles PP and therefore different K and L factor were tested with different perturbations of ±5% in the velocities of the vehicle, concluding if poles (PP) move to left semiplane, overshoot in V_X, V_Y, ω_Z and overshoot in reference speed signal for motors decreases.

With matrix K and L indicated, the error on V_X, V_Y and ω_Z is zero for stationary state and the settling time is 1.5s. Table 2 shows for stationary state the error in V_X, V_Y and ω_Z and control effort in reference speed signal for motors, when is used these proportional integral action in state feedback Master controller.

Table 2

Perturbation	Error in stationary state VX and/or VY and/or ωZ		Variations in Reference Speed (control effort)	
Master controller	Without Master Controller	With Master Controller	In motor(s) with perturbation	In motor(s) without perturbation
Four PI				
-5% in one wheel´s velocity	up to -1.25%	0	5%	0
-5% in two wheel´s velocity	up to -2.50%	0	5%	0
-5% in three wheel´s velocity	up to -3,75%	0	5%	0
-5% in four wheel´s velocity	up to -5.00%	0	5%	0
PI in state feedback				
-5% in one vehicle´s velocity	up to -5%	0	up to ±5%	
-5% in two vehicle´s velocity	up to -5%	0	up to ±10%	
-5% in three vehicle´s velocity	up to -5%	0	up to ±15%	

Master Controller Configuration. In order to control the vehicle it is necessary to have proportional-integral action in state feedback control of vehicle's velocities, V_X, V_Y, ω_Z. This control is designed to be integrated with the motor's controllers. The inputs of the Master controller are: X,Y direction movement joystick signal, Z spin direction joystick signal, Vehicle speed signal, Vehicle velocities V_X, V_Y, ω_Z. The outputs are: Speed and rotation direction signal for the controllers of the four motors.

Conclusions

Using a Master controller composed by four PI controllers, that has speed and rotation direction signals as outputs to each of the motor controllers and input the angular velocity of the motors feedback signal is possible to achieve required vehicle´s speed even with perturbations of ±5% in the angular velocities of the motors. The control effort depends of the value of perturbation, for example if the perturbation is equal to ±5% in one motor, the control effort changes ±5% in this motor and if the perturbation is equal to ±5% in two motor, the control effort changes ±5% in these. Even with the power limit of the real motors, this control effort is not always possible, because even if the signal is increased the motor will not be able to increase the output velocity.

Using a Master controller with proportional integral action in state feedback control, that has speed and rotation direction signals as outputs to each of the motor controllers and with vehicle velocity feedback signal V_X, V_Y, ω_Z, it is possible to achieve required vehicle´s speed even with perturbations of ±5%. Depending on operation mode and perturbation combination, the control effort changes in all motors even in those motors without perturbation. For example if the perturbation is equal to ±5% in one vehicle´s direction, the control effort changes ±5% in all motors and if the perturbation is equal to ±5% in two vehicle´s direction, the control effort changes up to ±10% in two of the motors and if the perturbation is equal to ±5% in three vehicle´s direction, the control effort changes up to ±15% in one of the motors and ±5% in the rest of motors. But, this is a problem, because a BLDC motor is not able to move at a 2.5% of its maximum velocity.

At the moment of implementation, to avoid a non-doable control effort due to the power limit of the motor the kinematic and dynamic behavior of each motor must be known. This means knowing the maximum velocity of each motor both clockwise and counter-clockwise, to adjust the maximum reference velocity according to the minor reference of the four motors in both directions. Besides, due to this simulation analysis only uses the kinematic model, the parameters of the master controller do not change if the requirements of mechanical power change. However, issues such as slip of the rollers and frictional forces will make necessary to change the parameters of the PID. Next step is to build both of the platforms with different physical, mechanical and electric specifications, and test them with the same master controller and verify PID parameters

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