CONCEPTUAL DESIGN OF AUTONOMOUS CART FOLLOWER FOR WHEELCHAIR USER

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ABSTRACT

This paper focuses on kinematics of the cart follower and the system identification of propulsion system by using brushed DC motor. The cart follower uses Ackermann configuration as the steering system. The modeling of kinematics equation takes into account the instantaneous center of rotation (ICR), velocity of each tire, heading angle, and simple movement of the cart. The cart is propelled by transaxle brushed DC motor. It is important to approximate an accurate transfer function to represent the motor as the plant module is unavailable. The motor is simulated by using Arduino hardware package in MATLAB®. Rotary encoder is used to record the angular velocity of the shaft. MATLAB® code is created in order to calculate the linear velocity and tabulate the datasets. System Identification Toolbox determines the transfer function of the motor and its performance. The variables measured in experiment to identify the transfer function of the DC motor system are output angular velocity and input voltage. The parameters taken from the DC motor's mathematical model are derived based on existing literatures. The graph of output velocity against time is plotted and the transfer function is estimated by using System Identification Toolbox in MATLAB®. From the results, it is demonstrated that the motor exhibits second order system.

Keywords: *Cart follower, wheel mobile robot, kinematics, system identification*

INTRODUCTION

This article presents the design and modelling of cart follower for the wheelchair user. Wheelchair users often have restrictions in carrying luggage; therefore, this cart following system is proposed in order to assist the wheelchair users in carrying their luggage. The designing of cart follower is divided into several constituents such as chassis, main body, steering system, tracking system, and the driving system. The designed cart follower system can be categorised as a wheeled mobile robot follower.

The wheeled mobile robot is a robot that depends on the friction force between its wheels and the contact surface to move [1]. Commonly used types of tires for the wheeled mobile robot are the standard wheels, Swedish wheels, castor wheels and also spherical wheels [2].

Kinematics equation of a wheeled mobile robot is the relationship between the motion and the physical of the robot. Kinematics modelling is important for motion planning and movement of the wheeled mobile robot [3].

The purpose of the steering mechanism is to facilitate the manoeuvrability of the wheeled mobile robot. For a four-wheeled vehicle, the best steering system is Ackermann configuration as it will cause the vehicle turning without any wheel shift [4]. Usually, for the non-holonomic robot, the motion involved in the pure translation (forward and backward movement) and combination of rotation and translation (turning) [5].

Ackermann configuration steering system is used in this work. The cart has two-front steerable standard wheels, and two-rear fix standard wheels to drive it.

The proposed cart follower will be moved by using a transaxle brushed DC motor. DC motor is one of the most common usable motors in various industrial fields due to its good performance and non-complex speed control [6]. The cost of a brushed DC motor is considered low compared with other types of DC motor. The DC motor should be able to achieve a desirable speed at a certain time [7]. One of the major problems is in enhancing the performance of the motor since manufacturers usually not providing sufficient data to the user.

Accurate transfer function estimation is important to design a good controller to improve motor performance. The experimental approach is needed as the plant module is unavailable. There are a lot of experimental methods introduced by scholars to investigate the parameters of the motor.

Due to low cost and simplicity, a bump test approach is conducted where constant voltage is supplied until the motor velocity reaches equilibrium. The estimation of the transfer function based on time-domain collected data is computed by System Identification Toolbox (MATLAB®).

There are various methods have been conducted to obtain parameters of DC motors such as identification based on Taylor series expansion method, state-space identification method, algebraic parameter estimation method, recursive least squares method, inverse problem method, and moment method. Parameter identification based on the Taylor Series expansion approach is dependent on motor input and output. The link between Taylor series coefficient and decided parameters is created. The motor is subjected to a constant voltage to obtain the response. The parameter is calculated based on the coefficient established in the modelling section [8].

State-space identification technique requires researchers to have a good mathematical modelling and control system theory knowledge. By using the state-space identification method, an experiment is conducted in order to approximate the parameters of a second-order state-space system. The parameter based on modelled equation such as armature Resistance, armature inductance, the moment of inertia, counter electromotive constant, and torque constant is determined by experiment [9].

Algebraic parameter estimation implements module theory, differential algebra and operational calculus. The parameters that are measured experimentally are the input voltage and the motor position. Motor parameters such as a moment of inertia, viscous friction, velocity and acceleration, and Coulomb's friction coefficient are calculated simultaneously on-line and in real-time. The advantages of this method are that it is not dependent on the motor input and output, and the noise occurred in experimental data sets [10].

The drawback of methods such as state-space identification and algebraic method is it involves high usage of a complex mathematical approach. This article attempts to apply a direct approach to determining the motor's transfer function. By using basic mathematical modelling, direct experimental approach, and minimal coding in MATLAB®, a good approximation of the transfer function of the DC motor can be determined.

The objectives of this paper are to design the cart follower for wheelchair users conceptually, to define the mechanism of the cart follower, and to identify the plant of brushed DC motor that drives the cart follower.

CONCEPTUAL DESIGN OF CART FOLLOWER

The 3D drawing and orthographic view drawing illustrated by using CATIA software (Version 2.0, 2016). The main mechanical structure of the cart follower is the body, chassis, driving and steering system. The cart follows the wheelchair by using colour tracking method. The colour tracking technique for this work was discussed by Ahmad et al. [7], [11]-13].

The conceptual 3D design illustrated in Figure 1 below. The cart has a length of 800 mm, a width of 367 mm, a height of 400 mm and a tire diameter of 150 mm. The 2D orthographic drawing is represented in Figure 2. The cart is steered by using Ackermann configuration that used two steerable front wheels. The rear wheels are connected to the transaxle motor to drive the cart follower.

CONCEPTUAL DESIGN OF CART FOLLOWER

Figure 3 depicts the global and local coordinates of the cart follower in the Ackermann steering configuration.

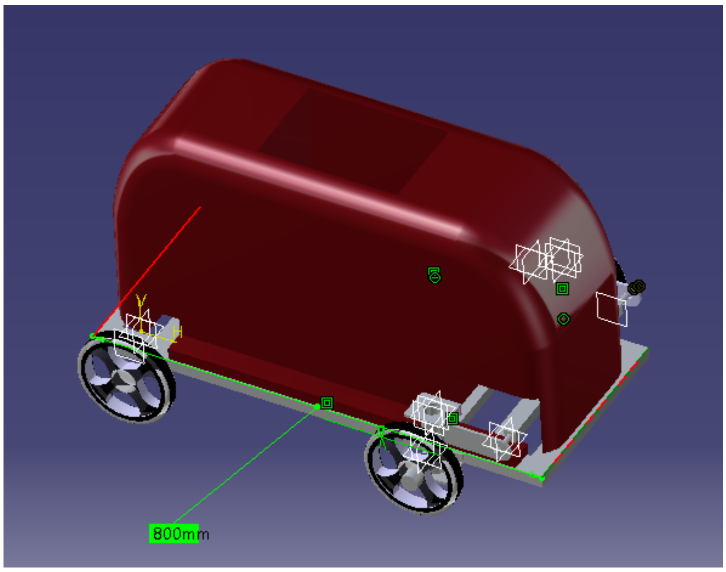

Figure 1 3D conceptual design of cart follower

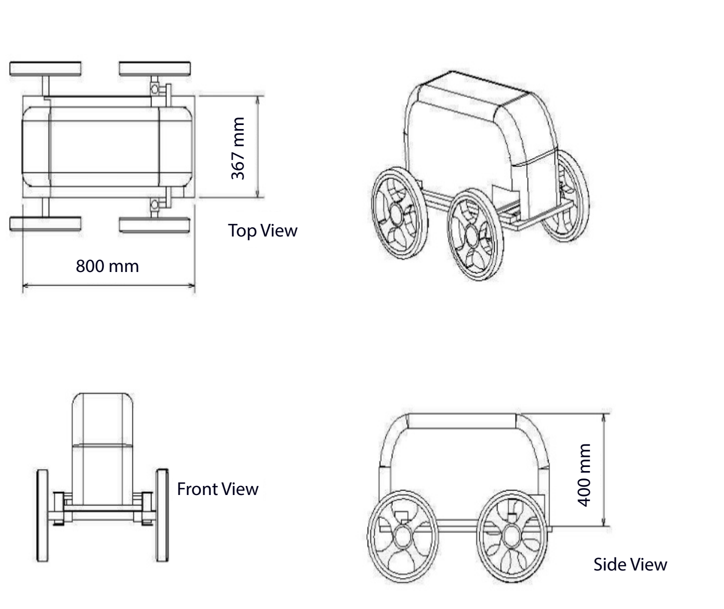

Figure 2 2D drawings of cart follower

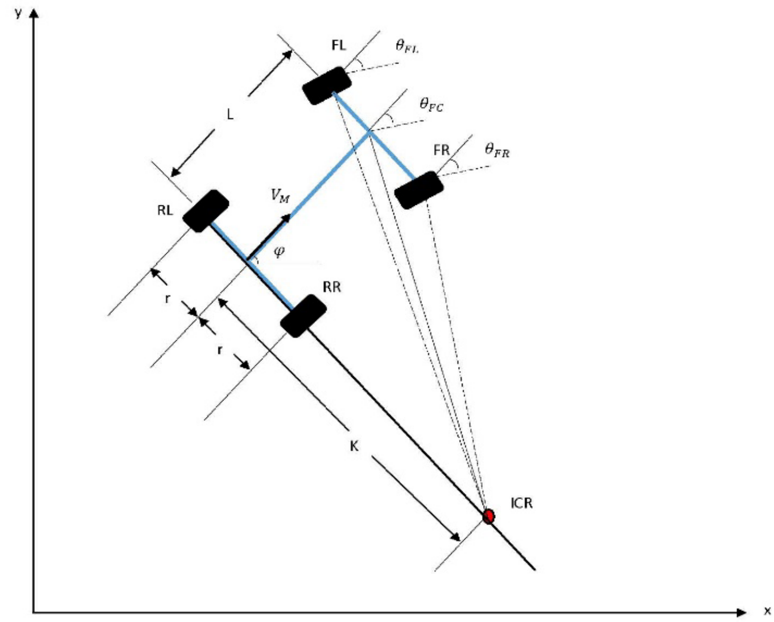

Figure 3 Kinematics of cart follower with Ackermann steering configuration

The notations used in the kinematics equation derivation are as follow:

ICR: Instantaneous Center of Rotation
φ: Heading angle based on the x-axis in global coordinate.
K: Turning radius of the cart
FL: Front Left wheel
FR: Front Right Wheel
RL: Rear Left Wheel

$$d\omega_M = K.d\varphi \tag{1}$$

$$K = \frac{L}{tan(\theta_{FC})} \tag{2}$$

$$d\varphi = \frac{tan(\theta_{FC})}{L}.d\omega_M \tag{3}$$

Equation 3 is divided by *dt* to obtain the $\acute{\varphi}$:

$$\dot{\varphi} = \frac{tan(\theta_{FC})}{L}.\dot{\omega}_M \tag{4}$$

$$\acute{\varphi} = \omega_M = V_M.\frac{tan\ (\theta_{FC})}{L} \tag{5}$$

Kinematic Equations of the cart based on global coordinate is as follow:

$$\dot{X} = V_M cos\varphi \tag{6}$$

$$\dot{Y} = V_M sin\varphi \tag{7}$$

$$\acute{\varphi} = V_M.\frac{tan\ (\theta_{FC})}{L} \tag{8}$$

Velocity component of each tire is described as follow:

$$V_{RL} = (K + r).\omega_M \tag{9}$$

$$V_{RR} = (K - r).\omega_M \tag{10}$$

$$V_{FL} = \frac{L}{sin\ (\theta_{FL})}.\omega_M \tag{11}$$

$$V_{FR} = \frac{L}{sin\ (\theta_{FR})}.\omega_M \tag{12}$$

Turning angle of front tires is described as follow:

$$\theta_{FL} = tan^{-1}\frac{L}{(K + r)} \tag{13}$$

$$\theta_{FR} = tan^{-1}\frac{L}{(K - r)} \tag{14}$$

SYSTEM IDENTIFICATION OF BRUSHED DC MOTOR

Figure 4 shows the brushed DC motor used in this work. PPSM63L-01 transaxle brushed DC motor manufactured by Shanghai Dixi Technical Co. Ltd. is the source to drive the proposed cart follower. The DC motor has an output power of 270 W and produces output RPM and torque of 4700 rpm and 10.95 Nm, respectively.

The final general transform function of DC motor can be described as:

$$\frac{\omega(s)}{v(s)} = \frac{K_m}{L_a J s^2 + (BL_a + R_a)s + K_m^2} \tag{17}$$

It can be seen that from the transfer function in Equation 17, the system exhibits a second-order system. The system contains no zero and two poles.

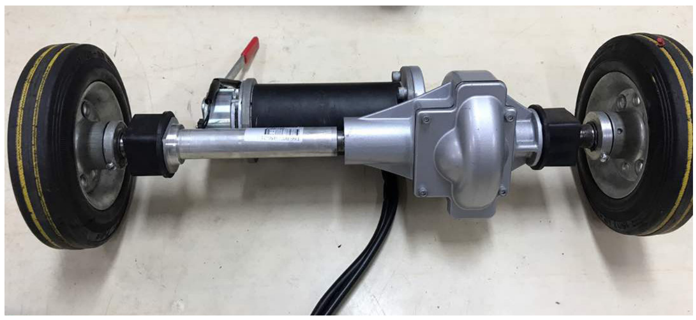

Figure 4 PPSM63L-01 transaxle brushed DC motor

Methodology

In order to approximate the transfer function, a mathematical model of the DC motor needs to be derived to estimate the system.

Figure 5 shows the circuit of armature controlled brushed DC motor. Based on the circuit the final form of governing equations (mechanical and electrical equations) of the DC motor can be finalised as:

$$R_a i_a + L_a i_i' + K_m \theta' = v_a(t) \tag{15}$$

$$K_m i_a = J\theta'' + B\theta' \tag{16}$$

For electrical Equation 15, $v(t)$ indicates applied voltage, R_a, L_a and i_a represent armature resistance, inductance and current respectively, K_m denotes the motor constant and θ′ is the shaft rotational velocity. For mechanical Equation 16, J and B indicate rotational inertia and viscous friction constant, respectively.

Equations 15 and 16 are transformed into the frequency domain by using the Laplace Transform. The number of zeros and poles in the system is crucial as the system identification toolbox in MATLAB® requires the users to specify the number of zeros and poles.

To approximate the transfer function in MATLAB®, the output velocity of a specific voltage input needs to be recorded. The DC motor is connected to the computer by using Arduino Mega 2560 and a motor driver. The experimental process of system identification is as shown in Figure 6.

The DC motor is connected with a rotary encoder to measure the revolution per minute (rpm) of the motor. The equation to convert rpm into linear velocity is given as:

$$velocity = (\frac{2\pi}{60}) \times rpm \times r \tag{18}$$

where *r* indicates the radius of the wheel. In this case, the radius of the shaft is assumed to be the radius of the wheel, because the objective is to approximate the transfer function of the motor without external load.

The sampling time for the datasets is 0.039 seconds, and the output is recorded for 20 seconds. The algorithm for data acquisition is created via MATLAB®. The experiment repeated three times to ensure the accuracy of the obtained results.

Based on the data log obtained from the experiment, *iddata* is created in MATLAB® in the time domain. The creation of *iddata* is crucial to use in the system identification toolbox.

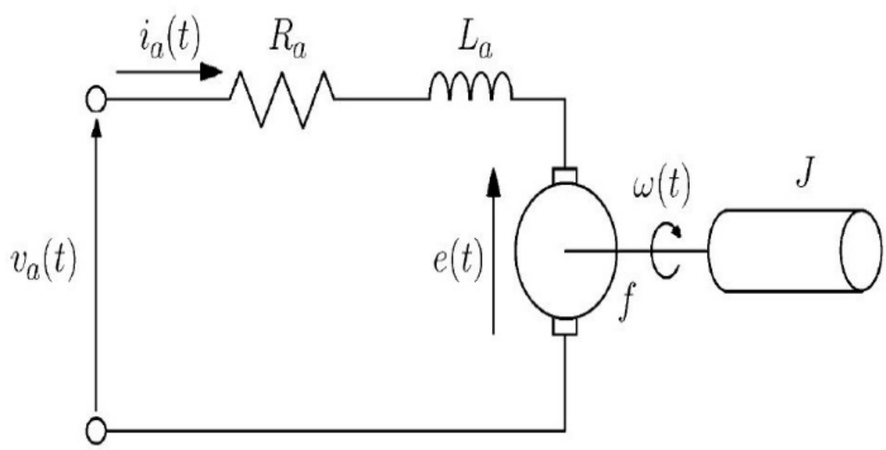

Figure 5 Circuit of brushed DC motor [9]

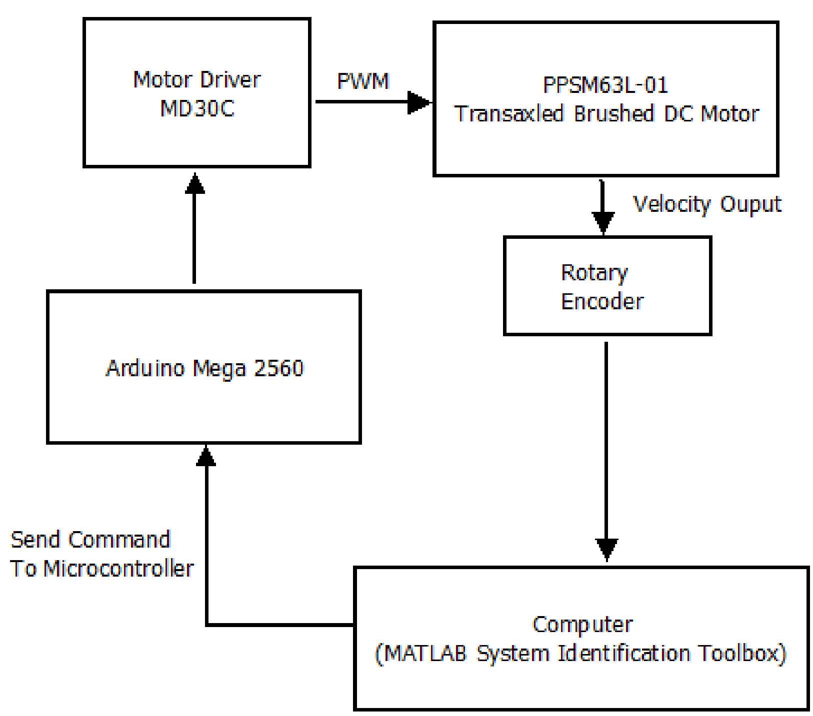

Figure 6 Experimental process for data collection

In the system identification toolbox, the transfer function could be generated directly by using the graphic user interface (GUI). The parameter that only needs to be specified is the number of zeros and poles. The transfer function is iterated in the toolbox. Graph of model output, transient response, frequency response, and zero and poles could be generated via the toolbox.

System Identification of Brushed DC Motor

The continuous-time transfer function obtained is as follow:

$$G(s) = \frac{104.9}{s^2 + 103.5s + 2617} \quad (19)$$

As stated in methodology, the transfer function obtained indicates the second order system where the motor constant obtained is 104.9. Figure 7 shows the measured data of the DC motor. The blue line indicates the simulated output by MATLAB®. The simulation estimates the best fit of the curve from the datasets.

Based on the transfer function of the DC motor, the step response of the function plotted as in Figure 8. From the graph, it can be seen that the rise time and settling time for the motor is 0.0668 seconds and 0.117 seconds, respectively. From the transfer function, the damping ratio, ζ is determined. The damping ratio, ζ of the DC motor is equal to 1. This indicates that the system is critically damped. The system based on the transfer function indicates no oscillation. The improvement suggested in the future is to decrease the settling time and rise time in the range of acceptable overshoot percentage.

The stability of the system can be identified by specifying the zero-pole plotted in Figure 9. In this case, there is no zero in the system. The location of the pole determines the stability of the system. The poles are reallocated at -59.6 and -43.9, respectively. The locations of poles are located at the negative side of the axis and on the real axis indicate that the system is stable.

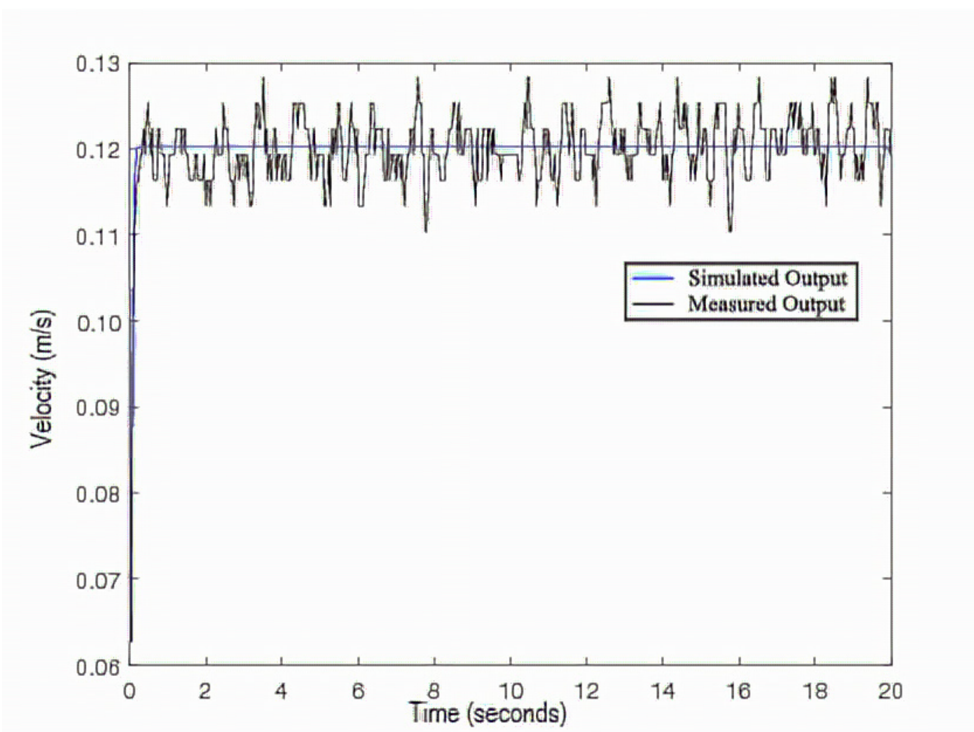

Figure 7 The measured and simulated output of the DC motor

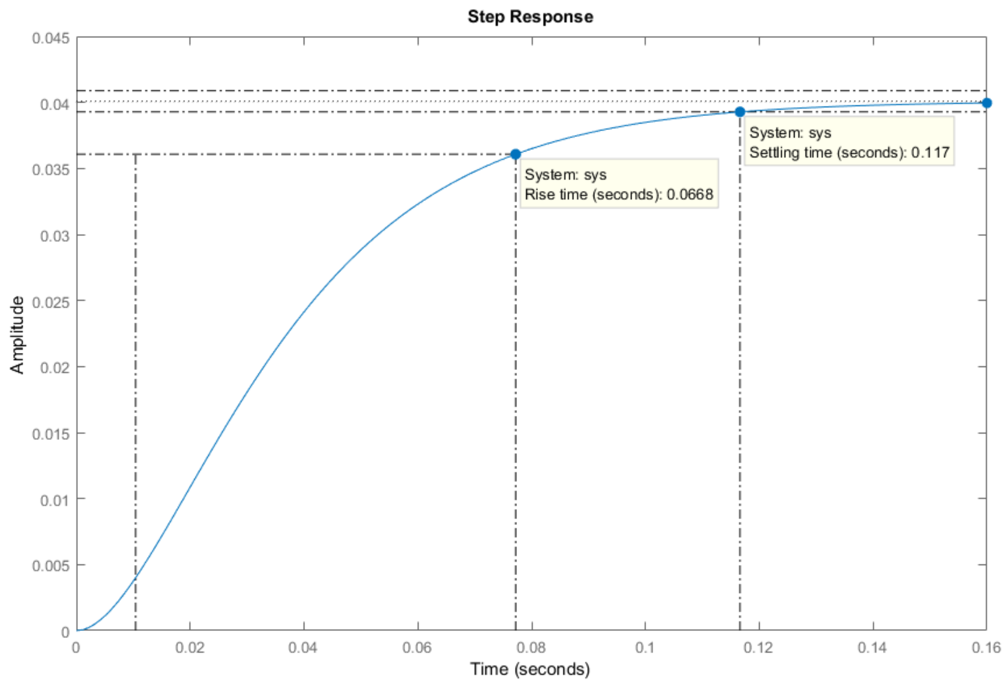

Figure 8 Step response of the DC Motor

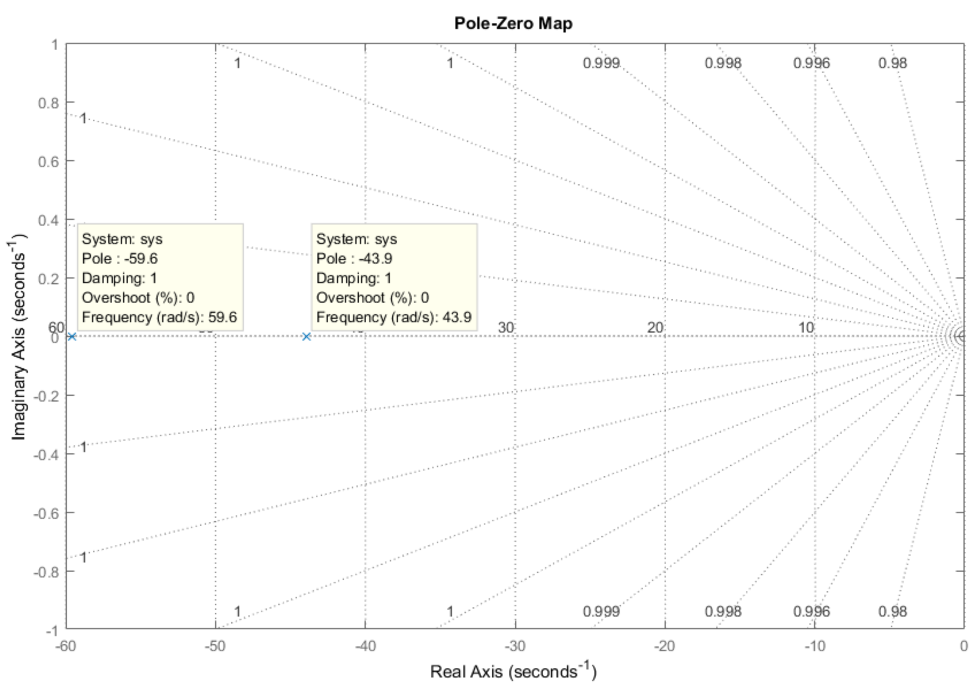

Figure 9 Zero-pole plot

CONCLUSION

The conceptual design of cart follower for a wheelchair user is drawn by using CATIA software. Ackermann configuration is used as the steering system. Based on the kinematics derivation of the cart follower, the motion and movement planning could be realised in the prototype.

System Identification Toolbox of MATLAB® approximates accurate transfer function as the plant module of the DC motor is not available. MATLAB® iterates the best fit curve from the raw data to obtain the best estimation of the system. The acquired system of the DC motor shows that it is stable and critically damped.

The approach used by this paper is direct and use minimal mathematical modeling compare with other existing methods. The limitation of this method is the noise of the data as the tools used is not specialized in data acquisition.

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