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Kinematics and Dynamics Analysis of an Autonomous Three-wheeled Bicycle Modeling

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***Abstract*—Three-wheeled bicycle, also known as pedicab, is well known as an eco-friendly transportation in Indonesia. The pedicab is usually operated by utilizing human power to transport objects. It also has high mobility in urban areas which is useful for areas with a heavy traffic. In the future, pedicab which operated by human power can be replaced by autonomous controller. This study aims to develop a model of autonomous pedicab. The kinematics and dynamics model of the pedicab motion were developed and analyzed. Furthermore, autonomous pedicab model is built in the simulated environment. Main components, i.e. sensor, module processing, and engine were added to the conventional pedicab. Initial design of the autonomous pedicab is simulated in Robot Operating System (ROS).**

Keywords-pedicab; kinematics; dynamics; autonomous; three-wheeled bicycle; robot operating system (ROS)

I. INTRODUCTION

The term pedicab, especially in Southeast Asia is referred to a three-wheeled conveyance operated by pedals-power which can carry passengers [1]. Generally, common pedicab has two front wheels and one back wheel and all the wheels are fixed-wheels. The direction of a pedicab is placed at the center rotation of pedicab pivot. Originally, the pedicab is designed to be used in downtown areas but nowadays it is developed for urban region tourism. Pedicabs becomes one of the eco-friendly transportations because of the zero-gas emission. Authentic design of the pedicab, especially Indonesian pedicab, is presented in Figure 1.

German car giants Volkswagen have developed an advanced pedicab concept in the form of e-bike for the commercial sector which can carry goods up to 210 kg [2]. The e-bike is a solution for the objects mobility challenges which is designed to be used in downtown areas. This vehicle is operated by an electric pedal. Moreover, the e-bike is time efficient because it can be used in pedestrian zones.

The heavy load vehicles operated by human power or electric pedal can be replaced by an autonomous system to increase time efficiency, diminish the physically demanding conditions, and optimize the mobility. It is deemed necessary to design an automatic pedicab build from the derivation of its kinematics and dynamics model for controller strategies. In past research on autonomous wheel robots, the main focus on kinematics and dynamics control method of the robot was increased to obtain more robust and most optimum performance [3].

Figure 1. Authentic form of "Becak" three-wheeled bicycle (author documentation)

Several researchers discussed about kinematics and dynamics model development for wheel mobile robot. Jason et al. [4] proposed the autonomous driving control systems in kinematics and dynamics vehicle model. The model's performance of the predicted error was analyzed by implementing experimental data, and the outcome of discretization on prediction error was studied. In [3], model controller strategy for front steer wheel in an autonomous three-wheeled mobile robot was developed. The system model describes the velocity control and autonomous trajectory control for robotic vehicle. Li et. al [5] proposed a method for modeling and kinematics simulation of a *mecanum* wheel platform for omnidirectional wheelchair. A theoretical strategy and kinematic analysis of a high-speed parallel robot for pick-and-place procedures was presented by [6]. Based on the previous research mentioned, there were no studies that discussed about kinematics and dynamics model for pedicab design. Hence this paper develops a model both kinematic and dynamic for a pedicab which consists of three fixed wheels with a pivot in the pedicab body as the center of direction rotation.

This paper also introduces new idea about developing an autonomous pedicab based on kinematics and dynamics constraints. An initial design of an autonomous pedicab is modelled in Robot Operating System (ROS) environment. The paper is systematized as follows. Part II discuss the

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conventional three-wheeled bicycle model. In Section III, the kinematics and dynamics modeling will be extracted and explained. Section IV depicts our initial design of autonomous pedicab and its model in ROS. Finally, section V present conclusion of this study.

II. THREE-WHEELED BICYCLE MODEL

In General, a pedicab is another design of inverted Cycle Rickshaw [7]. It allows the driver to sit in front of the passenger while the driver of the pedicab sit in rear when it is being operated. Figure 2 shows the real form of conventional pedicab from the different kind of view.

Figure 2. Original appearance of conventional pedicab

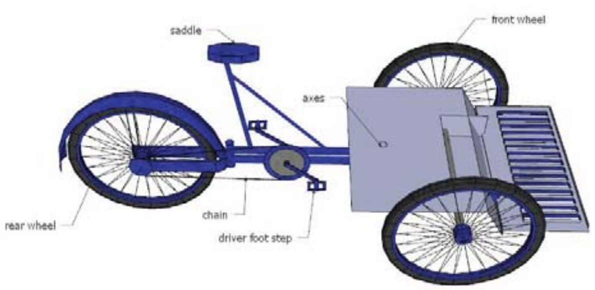

Figure 3. Main Framework of conventional pedicab

Figure 3 presents more explanation, to understand more about the design of the pedicab. Generally, a conventional pedicab starts moving due to power by the driver sitting in the back while controlling the pedicab direction [1]. The driver sits on the saddle and pedals. This makes rotates the gears below the driver. The rotation is connected by chain to the rear gear, which causes the wheels to rotate. It generates force that moves the pedicab. The Pedicab maneuvers by moving the right and left of the steering wheel in front of the driver. The shaft at the axes point makes the pedicab easily rotate to the right and left.

III. KINEMATIC AND DYNAMICS MODELING

Kinematics and dynamics model for a motion of the pedicab were derived. The model is presented as a mathematical description for the pedicab's motion. Kinematics model was built without considering the forces that affect the motion of the pedicab. Consider a model which describes the motion of the pedicab as shown in Figure 4 from top view and extracted to Figure 5 for the kinematics and dynamics structure. The kinematic construction of a mobile robot can be measured as a set of closed kinematics which is equivalent as the wheels that are in contact with the ground [8].

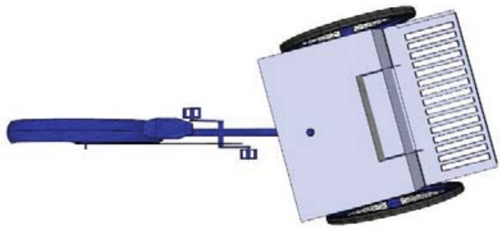

Figure 4. Pedicab top view

A. Three-Wheeled Bicycle Framework Proyection

The coordinate $(\bar{X}, \bar{Y})$ represents the pedicab position. A reference point G is chosen, which refers to the center of gravity of the pedicab body PQ with a length of $(l_a + l_b + l_f)$. Point O is the position of the pivot in the pedicab, which determines the direction of the pedicab rotation. The velocity of the pedicab V is defined at the reference point G. Its reasonable to assume that the angle β between V and the longitudinal axis of the pedicab is equivalent to the angle of the pivot rotation γ. The length between R and S, i.e center of the two front wheels is denoted as l_w with center Q.

The velocities of the right wheel and left wheel are denoted by variables v_r and v_l respectively. Those velocities are defined at the center of each wheel. The angles δ_l and δ_r represents angles between longitudinal axis of pedicab body PQ to the velocity vector of right wheel and left wheel respectively. Those angels are described the steering angle of each front wheel. Meanwhile the steering angle of back wheel is notated as δ. The velocities of the back wheel and front wheel are denoted by variables v_b and v_f respectively. Velocity v_b is defined at the center of back wheel while velocity v_f is defined at the center of the side RS.

The called heading angle Ψ is the angle between $\bar{X}$-axis to longitudinal axis of the pedicab body PQ, course angle $(\Psi + \beta)$ is the angle between $\bar{X}$-axis and the direction of the pedicab, where side-slip β is the angle between longitudinal axis of the pedicab body PQ to the velocity vector of the pedicab. The notation C refers to the instantaneous rolling center of the pedicab and the length from point C to reference point G becomes the radius of the pedicab's path r. The tire

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forces F_x for longitudinal force and F_y for lateral force are expressed in the pedicab frame.

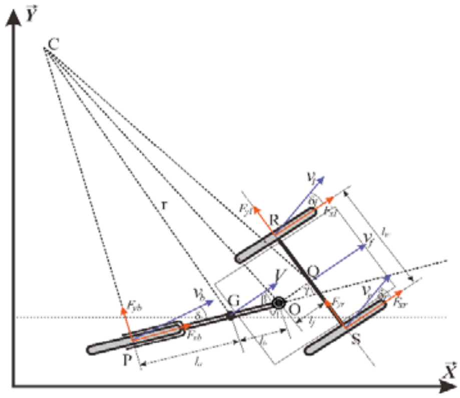
Figure 5. Kinematics and dynamics components

B. Assumptions

Several assumptions are utilized to develop the kinematics model of the pedicab. First, the velocity vectors at points P and O are in the same direction of the direction of the back wheel, while the velocity vector at the points O and Q is in the same direction to the direction of both front wheels. Therefore, velocity vector in the back wheel creates an angle δ to the longitudinal axis of the pedicab, velocity vector in the front-left wheel and front-right wheel creates an angle δ_l and δ_r to the longitudinal axis of the pedicab, respectively. Those assumptions are equivalent to declaring that the slip-angles at all wheels are convergence to zero. All lines, which formed from point C, are assumed to be orthogonal to v_b, V, and v_f respectively.

C. Kinematics Model

Based on [9] kinematics model for the pedicab can be described as these following equations:

$$\dot{X} = V\cos(\alpha+\beta), \tag{1}$$

$$\dot{Y} = V\sin(\alpha+\beta), \tag{2}$$

$$\dot{\Psi} = \frac{V\cos\beta}{l_a+l_b+l_f}\left(\tan\delta_f - \tan\delta_b\right), \tag{3}$$

where

$$\beta = \tan^{-1}\left(\frac{(l_a+l_b)\tan\delta + l_f\tan\gamma}{l_a+l_b+l_f}\right), \tag{4}$$

and

$$V = \frac{v_f\cos\gamma + v_b\cos\delta}{2\cos\beta}. \tag{5}$$

There are four inputs in the system equations (1)-(5), i.e γ, δ, v_f, and v_b. The velocity V can be assumed as a time varying function and can be obtained from a longitudinal pedicab model.

D. Dynamics Model

The dynamics model of the pedicab which is merged with a linear tire model [10] is written as in the system equations (6)-(8). The longitudinal and lateral velocity of the pedicab in its inertia border are denoted as v_x and v_y, respectively.

$$m\left[\dot{v}_x - \dot{\psi}v_y\right] = F_{xf} + F_{xb}, \tag{6}$$

$$m\left[\dot{v}_y + \dot{\psi}v_x\right] = F_{yf} + F_{yb}, \tag{7}$$

$$I_z\ddot{\psi} = l_f F_{yf} - l_b F_{yb}, \tag{8}$$

where the subscripts f and b denote to the front wheel and back wheel of the pedicab model respectively. Here, m is the mass of the pedicab, I_z is the moment inertia of the pedicab around yaw angle ψ.

IV. Design of Autonomous Pedicab

A. Initial Model

This section describes the innovation of pedicab to the electric pedicab or engine-powered pedicab and autonomous pedicab. Electric pedicab model is no longer driven by a pedal, but there is an additional electric motor to help the pedicab mobility. Electric motor is added under the driver saddle. This is implemented to keep the pedicab in a stable state, because the addition of load will compensate for the load generated by passengers in the front. The direction of control by the driver is still the same as the pedicab driven by the pedal, which is right in front of the driver. The electric pedicab design is shown in this following Figure 6.

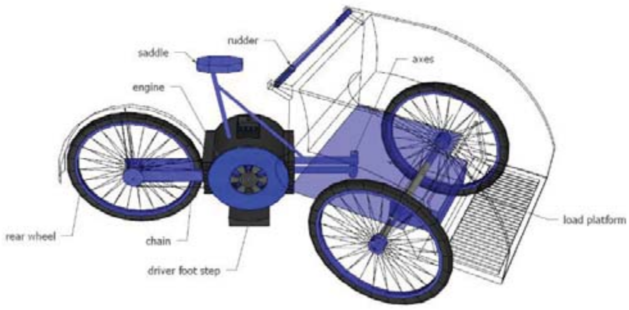

Figure 6. Design of electrical pedicab

Another innovation from conventional pedicab is autonomous pedicab. This autonomous pedicab implements sensors and computer algorithms to produce self-driving pedicabs. From this scheme, it is expected that pedicabs can apply the maneuvers in accordance with the inputted trajectory or move freely by avoiding obstacles in the field.

Figure 7 presents the design of the autonomous pedicab. The scheme is the same as the electric pedicab, except that it has additional sensors, controllers and actuators. The sensors are set to recognize the environment around the pedicab. This is conducted by getting variable values received by the sensor. In this case the pedicab implements two sensors, ultrasonic and LiDAR sensor. An ultrasonic sensor is applied so that the pedicab can find out the distance to the obstacles around the environment. The output of this sensor is distance. By recognizing the distance of the pedicab to the environment, the pedicab will instruct a decision to maneuver. The other sensor is LiDAR, whose function is to sense the environment and know what objects are in front of the pedicab. This sensor works as a camera that understands various objects.

Besides sensors, autonomous is composed of controller and actuator. The controller contains computer devices that

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process the data produced by the sensor. It also contains embedded algorithms to process sensor data automatically giving action from a readable sensor value. This controller will also regulate the speed of the pedicab. It will manage the electric motor connected to the chain about speed corresponds to the inputs given.

The other part is the actuator. This part is a motor that regulates a gear that determines the direction of the maneuver from the pedicab. The rotation of this gear will determine the amount of turning angle made by the pedicab, so that it produces a direction of change as desired.

In autonomous pedicab the parts for the driver are removed because the output of the autonomous system is to produce vehicles that can be controlled automatically. Therefore, this autonomous pedicab does not have the saddle component of the driver's seat, control for turning maneuvers and driver's footing. Instead, the engine remains installed in the back so that it can compensate for the load in front.

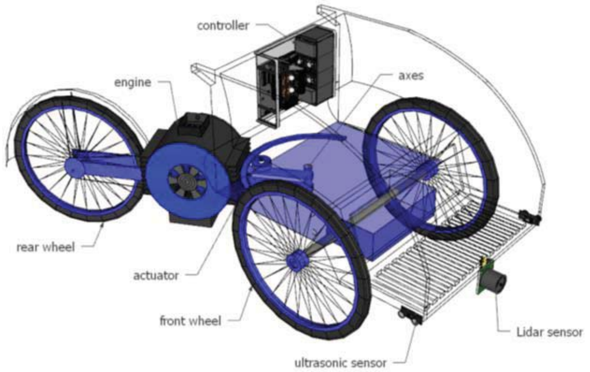

Figure 7. Proposed design of Autonomous Pedicab

From the above-mentioned model we can analyze that such forms have efficiency in terms of control. The three wheels are fix wheels, so there is no need to specify the axis of the turning wheel to turn. Then the required actuator is only one to turn, different from when controlling a vehicle with four wheels.

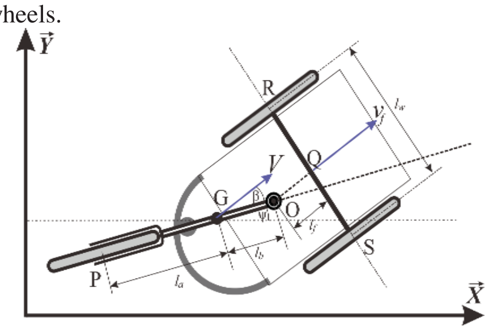

Figure 8. Proposed design of Autonomous Pedicab

In addition, the arrangement of three wheels also makes the structure more stable when compared to just two wheels like on an ordinary bicycle. Therefore, with this scheme, it does not require complex balance arrangements but still makes it easy to maneuver freely. The kinematic analysis of autonomous pedicab is shown in the Figure 8. The notations in Figure 8 is the same as Figure 5.

B. Building Autonomous Pedicab Model in Robot Operating System (ROS)

The pedicab model was created in a Sketchup Application. Those objects were saved in Colada file (*.dae). Afterwards, we build the simulation in an ROS Gazebo robot simulator. The autonomous pedicab model is spawned to this simulator in an empty world environment. Figures 9, 10, and 11 show the autonomous pedicab model in gazebo simulator.

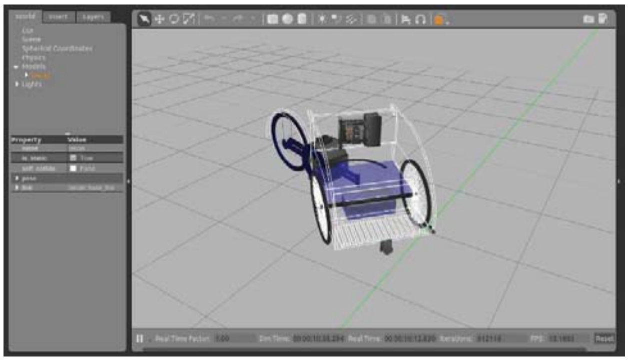

Figure 9. Autonomous pedicab in ROS Gazebo robotic simulator (front view)

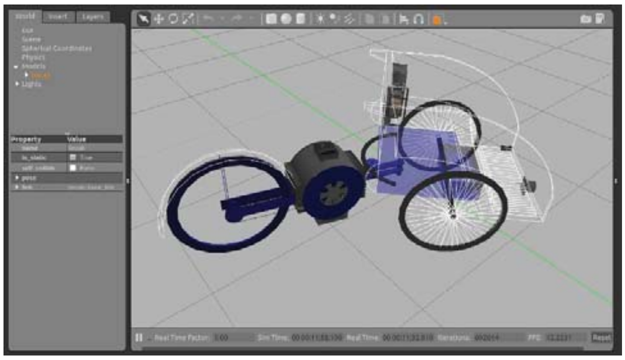

Figure 10. Autonomous pedicab in ROS Gazebo robotic simulator (side view)

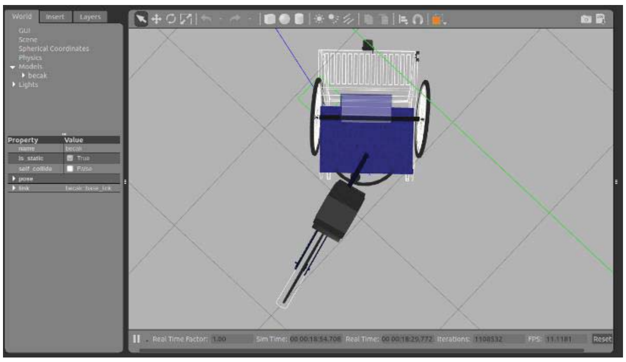

Figure 11. Autonomous pedicab in ROS Gazebo robotic simulator (bottom view)

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Autonomous pedicab means that this model could create motion planning by implementing its work of sensors and computer intelligence. When given several information about environment and final state or sets of position, navigation includes the ability of the robot to perform based on its information and sensor value so as to reach its goal position as efficiently and as reliable as possible [11]. Goal position of the robots will be obtained when the autonomous mobile robot is enhanced with the ability of path motion planning. Path planning based on reinforcement learning process for mobile robots [12] becomes one of the next future works to complete the propose of autonomous pedicab design.

V. CONCLUSION

In this research, we conduct a model both kinematic and dynamic for a pedicab structure which consisting three fixed wheels with a pivot in the pedicab body as center of direction rotation. The outcomes will be performed strategy controller for design of an autonomous pedicab. The kinematics and dynamics model of the pedicab motion were developed and analyzed. Autonomous pedicab model is built in the simulated environment. Initial design of autonomous pedicab, which build from kinematics and dynamics model, is simulated in Robot Operating System (ROS). In the future, by implementing some planning and mapping, the simulation could contribute the data analysis for model performance.

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REFERENCES

[1] B. T. S. Soegijokot, “Becaks of Java,” *Habitat Int.*, vol. I, no. i, pp. 155–164, 1986.

[2] T. G. R. Bot, “Volkswagon Premieres New Zero Emission Models – Including Cargo Electric Bike,” *bicyclist*, 2018. [Online]. Available: https://bicyclist.xyz/brief/volkswagon-premieres-new-zero-emission-models-including-cargo-electric-bike/. [Accessed: 04-Apr-2019].

[3] A. Pandey, S. Jha, and D. Chakravarty, “Modeling and control of an autonomous three wheeled mobile robot with front steer,” *Proc. - 2017 1st IEEE Int. Conf. Robot. Comput. IRC 2017*, pp. 136–142, 2017.

[4] J. Kong, M. Pfeiffer, G. Schildbach, and F. Borrelli, “Kinematic and dynamic vehicle models for autonomous driving control design,” *IEEE Intell. Veh. Symp. Proc.*, vol. 2015–August, no. Iv, pp. 1094–1099, 2015.

[5] Y. Li, S. Dai, Y. Zheng, F. Tian, and X. Yan, “Modeling and Kinematics Simulation of a Mecanum Wheel Platform in RecurDyn,” *J. Robot.*, vol. 2018, pp. 1–7, 2018.

[6] Q. Meng, F. Xie, and X. J. Liu, “Conceptual design and kinematic analysis of a novel parallel robot for high-speed pick-and-place operations,” *Front. Mech. Eng.*, vol. 13, no. 2, pp. 211–224, 2018.

[7] S. Zielinski, P. K. C. Abraham, A. Thomas, R. Abraham, and A. D. D, “E-Rickshaws : - The Road ahead CPPR Policy Brief Series II Vol 1,” *CPPR Policy Br. Ser. II*, vol. 1, no. April 2014, 2014.

[8] D. García-Sillas, E. Gorrostieta-Hurtado, J. E. Vargas Soto, J. Rodríguez-Reséndiz, and S. Tovar Arriaga, “Kinematics modeling and simulation of an autonomous omni-directional mobile robot,” *Ing. e Investig.*, vol. 35, no. 2, pp. 74–79, 2015.

[9] R. Rajamani, *Vehicle Dynamics and Control*, vol. Spec No. 2001.

[10] P. Polack, F. Altche, B. DAndrea-Novel, and A. De La Fortelle, “The kinematic bicycle model: A consistent model for planning feasible trajectories for autonomous vehicles?,” *IEEE Intell. Veh. Symp. Proc.*, pp. 812–818, 2017.

[11] R. Siegwart and I. R. Nourbaskhsh, *Introduction to Autonomous Mobile Robots*, vol. 21, no. 97. 2016.

[12] A. Khare, R. Motwani, S. Akash, J. Patil, and R. Kala, “Learning the goal seeking behaviour for mobile robots,” *Proc. 2018 3rd Asia-Pacific Conf. Intell. Robot Syst. ACIRS 2018*, pp. 56–60, 2018.

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