Two-wheel Balancing Robot; Review on Control Methods and Experiments

M.R.M. Romlay, M.I. Azhar, S.F. Toha, M.M. Rashid

Abstract— Two-wheel mobile robot has been active field of study and research as it provides simple mechanical design and high maneuverability. Various developments continue to take place in the process of achieving stability, navigation from one place to another. This article intended to address the control methods of balancing two-wheeled mobile robot from linear controller, non-linear controller and adapting and self-learning algorithm. The focus of the review will be the evaluation and experiment done on two-wheel mobile robot. With the objective of mobile robot advances further from self-balancing, navigating or obstacle avoiding, towards completing sophisticated external task such as transporting and monitoring the surrounding. It is believed that this review will help researchers in developing substantial two-wheeled mobile robot.

Keywords: Two-wheel mobile robot; linear controller; non-linear controller; self-adapting algorithm

1. INTRODUCTION

Mobile robots are gaining attention and increasingly popular today, as it offers various application in machining, research and entertainment [1]. Particularly wheeled robot, being a topic of interest for researcher as it is efficient, possess simpler mechanical and dynamics requirement. Among wheeled robots, configuration using four wheeled are high in stability, resembling moving cars and vehicles. Nonetheless, with more wheels the system tends to be over constraint and addition of suspension system is required unless it moves on flat surface.

The two-wheeled self-balancing breaks through the conven-tional car concept, with main structure of merely right and left wheel with body in the middle[2]. Two wheeled robot presents simpler design and control than legged robots. It possesses high maneuverability, requiring small angle to take turns. It can lean forward during inclination, towards the slope thus remaining its stability. Size can be mad flexible, allowing movement for narrow and tight corners. In comparison with three-wheel mobile robot with similar footprint, two-wheeler inverted pendulum robot have the ability to carry baggage or load with higher position by keeping it stable with state feedback control [3].

Two-wheeled balancing robot is usually attached with DC mo-tors with the stators fixed on the platform rigidly. The wheel rota-tion holds the system in vertical position. Sensors involved include gyro sensor, accelerometer and IMU. Because of the hardware requirement of less motor driving the robot, it gives better power consumption and longevity.

There are even self-balancing two-wheel robots being com-mercialized [4], either with a handle in the form of a scooter, or without handle or better known as hoverboard.

Past review paper [1] explores controllers that have been used for balancing, movement in flat and uneven terrain, secondary objectives and additional actuators.

The contribution of this paper includes summary of recent control methods. The focus of the review would be the evaluation and experiment done on two-wheel mobile robot. With the objective of mobile robot advances further from self-balancing, navigating or obstacle avoiding, towards completing sophisticated external task such as transporting and monitoring the surrounding.

The review paper is arranged as below. Section 2 discusses dynamics of the system and controller methods. Section 3 shows the test and experiment conducted, how the control method is evaluated, and task completed with the mobile robot including interactions with the surrounding environment. And finally, con-clusion of the review paper discussed in section 4.

2. THE TWO-WHEELED BALANCING CONTROL

In this section, we will discuss about the dynamic of the system, before going in depth of the types of controller implemented in mobile robots.

2.1. Dynamic of the system

Configuration of the dynamic system of two-wheeled mobile robot can be described either in white box model or mathematical repre-sentation or black-box model

2.1.2. White box model

White box representation uses just mathematics and simulation to accomplish dynamic equilibrium of the system [5]. Common dy-namics of the system includes Euler-Lagrange equation [6], New-ton's laws of motion [7], [8] or Kane's method [1]. Xia, Guo, Du, & Zhang [9] models the system based on Lagrange equations, with N. Zhang et al. [4] includes consideration of non-horizontal road surfaces for dynamic mathematical model. The simplest model simulation only considers forward and backward trajectory, comprises of two degree of

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Freedom in tilting angle and longitudinal displacement of the body. Further improvising of the system is done, taking into consider-ation of turning or yaw angle, with x and y-coordinates used for positioning of the model. Thus, it gets more complex with the system becomes non-linear model.

2.1.2. Black-box model

A system can be categorized as black-box when it is modelled according to its input and outputs without knowing how the internal works. Based on the experimental data and system identification method, an accurate dynamic model of the robot is attained. Through black-box model, how the dynamic system works is not the main concern, rather the variables are tuned to get the best output possible. Hammerstein-Wiener [5], Mamdani and Takagi-Sugeno Fuzzy Logic Controller (FLC) are the examples of imple-mentation of black box model in configuring the dynamics of two-wheel mobile robot.

2.2. Linear controller

In mobile robot controller, the primary objective is to keep it in balance. Then certain trajectory or navigation can be made while preventing the entity from falling over. Consequently, avoiding obstacle or manipulating the surrounding of the mobile robot could be the way forward.

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Should we assume a linearized model, a linear controller can ac-count to trail back to previous reference state [1]. Ivoilov, Zhamud & Trubin [10] designs a complementary filter to estimate tilt angle estimation to overcome mid and low-frequency accelerometer distortions. Proportional–integral–derivative (PID) controller is used to balance tilt angle and preventing unpredictable movement of the system in the horizontal plane. Jung & Kim [11] perform angle controller using PID, but cart position was unmanageable. PID controller is used as a comparison to neural network NN for angle and position control of mobile robot. PID controller with Kalman filter for gyroscope and accelerometer data are implemented by Ali & Hossen [12]. Zhang, Zhang, Wang, Li, & Zhang [13] adopted PID controller to stabilize the robot in hopping movement. The angle between the vertical axis and mobile robot is deliver back to the controller, and a torque command is produced so that the wheels are droved to stabilize robot to be in the state of vertical. As angular displacement is detected by the sensor, pulse width modulation (PWM) value is adjusted by the PID control algorithm, which in return will change the speed of the wheel.

Wenxia & Wei [14] simulates model of self-balanced robot with the value of Q and R on the system analysed. Gonzalez, Al-varado, & Pena [15] combines two linear controllers for construc-tion of low cost balancing robot. LQR controller is used to control tilting angular speed, tilting angle and angular speed of the wheel. Then, angular acceleration of the wheel will be referred to PI con-troller for magnitude control. There are two PI controller, one for each wheel. Engin [16] deals with the nonlinearity balancing f two wheeled robot with LQR controller. Relative weightage of Q and R element in ratio makes a trade-off between performance and control of the mobile robot.

Some study combines LQR and PD controller for turn and velocity controller. Kung [17] constructs small autonomous two-wheeled robotic platform with machine vision module, making use of on-board single camera. Single range camera for identifying object, overcome small obstacle and communicate long range via Bluetooth module. LQR controller is designed with state estimation is proposed by Uddin et al. [7]. Luenberger-based observer is implied to anticipate the unmeasured state on the rate of pitching from the gyro sensor.

2.3. Non-linear controller

Non-linear controllers have also been associated with wheel mobile robot controllers. Commonly used non-linear controller include fuzzy logic controller (FLC). Rjlf & Khhohg [18] used Arduino and NXT LEGO robot platform and implement FLC to achieve zero tilt angle within 2 seconds of settling time. Various membership function and fuzzy rules were tested in the process. Wang, Huang, & Hung [19] developed Fuzzy-PID controller on Arduino Leonardo platform, perform balancing while standing, moving and carrying load. Kao & Lee [20] proposed fuzzy approach for balancing controller and yaw controller implemented to driving wheels.

Huang, Member, Ri, Wu, & Member [21] presents integrated intervals type-2 fuzzy logic method to both model and control two-wheeled mobile robot. Four controller of interval type-2 fuzzy logic is integrated to describe dynamics of the system, balancing, position and direction. First two fuzzy logic implemented Takagi-Sugeno method, and Mamdani model for the following two fuzzy controllers. Ri, Huang, Ri, Yun, & Kim [22] designed another type-2 FLC to maintain balance, tested with model uncertainties and external disturbances. Three controllers are proposed, which is balancing controller, velocity controller and yaw steering controller.

Tsai, Li, & Tai [23] designs backstepping sliding-mode control for network of nonholonomic mobile robot for trajectory data tracking. A network of wheeled mobile robot is tested to achieve movement in formation, as well as tracking their desired trajectory. For normal horizontal path, uneven surface with varying degree of unevenness, slope inclination and bumpy road, N. Zheng et al., [4] uses hierarchical fast terminal sliding-mode control (HFTSMC) for simulation of outdoor situation.

Lyapunov-based backstepping techniques for position and ve-locity error is proposed by Z. Yu, Tong, & Wong [24]. The con-trolling process can be classified as three stages depends on differ-ent type of errors. Initially, the position and velocity stage, the force vector fully drive the body. In the second stage and the third stage where the force and angular velocity calculation process takes place, the robot shows shortage of driving force in sway direction.

Kim & Kwon [25] introduced state-dependent Ricatti equation (SDRE) control framework, a non-linear version of LQR control system. as like LQR where Q and R

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(parameters that define weight in the states and weight on the control input) value are determined, SDRE design lies on selecting the right state dependent coefficient (SDC) for optimal gains.

2.4. Machine learning and optimization technique

Among machine learning method, neural networks (NN) has been incorporated with various learning algorithms to overcome re-quirement in mobile robot. Tsai, Huang, & Lin [26] presents adap-tive control using radial basis-function neural networks (RBFNNS) for stabilization of self-balancing scooter and yaw motion controller. Rate of pitch from gyroscope and angle of pitch from tilt sensor are filtered and utilized as input, before output torque commands speed on the scooter. Jung & Kim [11] chose neural network NN with reference compensation technique (RCT) algorithm for feedback error learning scheme. The proposed NN are of two layered with six input particles, nine particles for hidden layer and six particles of output. Then the tracking errors goes through PID controller for cart position and pendulum angle controller.

G. Yu [27] proposed particle swarm optimization PSO-based Fuzzy Logic in order to stabilizes self-balance control system and also seeks best control gains. PSO, swarm-based optimization method is implemented to search for best feedback gain integrated into Takagi-Sugeno (T-S) fuzzy controller.

A controller design method of (T-S) FLC integrated with ge-netic algorithm (GA) to regulate proper state feedback gains is presented by Cao, Huang, & Hung [28]. Two fuzzy membership function is formed by heuristic experiment; vehicle angular velocity and vehicle body angle.

Reinforcement Learning with Q-Learning method to adjust the motor according to the dip angle and angular velocity is done by Chang & Chang [29]. The objective of the learning algorithm is to get back to balance state within the shortest time frame when encountering external force.

2.5. Summary

Dynamics of the mobile robot can be categorized into two catego-ries, namely white-box mathematical model or black box model. The summary of control method of self-balancing two-wheel mo-bile robot is as shown in Figure 1.

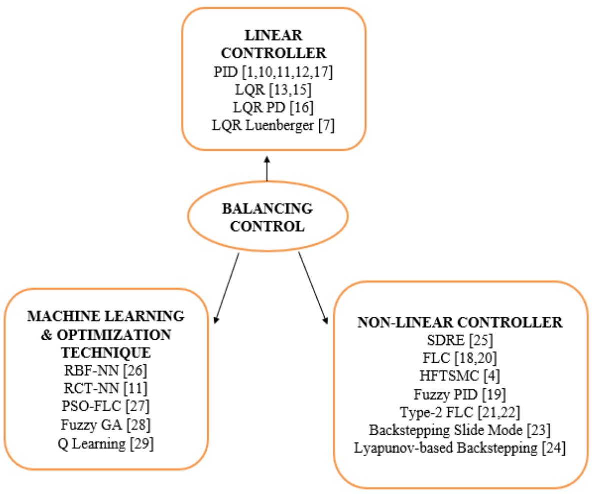

Fig. 1: Balancing controller for two-wheel mobile robot

3. RESULTS

EXPERIMENT EVALUATION

Most common inverted pendulum system applications of control is 1D-type where the cart moves back and forth in a straight forward line [11]. Engin [16], and Huang et al., [21] considers straight forward movement and taking turns to achieve predetermined destination target. However, with the advancement of the control system, mobile robots are now entrusted with higher level experi-ment and test simulation for research purposes.

3.1. Trajectory

Tsai et al. [26] moves two-wheeled mobile scooter forward and perform 180 turn for experimental purposes while carrying a human test subject. Takei et al. [3] tested two-wheel mobile robot in a navigation path encompass of two straightforward narrow corridors which meet at a right angle near the corner. The path's width did not exceed 3m. The first section's length was 30m from the starting point towards the corner, whereas the second section was situated 40m distance from the corner towards the final goal. Next, a corridor of 5m in width crossing the middle of the second section follows. Both of the corridors are surrounded by walls which is not entirely flat. The robot moves by using odometry, connecting those Sub-goals in sequence. Maps with information of width of corridors, position of the corners included in the map. At every sub-goal, the robot stops before measuring its position in reference to the side of the wall by using a laser range sensor.

Tsai et al. [23] considers a group of wheeled mobile robot to move in desired pattern, along a desired trajectory. A virtual leader is moving followed by other robots aiming to show merit and proposed backstepping sliding mode control method.

3.2. Speed and acceleration

Takei et al.,[3] conducted experiments to travel 6.28m of straight line, with maximum reference velocity set to 300cm/s. Acceleration is limited to 30cm/ to avoid vibration of backlash. Jung & Kim [11] conduct an experiment to achieve desired trajectory tracking control. A trajectory is considered as two times faster than the next one, with the period 4 s and 8 s. The sinusoidal trajectory value is recorded at 0.25m. Tsai et al.,[23] sets trajectory of a network mobile robot consist of three entity moving through predetermined path at a constant speed of 2 m/s. the proposed backstepping sliding mode controller keeps the robot to move according to a cooperative formation law.

Gonzalez et al.,[15] shows angular speed change with wheel reference ranging from -2rad/s to 2rad/s. Angular speed of wheel trajectory and tilt angular speed is measured for the experiment, with the controller ability to track tilt angle error less than 0.1 rad and error in angular speed of 0.6rad/s.

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3.3. Obstacle in the environment

Takei et al. [3] directs the mobile robot in predetermined path with obstacle on the way. Tsai et al. [23] test the robot in a path where there were columns of 30cm in width, including foreign objects in the likes of fire extinguisher, a dust box, and chairs which is palced about 50cm from the wall following the corner.

3.2.1. Non-linear damping and road disturbance

Z. Yu et al. [24] addressed the problem of control an underactuated two-wheel robot to follow a desired tracking path under unknown road disturbance. Based on the robot practical kinematics and dynamics model, the unknown road damping force should be nonlinear and related with wheels' velocity.

3.2.1. Uneven terrains

An in depth study on uneven terrain can be found in [4] proposed by N. Zheng et al., where outdoor environment is categorized into four circumstances. (a) on horizontal terrain, (b) inclined slope, (c) on the bump and (d) on random terrain with a degree of uneven-ness. Pitch angle, yaw of the vehicle and wheel velocity are col-lected to compare proposed hierarchical fast terminal sliding-mode control (HFTSMC) with PD control method.

3.2.2. Step ascension

Bannwarth, Munster, & Stol [30] models a two-wheeled robot to climb stairs. There are 3 stages in step ascension, where there are two points of contact stage, corner stage while uplifting and drive off stage, where the robot is in the state of balancing after step climb. Two main components of the controller are feed-forward torque balancing and gain matrix of LQR controller.

3.2.2. Hopping robot with linkage mechanism

Zhang et al. [13] addressed the shortage of overcoming obstacle and rough terrains with hopping robot using combined wheel lo-comotion and bounce movement. There are four bar linkage, giving out different trajectory and balanced control of the two-wheeled mobile robot. The gear system consist of two incomplete gear is engaged in the hopping robot rather than using a cam, to save space. The hardware configuration of the four-bar linkage is to enable jump motion to higher position and run in faster speed. The leg has four bars with varying length to imitate real Kangaroo leg. Conducted experiment records 120mm average jumping height, and 140mm as the maximum height. The distance of horizontal jumping is 50mm and the starting velocity is recorded at 1.66m/s.

3.4. External task

3.4.1 Load Carrier and transporter

Two-wheeled mobile robot are used as a transporter for either baggage or human test subject. Takei et al. [3] maintains balance carrying 7.5 kg loads in the size of 40cm x 40cm x 40cm. Tsai et al. [26] carries human test subject to move forward and backwards based on tilt angle sensor. Experiments show the designed RBFNN controllers is affective to steer vehicle at slow speeds.

3.4.1 End-effector with gripper mechanism

Two wheeled mobile robot with gripper attached to the robotic manipulators to pick up objects is proposed by Kao & Lee [20]. Object detection is done through image processing. Manipulator arm are made of servo motor, while gripper opening and closing is controlled by RC motor. Together with web camera, accelerometer and gyro sensor makes up the hardware architecture of the robot. Raspberry Pi2 handles the image processing and Arduino MEGA board controls the movement and direction of the robot.

3.4.2 Machine vision system for monitoring

Kung, [17] constructs small autonomous two-wheeled robotic platform with machine vision of on-board single camera. It identi-fies the object, overcome small obstacle and communicate long range via Bluetooth module. It has on board sensors and LQR and PD controller for turn and velocity controller. Infrared (IR) sensor, accelerometer, Bluetooth module implemented the camera for the hardware system. Via Bluetooth module, it reports the location and status to be monitored in real time to the user. The computer software is sufficient to support up to 15 circumstantial processes, maintaining 1 millisecond sampling interval for the algorithm's control feedback.

3.4. Summary

The types of experiment and test done on the mobile robot are shown below. Table 1 shows two-wheeled balancing evaluation based on the theme of trajectory, obstacle avoidance and interaction with the environment. The methods used, comparison method and result from the experiments are thoroughly discussed. Remarks on each research shows the limitation and room for improvement which can be implemented to further improved the two wheeled mobile robot design.

Table 1: Critical analysis on methods of two wheel robot controller

Category	Ref	Simulation	Proposed Controller	Compared Method	Result	Remark
Trajectory						
Navigation	[26]	Performance simulation of the pitch angle tracking & the effectiveness of RBFNN yaw motion controller.	Radial basis-function neural networks (RBFNN)	State feedback controller	Proposed RBFNN has a faster speed convergent and better response than the compared method of state-feedback controller.	Control actions are made to steer the vehicle at lower speed only.

	[23]	Group of mobile robots moving together in a desired formation pattern, moving along a desired trajectory at a constant speed of 2m/sec.	Backstepping Slider Mode		The proposed controller performance is efficient in controlling the three NWMRs to cooperatively move along their desired formation	Delay time and back stepping sliding-mode parameters is not optimal, formation error and chattering phenomenon occur in the simulations.
Speed & Acceleration	[11]	The pendulum is disturbed by external force intentionally while the mobile pendulum system try to remain balance	Reference compensation technique neural network (RCTNN)	PID	PID controllers are able to maintain the balance but fails in controlling cart position. Proposed controller is robust; able to maintain the balance well. The mobile pendulum system preserves a predetermined position after each impact.	Occurrence of position error because of the slippage of wheels induced by physical impacts. In trajectory tracking test, the error of angle is not beyond 0.05 rad, and error of position tracking is not over 2 cm.
	[14]	Simulation and result on displacement, speed, angle and angular velocity.	LQR	Varying selection of Q and R matrix	Based on the data simulation, Q and R parameter are adjusted until the output of the actual robot attaining the ideal. Decent control effect is achieved.	No comparison on the controller's performance with other method.
Obstacle in environment						
Non-linear damping	[24]	Circle like path was designed to lead the robot tracking with nonzero initial velocity	Lyapunov-based Backstepping		The system is stable, and performance is acceptable in the large modelling errors. Comparing simulation result with experiment performance data, the controller can still be optimized.	Further improvement includes hardware development and the controller algorithm optimization
Uneven terrains	[4]	Test is done on three condition 1) Horizontal terrain 2) On the bump 3) Uneven terrain	Hierarchical fast terminal sliding-mode control HFTSMC	PD controller	HFTSMC improve the transient performance and weaken the chattering problem effectively. The pitch of vehicle changes more seriously when controlled by PD resulting more pitch angle when under disturbance.	Future research on hardware validation required.

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Step ascension	[30]	Step climbing simulation	Novel partial feedback linearization and optimal LQR controller	Baseline controller	Proposed controller successfully climb a 2.5 cm step in the period of 1s, while up to 86 % lower tracking errors is recorded when compared to baseline controller.	Nonlinear controller developed to be implied and tested on the scaled-down model of the mobile robot with two-wheel for validation purposes.
Hopping robot	[13]	Jumping experiment	PID		The minimum jumping height of the robot is greater than 117 mm. The robot can jump up to 83% of its height, which is 14 cm.	Hardware should be designed to increase energy efficiency. Control algorithm need to be optimized and obtain improved robustness and balance for jumping and landing.
External task						
Transporter Load	[3]	Travel from the starting point to the end point with a 7.5-kg baggage	State feedback control Yamabiko KURO		The robot able to reach and stop very near to the sub goals marked in the map and able to attain the end goal.	Method can only be implied on horizontal ground
Gripper end effector	[20]	Object pick up simulation. Placed on the chest level of the mobile robot	FLC		Microcontroller moves robot body and arms to place it properly through the AI motor. Object is pick up by robot through the RC motor to let the opening and closing action of the gripper.	Needed critical test for balance and object pick up validation. Requires external computation
Machine vision monitoring	[17]	Indoor navigation and simulation	LQR-PD		Monitor software to monitor sensor status in real-time. Module allow robot to report its location up to 4km.	Decision are hard coded into the software, microcontroller not equipped with decision making

4. CONCLUSION

There are numerous studies that have been made regarding the two-wheeled mobile robot recently. With improved control methods and artificial intelligence techniques achieving balance control have been made easier. With linear controller, non-linear controller and self-adapting controller all contributing for effective control of the system.

The mobile robots are now entrusted with more complicated and sophisticated task of avoiding obstacle and carrying load or passenger on its own. Test and experiments are done in the theme of setting trajectory, desired speed and acceleration, obstacle avoiding technique and interaction with surrounding objects.

However, it has been difficult to compare the controller system entirely as the test subject and requirements of each research is different. A more direct comparison and objective aim of the mobile robot can be demonstrated to really evaluate robustness and effectiveness of control method in the future.

In this study we have successfully presented controller meth-ods for two-wheel mobile robots in the theme of linear controller, non-linear controller and self-learning and adapting algorithm. The experiments done on is evaluated in terms of trajectory, speed and acceleration setting, avoiding obstacle and interaction with the surrounding environment. This review can be a source of reference for future research and study on this topic.

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