Four Wheeled Mobile Robots: A Review

Jovina Seau Ling Leong [1,*], Kenneth Tze Kin Teo [2], Hou Pin Yoong [3,*]

[1, 3] Biomechatronics Research Laboratory
Faculty of Engineering, Universiti Malaysia Sabah
Kota Kinabalu, Sabah, Malaysia
Email: jovina96leong@gmail.com [1], yoongpin@ums.edu.my [3]

[2] Modelling, Simulation and Computing Laboratory
Faculty of Engineering, Universiti Malaysia Sabah
Kota Kinabalu, Sabah, Malaysia.
Email: kenteo@ums.edu.my

***Abstract*—Wheeled mobile robots are becoming popular in recent years due to their applications that have impacted various aspects of daily life. With the advancement of technology, the demand for wheeled mobile robots especially four wheeled mobile robots has risen. The rise in demand had urged further research and development of more advanced wheeled mobile robots. In this paper, the recent development and focused on four wheeled mobile robots such as the types of wheels, types of steering systems, and control methods are reviewed. For the four wheeled mobile robots to have better steerability and superior cornering stability, the four-wheel steering systems are employed. Depending on the application, the used of standard or fixed wheels in four-wheel steering system also has better efficiency and accuracy compared to the Omni or mecanum wheels with similar maneuverability for indoor designs application. To effectively deal with the four-wheel steering mobile robot dynamic behavior, the payload uncertainty, system uncertainties and unknown disturbances including the parametric vibrations that lead to tracking performance limitations have to be overcome. For further improvement in tracking the performance of four-wheel steering mobile robots, the main issue is to tackle the payload uncertainty. An adaptive control method is proposed to overcome the issue and this method provided future research directions for the four-wheel steering mobile robot.**

Keywords—Wheeled mobile robots, four-wheeled mobile robot systems, types of wheels, types of wheel steering systems, and control methods.

I. INTRODUCTION

Mobile robotics is one of the fastest expanding scientific research fields that include terrestrial, air, and aquatic mobile robot. Initially, mobile robot development was to substitute humans to perform task in hazardous environments. However, the development of mobile robotics in recent years expanded in many fields such as restaurants, parcel delivery, information services, farming, sports, and others [1].

Depending on the application, terrestrial mobile robots can equip with wheeled, legged, or chained based on the payload capacity and terrene. Wheeled mobile robots that outstand the others in the categories of the mobile robot have received greater attention from the scientific community due to their power efficiency. Wheeled mobile robots are becoming popular, and their application has evolved to various aspects of our daily lives. These applications include transportation, exploration, inspection, and others [2]. The use of wheeled mobile robots not only helps to improve the industrial and military it also includes providing services and performing household tasks. Hence, the demand for wheeled mobile robots has raised due to their application in a broad area.

For wheeled mobile robots, the usage of wheels is more straightforward to design and build because the robot is moving on nonrugged terrain. Since the design of wheeled mobile robots is more concise and more accessible, the cost of construction and maintenance tends to be lower than the other types of mobile. Besides that, the wheeled mobile robots do not have balance issues because the wheels are usually in contact with the ground surface. However, the wheels become less efficient when moving over obstacles on uneven terrain such as sharp surfaces or rocky terrain. It also faces the problem with low friction surfaces because it will become unstable to maneuverer at high speed when turning [3]. To achieve good control of the wheeled mobile robot, many researchers had formulated mathematical model for the wheeled mobile robot and various control systems had been developed to control mobile robots [4].

This paper aims to provide an overall view of recent developments and focused on four wheeled mobile robots. The article is systematized in the following section. Section II shows a review of the wheeled mobile robot system, including the types of wheels and wheel steering system. The descriptions, figures, pros, and cons of the kinds of wheels are also included in Section II. In Section III, the type of control methods used in the four wheeled mobile robots, descriptions, pros, and cons of the control methods are presented. Lastly, Section IV gives a conclusion to this review.

II. WHEELED MOBILE ROBOT SYSTEM

The number, configuration, and type of wheels are essential for the wheeled mobile robot system in developing the kinematics and dynamics model of the robot system [4]. The main objective of developing robot model is to virtually study the robot system design for understanding its required torque, stability, controllability, and other parameters. The virtual study can be used to verify the feasibility of the robot system for its application before it is developed.

The number of wheels of the mobile robots is one of the main criteria defining the stability of the wheeled robot system. Among the wheeled mobile robot systems, a four wheeled mobile robot system with the wheels attached to each corner is the most stable system. This is because the centre of gravity is placed inside the rectangular or square formed from the four wheels to maneuverer on smooth terrain. For the wheeled mobile robot to maneuverer over slopes or rough and sandy terrain, it will require more contact surface with the

*Corresponding author

ground. Thus, additional wheels can be used to increase the contact surface with the ground and improve the stability of the wheeled mobile robots. However, creating a wheeled mobile robot with more than four wheels is complex and more parts will be involved in the system, which will increase the cost of construction and maintenance. Hence, if a four wheeled mobile robot system is sufficient, it will be the most cost-effective and simplest design [1].

Generally, a four wheeled mobile robot is divided into two types of steering systems which are two-wheel steering systems and four-wheel steering systems. The two-wheel steering system first existed to control the movement of four wheeled mobile robots. A four-wheel steering system is then developed and employed in the four wheeled mobile robots [5]. This is because the four-wheel steering system can achieve better maneuverability at high speeds in terms of improving steering response and smaller turning radius [6].

A. *Types of Wheels*

Wheels are essential in the design of wheeled mobile robots. Besides providing maneuverability, the wheels are required to withstand the entire weight of the wheeled mobile robot, the payload, and other forces caused by the regular operation. The wheels are not only required to be strong enough, but the power required to drive the wheel is also a concern in the wheel selection while designing the robots. Generally, narrow wheels consume lower power with lower rolling resistance are often preferred for wheeled mobile robots moving on flat terrain. In comparison, large wheels with higher power consumption and better grip are often utilized for wheeled mobile robots moving on uneven terrain. Since larger wheels required higher power consumption, a more powerful motor is also required, which will lead to an increase in the cost of construction [3]. Hence, the most suitable types of wheels are used based on the applications of the wheeled mobile robot. Besides the size and the strength of the standard or fixed wheels, various types of wheels such as ball wheels, Omni wheels, and mecanum wheels are also available for various maneuverability.

The standard or fixed wheel has one degree of freedom where this wheel can move in two directions: forward and reverse. These wheels are normally used as drive wheels in the wheeled mobile robot design. These wheels are beneficial with their simple structure, wide ranges of sizes, and good reliability, but provide the nonholonomic velocity constraint with no sideslip condition that will limit the robot motion. These wheels are only suitable for indoor designs [7]- [8].

Next, the ball wheel is one of the most spartan wheels used to balance the robot with 360 degrees of freedom. These ball wheels provide nonholonomic constraints where the robot can be moved with any desired linear or angular velocities at any time. Besides that, these ball wheels can achieve smooth and continuous contact between the wheels and the ground. Nevertheless, the design of the mechanism is intricate, and the payload is low. These ball wheels have high rolling resistance with poor traction that is commonly used as the support wheels in robots. Furthermore, these ball wheels are unsuitable for uneven, dusty, and greasy surfaces [7]- [8].

The Omni wheel, also known as the Swedish wheel, has passive wheels attached around the circumference of the centre of the wheel that enable it to maneuver in any direction. These Omni wheels can be used as both drive and steer wheels because they exhibit low rolling resistance with high efficiency and can move fast in all directions. Besides that, the Omni wheel has a long lifespan and it is cheaper compared to the mecanum wheels. However, the Omni wheel causes friction loss when the rotation of the wheels is in a different direction of movement, and it is computationally complex to calculate the angle of movement [7], [9].

The mecanum wheel is a type of Omni wheel except that the passive wheels are attached at 45 degrees angle around the centre of the wheel. These mecanum wheels can also be used as both drive and steer wheels in the design of the wheeled mobile robot. Mecanum wheels are swift dynamic motion in every direction compared to the other types of wheels. Besides that, the mecanum wheels can transfer forward wheel spin into sideways motion quickly and efficiently. In addition, the mecanum wheels are suitable for both indoor and outdoor designs and have a longer lifespan compared to the traditional rubber wheel. However, this wheel is expensive, heavy, and slow compared to the other types of wheels. Table I summarises different types of wheels with descriptions, figures, pros, and cons included for every kind of wheel.

B. *Types of Steering Systems*

The four wheeled mobile robots with a four-wheel steering system outstand the two-wheel steering system because the cornering behavior of the system is more stable and controllable at high speed and on wet or slippery terrain [6]. Furthermore, the four wheeled mobile robots with the four-wheel steering system are better to navigate on narrow terrain because counter-phase steering of the rear wheels minimized the turning radius, thus decreasing the steering wheels' side-to-side rotation, making the four wheeled mobile robots easier to turn. Besides that, the four-wheel steering system development helps to improve the steering response and precision of the four wheeled mobile robots. With better steering response and precision, four wheeled mobile robots can respond faster to the steering input and more precisely throughout the entire speed range. This is important for the scenarios in avoiding an unexpected obstacle when moving or turning. Therefore, the four wheeled mobile robots required only a small steering correction to uphold the desired direction. However, the four-wheel steering system's construction and maintenance costs will be higher because more components are involved and the cause of wear and tear could put the system to malfunction [10].

III. Control Methods in Four Wheeled Mobile Robots

With the rapid growth of the demand for active safety, electrification and intelligence, these become the new direction for modern automobiles. The four-wheel steering system provides many advantages that can be employed over a wide range of four wheeled mobile robots as an automated transportation tool. Based on past research and developments, the four-wheel steering system can effectively enhance the transient response of four wheeled mobile robots [11]. Hence, the control methods used in four wheeled mobile robots with four-wheel steering systems are essential to ensure the robot achieves the desired performance requirements.

In recent years, there are many different types of control methods have been applied to the four-wheel steering system. The types of control methods include fuzzy logic control, linear quadratic regulator (LQR) based control, robust control, sliding mode control, and proportional-integral-derivative (PID) control. The pros and cons of each control method applied to the four-wheel steering system will be included.

TABLE I. TYPES OF WHEELS

Types of Wheels	Figures	Descriptions	Pros	Cons	References
Standard/ Fixed wheels		Moves in two directions. Commonly used as drive wheels.	Simple structure. Good reliability. Wide range of sizes.	Provide nonholonomic velocity constraint where no side slip condition will limit robot motion. Only suitable for indoor designs.	[7]- [8]
Ball wheels		One of the simplest types of wheels used to balance the robot. Contain hard spherical material with 360 degrees of freedom that positioned within a holder. Commonly used as support wheels.	Provide nonholonomic constraints where the robot can be navigated with any desired linear or angular velocities at any time. Accomplishes smooth and continuous contact between the wheels and the ground.	Difficult to design. Low payload. High rolling resistance with poor traction Not suitable for uneven, dusty, and greasy surfaces.	[7]- [8]
Omni wheels		Also known as Swedish wheels. Wheels with rollers at a 90-degree angle around the circumference of another. Multi-directional movement. Used as both drive and steer wheels.	Move fast in all directions. High efficiency with low rolling resistance. Long lifespan. Cheaper than mecanum wheels.	Causes friction loss. Computationally complex due to the angle calculations of movement.	[7], [9]
Mecanum wheels		One type of Omni wheel with the exception that rollers are attached 45 degrees angle around the circumference of another. Multi-directional movement. Used as both drive and steer wheels.	Very fast dynamic motion in every direction. Rapidly and efficiently transfer forward wheel spin into sideways motion. Suitable for both indoor and outdoor designs. Long lifespan.	Expensive. Heavy. Slow movement.	[7], [9]

TABLE II. TYPES OF CONTROL METHODS

Types of Control Methods	Descriptions	Advantages	Disadvantages	References
Fuzzy logic control	Formulated based on the operator's knowledge and understanding.	Compensate bad influence by nonlinearity and uncertainties depending on the operator's knowledge. Strong robustness. Independent of a mathematical model. Simple to use. Fast response. Low cost. Easily maintained.	The controller design may vary because required high human expertise. Regular updating of fuzzy rules based on real-time operation.	[12]- [14]
Linear quadratic regulator (LQR) based control	Adopting a mathematical algorithm that reduces a cost function with weighting factors provided by the operator.	Better performance index of the system. Simple and easy to implement. Better maneuverability and handling stability in following the desired path.	Required good knowledge about the state of the problem and the adjustment of the weighting factors. Not effective for complex or non-linear systems.	[15]- [17]
Robust control	For μ synthesis robust control, the structured singular value μ is used to deal with differential uncertainty.	Better maneuverability. More vital ability to resist the disturbance. Good robustness against fluctuating loads and change of velocity of the four wheeled mobile robots.	Trade-off made between performance and stability against disturbances and parameter variations.	[18]- [21]
Sliding mode control	Using discontinuity of the sign function in the control law.	Fast response. Good transient performance. Insensitiveness to unmodelled dynamics. Insensitiveness to external disturbances. Insensitiveness to parameter perturbation of the system.	Chattering phenomenon occurs. Discontinuous Control law. Limited to single-input systems.	[11], [22]- [26]
Proportional-integral-derivative (PID) control	Using proportional, integral, and derivative terms to calculate the variance between the desired output and the actual output.	Simple structure. Low-cost implementation. Easy to implement.	Effective only for linear and near linear non-linear systems. Noise in the derivative part. Low robustness.	[27]- [30]

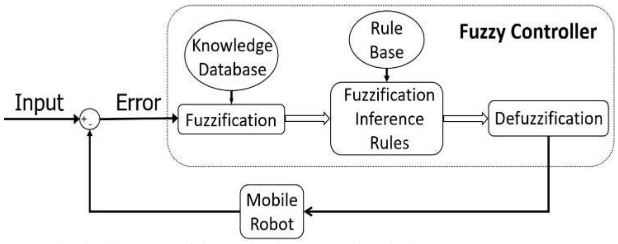

Fig. 1. Block diagram of fuzzy logic controller design

A. Fuzzy Logic Control

The fuzzy logic control method has been widely used as an effective tool to implement engineering heuristics into a control solution for non-linear and complex systems. Compared to model-assisted control methods, the fuzzy logic control method can achieve effective control without the detailed models of the system. A fuzzy logic controller is usually formulated according to the operator's knowledge and understanding of the process or identified from measured control actions, which will then result in varied designs of controllers. Based on the operator's expert experience, the fuzzy logic controller can be formulated to overcome the nonlinearity and uncertainties of the mobile robot. In the fuzzy logic controller design, as shown in Fig. 1, the major components are the fuzzifier, fuzzy knowledge base, fuzzy rule base, inference engine, and defuzzifier. The role of the fuzzifier in the fuzzy logic controller design is to convert the input values into fuzzy values. In the meantime, the fuzzy knowledge base stores the knowledge about all the input-output fuzzy relationships and the membership function that defines the input variables to the fuzzy rule base, and the output variables to the mobile robot under control. Then, the knowledge about the operation of the process of a domain is stored in the fuzzy rule base. The inference engine acts as the core of the fuzzy logic controller design that imitates human decisions by fulfilling approximate reasoning. After that, the defuzzifier is used to change the fuzzy values into output values from the fuzzy inference engine [12]. The fuzzy logic controller has strong robustness and is independent of a mathematical model. Furthermore, fuzzy logic controllers are also advantageous with their simple design, fast response, low cost, and effortlessly maintained as the fuzzy rules can be interpreted by any operator [13]- [14]. As the fuzzy logic control design required high human expertise, this will be one of the drawbacks as the accuracy of the system is depending on the knowledge and skill of the operator. Then, the fuzzy logic controller required regular updating of fuzzy rules based on real-time operation [14].

B. Linear Quadratic Regulator (LQR)

Linear Quadratic Regulator (LQR) is a control method that offers optimally controlled feedback gains to enhance the system's closed-loop stability and performance index of the system. The LQR controller uses a mathematical algorithm that diminishes a cost function with weighting factors defined by the operator. For the LQR controller design, the optimal gain in (1) is chosen based on linearization models to minimize the quadratic objective function in (2) through the state feedback method as in (3) [15]. LQR is simple and easy to implement in the four wheeled mobile robots to enhance the robot's stability and maneuverability when the robot is controlled to follow the desired path. To improve the robot's stability and maneuverability, it is important to maintain the robot's actual motions, yaw rate, and slip angles close to the desired responses with a minimum external yaw moment. Therefore, LQR is important for the development of the yaw moment and steering angle control law [16]. However, the LQR controller required good knowledge about the state of the problem and the adjustment of the weighting factors as it will have a significant effect on the reliability of the controller. The LQR controller is also not effective for complex or nonlinear systems [17].

$$K = R^{-1}B^T S \tag{1}$$

$$J = \frac{1}{2}\int_0^{\infty} [(x_d - x)^T Q (x_d - x)^2 + u^T R u] dt \tag{2}$$

$$u = -Kx \tag{3}$$

where x_d is the desired state of the system, u is the control input, B is the input matrix, K is the symmetric matrix of feedback gain, S is the feedforward gain matrix, Q is the positive semi-definite state weighting matrix, R is the positive semi-definite control weighting matrix.

C. Robust Control

In robust control, the μ synthesis robust control is an effectual technique of robust control analysis and synthesis. This method can effectively model the differential uncertainty and deal with the system's stability robustness and performance robustness simultaneously. The μ synthesis robust controller uses structured singular value μ to deal with differential uncertainty. In the μ synthesis design procedure, the weighting function is the main matter to deal with the system perturbations. The design of the robust controller is required to formalize the uncertainties and system specifications as shown in Fig. 2. Based on Fig. 2, the front wheel steering angle of the four wheeled mobile robots is used as the input signal, while the rear wheel steering angle control is designed by considering some of the possible uncertainties [18]. In Fig. 2, G_f and G_r is the transfer function of the front and rear steering input to yaw rate r. The robust controllers have more advantages because of their more vital ability to resist disturbance and achieve better maneuverability. The robust controller also provides good robustness against a relatively more comprehensive system perturbation such as loads fluctuation and changes in the velocity of the four wheeled mobile robots [19]- [20]. However, there will be a contradiction between performance and stability in the robust control, hence a trade-off must be made between performance and stability against disturbances and parameter variations [21].

D. Sliding Mode Control

Sliding mode control is a practical method that can control both uncertain linear and non-linear systems. The sliding mode controller uses discontinuity of the sign function in control law that is advantageous in fast response, good transient performance, insensitiveness to unmodelled dynamics, insensitiveness to external disturbances, and insensitiveness to parameter perturbation of the system [11]. In a sliding mode controller, numerous different continuous functions map the four wheeled mobile robot's state to a control surface, and the switching among different functions is determined by the robot's state that is represented by a switching function. A sliding mode controller without the loss of generality for the second-order system can be designed as in (4). The composition of a sliding mode controller as in (5) is chosen where u_{eq} is the equivalent control used for the system state in sliding mode. In (5), k is the maximum controller output which is a constant and S is the switching function as the control action switches depending on its sign on the two sides of the switching surface, $S = 0$ [22]. However, the sliding mode controller will cause the chattering phenomenon because such an intermittent high gain controller may excite unmodelled dynamics and causes unpredicted instability in many applications [23]. In addition, the disadvantages of the sliding mode control include discontinuous control law and are limited to single-input systems [24]. To reduce the chattering effect, one of the approaches of substituting the sign function as in (5) with a smooth function as in (6) is developed [25]. It is better to achieve a sliding mode control scheme free from chattering to effectively deal with the four-wheel steering mobile robot. Thus, an asymmetric barrier function-based adaptive control method is implemented to improve the trajectory tracking performance. This method guarantees the resultant trajectories are closed to the desired despite the unknown disturbances and system uncertainties [26]. The block diagram of sliding mode control applied for the four wheeled mobile robots is shown in Fig. 3.

$$\ddot{x} = f(\dot{x}, x, t) + bu(t) \tag{4}$$

$$u = -k\ sgn(S) + u_{eq} \tag{5}$$

$$\mathrm{sgn}(s) = \frac{s}{|s| + \delta} \tag{6}$$

where $u(t)$ is the input and δ is a smaller positive constant.

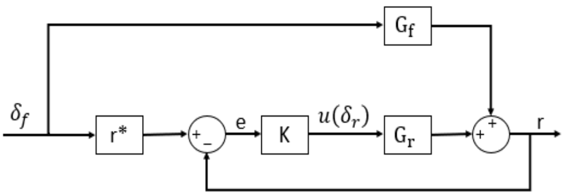

Fig. 2. Closed-loop control system based on μ synthesis [18]

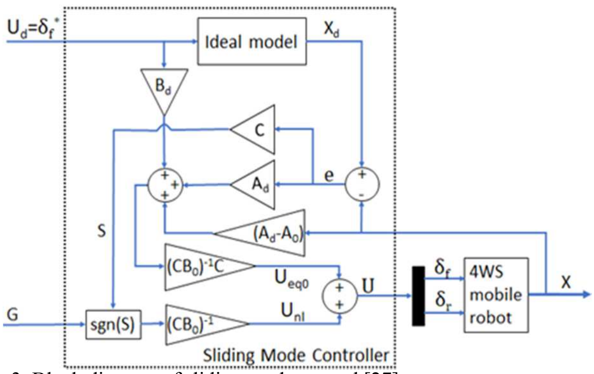

Fig. 3. Block diagram of sliding mode control [27]

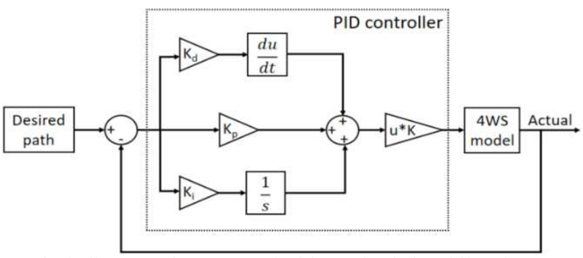

Fig. 4. Block diagram of PID control of four wheeled mobile robots [16]

E. Proportional-Integral-Derivative (PID)

PID is one of the most commonly used control algorithms in linear or near linear non-linear systems. This control method has proportional, integral, and derivative terms to compute the difference between the desired output and the actual output. For the PID controller design, a proportional controller (K_p) is used to decrease the rise time and steady-state error. An integral control (K_i) is used to eliminate the steady-state error for a constant or step input but the transient response will become sluggish. A derivative control (K_d) is used to diminish the overshoot and improve both the stability and transient response of the system [15]. These correlations are not necessarily correct because K_p, K_i, and K_d are reliant on each other. Hence, modifying one of these variables will affect the other two. In addition, the constant controller parameter limits the PID controller to linear and near linear non-linear systems only, which greatly setback the PID control system. Furthermore, there will be noise in the derivative part and low robustness for the PID controller [28]. In industrial, PID controller is still widely used due to its simple structure and low-cost implementation [29]. Besides that, it is easy to implement in real control systems [30]. The block diagram of PID control applied for the four wheeled mobile robots is shown in Fig. 4. Table II summarizes different types of control methods with descriptions, advantages, and disadvantages included for each type of control method.

IV. Conclusion

In this paper, a review of the wheeled mobile robots highlighted in the four wheeled systems is presented. This paper starts by underlining the significance of the purpose of the mobile robot in the process of designing the robot. Feature selection based on the purpose of the mobile robot will lead to the mathematical formulation of the system, that allows the virtual study of the system to verify the robot system before it is built.

In the virtual study of the robot system, the number, configuration, and type of wheels will result in different robot models. Besides that, the number of wheels also defines the stability of the wheeled robot. As far as the smooth terrain is concerned, the four wheeled mobile robot system is the most stable and cost-effective system. Meanwhile, for rough and sandy terrain, additional wheels can be used to increase the contact surface with the ground and improve the stability of the mobile robot. However, this led to an increase in design complexity, construction, and maintenance costs.

The types of wheels are also imperative in the design of wheeled mobile robots. This is because the wheels used in the design are only required to withstand the weight of the wheeled mobile robot and the payload, it also needs to provide the maneuverability required. For indoor designs application, the standard or fixed wheels and ball wheels are the most suitable wheels to be used for the wheeled mobile robot system. Whereas for narrow path applications, the Omni wheels and mecanum wheels are the most suitable wheels to be used for the wheeled mobile robot. Because it can provide multi-directional movement and no turning space is required. But the use of Omni wheels and mecanum wheels required a complex maneuver algorithm.

Avoiding the complex manoeuvrer algorithm of the Omni wheels and mecanum wheels system, a four-wheel steering system can be adapted to achieve similar maneuverability with a less complex manoeuvrer algorithm. The four-wheel steering system also provides better steering response, precision, and power efficiency to the four-wheeled mobile robots. A control system is also developed to achieve path control and to perform precision maneuvers.

Due to the advancement of technology, many different types of control methods are developed and employed in the four wheeled mobile robot. Each control method has different pros and cons that can be employed in the four wheeled mobile robot system. To achieve good control of a four-wheel steering mobile robot, sliding mode control is a potential method that proposes better insensitivity to unknown disturbances and guarantees the achieved states are forced to the sliding regions. However, the discontinuity feature of the sliding mode control will cause a chattering phenomenon. Hence, a control scheme to overcome the payload uncertainty, system uncertainties and unknown disturbances including the parametric vibrations that led to tracking performance limitations have to be obtained for the control of four-wheel steering mobile robot. To improve the trajectory tracking performance of four-wheel steering mobile robots, payload uncertainty is the main issue to be tackled especially for load carrying purpose. To overcome the payload uncertainty, an adaptive control method can be proposed to implement in the four-wheel steering mobile robot. This proposed method provided possible research directions for the four-wheel steering mobile robot to further improve its trajectory tracking performance in the near future.

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