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A review of controller approach for autonomous guided vehicle system

Faiza Gul[1], Syed Sahal Nazli Alhady[2], Wan Rahiman[3]
[1,2,3]School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM), Malaysia
[3]Cluster of Smart Port and Logistics Technology (COSPALT), Universiti Sains Malaysia, Malaysia

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ABSTRACT

The autonomous guided vehicle is a great and important platform for control systems. Their non-linear nature helps in analysing the control algorithms more efficiently and effectively. The main purpose of path planning is to find the optimal path avoiding the time complexity so environment can be modeled completely. For path planning numerous algorithms have been proposed to solve their non-linear nature. The paper contains brief explanation on AGV application, and its controller design architecture have been discussed with advantages and disadvantages, e.g. Fuzzy control, Neural Control, Back-stepping control, Adaptive control, Sliding mode control and PID control and linear quadratic regulator. At last a brief conclusion has been drawn on the bases of strength and weakness of all algorithms. The research will help the readers to understand mobile robotic path planning with different controllers.

Corresponding Author:

Wan Rahiman,
School of Electrical and Electronic Engineering,
Universiti Sains Malaysia,
Nibong Tebal, 14300, Penang Malaysia.
Email: wanrahiman@usm.my

1. INTRODUCTION

The automated guided vehicle can be upgraded into autonomously controlled, famously known as autonomous guided vehicle (AGV), is used in industrial applications to transfer materials from pickup place to drop off place. It is the only kind of transportation, which follows guidance to reach destination. Material handling systems uses AGV, which are used in facilities such as distribution centers, manufacturing plants, terminals and warehouses. Their performance effects the whole delivery system. Wheel based or computer based are their controlling parameters. Their motion is dependent on the combination of sensor-based guidance and software-based guidance systems. They have a predictable path for their movement which also includes obstacle avoidance and detection. They include transportation of goods and raw material inside the vicinity of industry or warehouses avoiding the obstacle and ensuring the safe delivery at destination point. Material handling by the help of AGV has also gained importance in facilities such has warehouse, manufacturing plant, distribution terminals and centers. In terms of algorithm design, autonomous navigation is using control structure architecture based on automated guided system. Then the issues related to these facilities using AGV can be divided into; estimated number of vehicles, guide path, idle-positioning, and vehicle scheduling and battery management. Bio-inspired techniques are most popular, and researchers are implementing them solving path planning problem for AGV or mobile robots [1]. The popular bio-inspired algorithms are based on the living creature behavior which include birds, bees, ants, whale, bat, fish, wolf [2-8]. Randomly exploring tree algorithm with pure pursuit controller can be found in [9]. Examples can be found in, robotics, physics, and control engineering and rehabilitation science [10]. The paper describes the review related to AGV. There are records of considerable number of researches that describe addressing path planning and obstacle avoidance problem using algorithms [11-13].

Zheng et al. proposes waterborne AGVs, inspired by conventional automated guided vehicles and autonomous surface vessels, for transport over water. The controller can achieve energy efficiency and smooth tracking with arrival time awareness for transport-oriented applications. Tracking errors are also formulated. For smooth tracking the lower level is embedded with online MPC (Model Predictive Controller). Simulation results illustrate the effectiveness of the proposed modeling and control design for waterborne AGVs [14].

Pedapati et al. have studied the Non-linear adaptive control of an AGV. The control strategy follows two points: i) trajectory tracking in presence of actuator ii) free movement of the AGV in an obstacle cluttered environment. The author presented the controller which exploit a conventional feedback controller in conjunction with an adaptive inverse dynamic's strategy for the actuators. Auto-Regressive Exogenous Model (ARX) and Non-Linear Auto-Regressive Exogenous Model (NARX) have been used for identifying the AGV actuator inverse dynamics. The simulation proofs the efficiency of proposed indirect adaptive controllers in comparison to Inverse Dynamic Conventional Feedback Controller (IDCFB) [15].

Chen et al. proposed a predictive sliding mode control method based on multi-sensor fusion to solve the problem of insufficient accuracy in trajectory tracking caused by actuator delay. The controller, based on the kinematics model, uses an inner and outer two-layer structure to achieve decoupling of position control and heading control. The experimental results depict that the new control algorithm can improve the performance of the AGV controller by referring to the positional change rate, thereby improving the AGV operation without derailing [16].

Wan Rahiman et al. have studied an autonomous car navigation system based on Global Positioning System (GPS). The primary objectives of the authors were to make an auto-navigational car model that can route through known or pre-programmed co-ordinates autonomously without any control by human. The design uses a low-cost inertial measurement unit (IMU) to navigate between intermittent GPS fixes. The hardware consists of a IMU, GPS receiver, compass and a data processing computer [17].

Taghavifar et al. focuses on the controller design for path-tracking problem of autonomous ground vehicles by employing a multi-constraint nonlinear predictive control (NMPC). It is aimed to improve the transient performance of the vehicle and to consider a rollover prevention criterion in the proposed method. The validity of the presented control system is verified by comparing with the traditional NMPC technique by employing a high fidelity CarSim/MATLAB framework [18].

Alireza Asvadi et al. worked on 3D lidar and presented the 3D perception system based on planes and voxel for obstacle avoidance and modeling of a ground environment. The algorithm is divided into two parts, first part includes estimation of ground environment using RANSAC and piecewise plane fitting method and the second part works on determining the dynamic and static objects using voxel-grid model and ego formation. The authors did experiments by utilizing Velodyne Lidar for point-cloud and used inertial navigation system for localization. The obtain results were checked on urban scenes and proved the efficiency of results [19].

In view of implementation autonomous system in industral mobile robot application, a detail of different types of AGVs are discussed below: Fork-lifts: Fork-lift truck applications are considered relatively new. Guided fork trucks are also common in use as they have ability to automatically pick up items of load and drop them at destination without human intervention. They are used when any system requires an automatic pickup and drop off loads from stand level or floor level. The vehicle can position its forks according to desire load level with different heights.

Unit Load: Unit load application involves specific assignments for load delivery. They are popular in integrating conveyors with storage retrieval or assembly operation system. They are famous for transferring load from one station to the other station with remote management facility relatively used for shorter distance but higher volume of load. They are applied in distribution and warehousing system. Roller decks or lift decks can also be integrated with unit load train to shift load by conveyors where the maneuverability of vehicle is difficult. In this way, it provides efficient versatility in moving products because they operate in independent manner and can perform task by passing each other and reaching to specific destination.

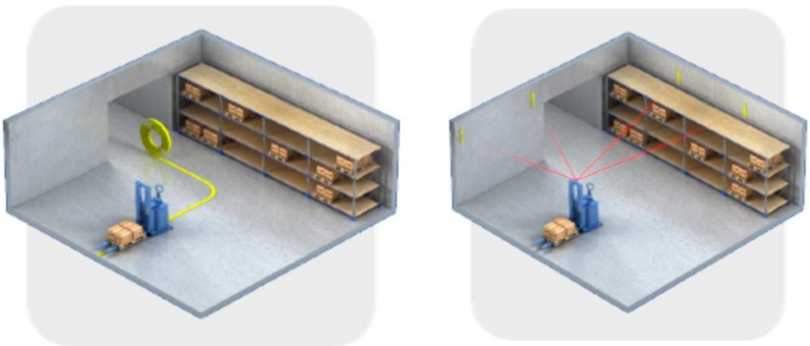
Tugger/Tow: They are also called as driver-less train and considered as earliest kind of AGV. They are involved in transferring bulk of product in and out of warehouse area. They carry trailer cart with themselves for dropping off products at destination that is also considered as chain movement of product. To unload the product several stops are taken to unload product. This kind of movement is used when the distance is very long in distributed area. This method is considered as very efficient as compared to fork truck due to its ability to carry massive and large amount of product in short time. The dynamics of the AGV are considered non-linear and has numerous uncertainties during their movement, therefore its a challenging venture to explore. This has led to several control algorithms proposed in the literature. In this work, a review of the prominent control algorithm together with controllers applied to the AGV are discussed.

2. TECHNIQUES FOR AGV GUIDANCE

They are several kinds of AGV presents through which the desired task can be performed. For making them efficient and reliable they are incorporated with other sensors to make them more efficient. Some AGV kind are discussed below.

a) Wire Guide is constructed with a wire cut and placed into the floor approximately 1 inch below the surface as shown in Figure 1(a). The slot is cut down along the path of AGV to follow. Then the wire is used to transmit radio signal so the sensor that is installed at the bottom of the AGV near to ground can detect the signals and follow the path. Sensor helps in detecting the relative position of signals from wire, which helps in steering motion of AGV.
b) Guide Path may follow the painted line/tape or magnetic bar embedded in floor as guidance. They also use guide sensor to follow the path. Floor taping is usually considered as less expensive but has disadvantage of getting damaged or dirty in high traffic area whereas magnetic bar is considered as flexible due to dual polarity but suffers from same problem as wire embedded in floor. The major advantage of tape guidance is that it can be easily relocated and removed according to need.
c) Laser Guidance very effective and efficient method for AGV path planning is done by the use of LASER. Reflective tapes are mounted on walls inside the vicinity of warehousing as shown in Figure 1(b). AGV carries the laser transmitter and receiver. The beam is transmitted and received from laser sensor through which distance and angle are measured and AGV position and orientation is calculated which is then calculated with pre-installed path programmed map in the memory of AGV to the layout map. The main advantage of LASER guidance is that it can navigate to any desired destination by continuously updating position.

The results in a guidance technique which behave as usual, but the complexity level depends on various navigation system development and construction processes. Table 1 shows the comparison among different kind of techniques involved in AGV.



(a) (b)

Figure 1. Type of AGV navigation method; (a) magnetic tape (b) laser

Table 1. Comparison of control algorithms for AGV

Navigation Techniques	Easy installation	Implementation cost	Efficiency	Tracking ability	Simplicity
Wire Guided	High	Low	Low	Average	Low
Guide Path	Easy	Low	Average	Average	High
Inertial Guidance	Low	Low	Average	Good	Medium

3. VECHILE DYNAMICS

In automatic guided vehicle, path planning is carried out by path tracking and motion control process. Path planning helps in generating collision free path in an obstacle filled environment. Path tracking tells how much steering angle and speed be required by vehicle to determine where it should move from one position to another following the desired path and motion control maintains the trajectory of vehicle along the predefined path. For this purpose, variety of advanced techniques have been developed to solve path-planning problem. Simple control strategies are employed to simplify the vehicle dynamics for low-speed vehicles. So complex vehicle aspects are neglected e.g. throttle, brake, roll and tire slippage to keep the vehicle model simple and easy to implement. Different kind of wheels are used to support the vehicle speed and orientation. Independent driving wheels can be used at the front of the chassis on same axis to provide braking and driving the vehicle and a separate castor wheel at the front or at the back of the chassis can also be used to give balance to vehicle. Also, four separate differential wheels are used to give stability to vehicle. Front wheels support vehicle in forward and backward motion as well as also helps in avoiding cornering. Back wheels are used to support in braking system. Figure 2 shows the geometric description of 4-wheel differential mobile robot. Where θ represents the orientation angle of robot w.r.t world coordinate system $[Xw, Yw]$ together vehicle pose $[x, y, \theta]$. Figure 3 shows the 4-wheel differential driven robot.

Two differentially driving wheels are mounted on the same axis together with rear/castor wheel to stabilize the vehicle. For navigation method, the orientation and motion are acquired by independent actuators of both wheels and DC motor provides required torque to front wheel. The drive module coordinates the operation of the two-wheel drive motors through the motor controller to realize the forward, reverse and steering of the AGV. A strategic design in this platform is to allow for smooth movement in a confined space compare to 4-wheel AGV. Figure 2 shows the 2 differentially driven vehicle. Where r is the radius and v_r and v_l are the right and left wheel velocities. XY are the global co-ordinate system and X_R, Y_R are the local coordinate system frame and d are the distance from the centre of the wheel. The position of AGV can be determined from coordinate vector $q = [x, y, \theta]$ where x and y are the coordinates points in global system and θ is the orientation angle. Where wr, wl and vr, vl are angular and linear velocities of right and left wheels. Assuming wheels has no slip and roll.

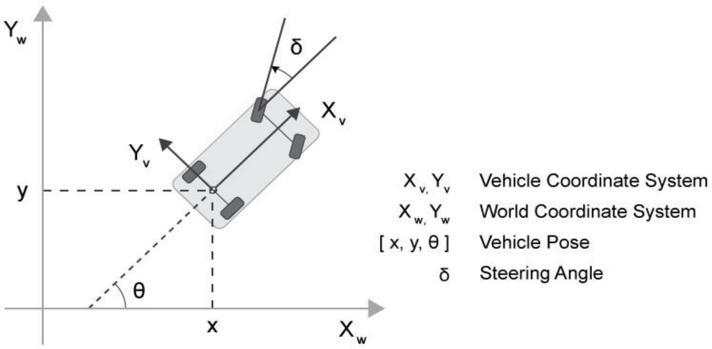


Figure 2. 4-wheel differentially driven robot

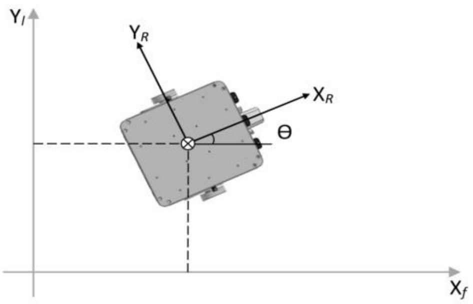


Figure 3. Representation of robot in coordinate system

The kinematic motion equation of vehicle that describe the mathematical relationship between the parameters of the AGV's motion can be written as following:

$$v_r = r * w_r \quad (1)$$

$$v_l = r * w_l \quad (2)$$

$$r = \frac{v_r + v_l}{2} \quad (3)$$

$$v = \frac{r}{2} * (w_r + w_l) \quad (4)$$

The control problem for AGV has widely been researched. Faisal et al. [20] the authors steered the mobile robot to final destination point and implemented the fuzzy logic for avoiding obstacles. Abdallah K. et al. [21] the authors have designed a fuzzy logic controller for path planning and target search with obstacle avoidance. Hajer Omrane et al. [22] implemented the path tracking control robot in a environment by using the DC motor and infrared sensor for measuring distance to & from obstacles and encoders to adjusting the speed. A bumper event approach was employed to develop an algorithm for obstacle avoidance of Turtlebot in [23]. The approach however did not provide free collision navigation.

4. AGV NAVIGATION

The navigation architecture of AGV includes path planning, exploration, obstacle avoidance and localization. Path planning is considered as a cognitive level for AGV. It involves integration and aggregation of ambient information so that AGV manoeuvrability can be enhanced. For successful path planning, path information must be updated continuously, and unanticipated events should be handled in a constructive manner. Figure 4 shows the architectural diagram of autonomous guided vehicle.

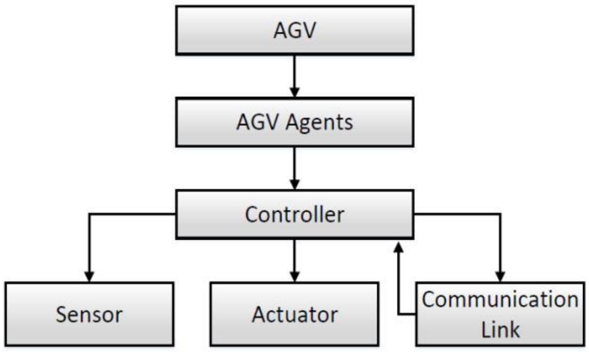


Figure 4. Block diagram of autonomous guided vehicle

4.1. Survey of control algorithms

The dynamic nature of AGV has led to develop several control algorithms. The control system can broadly be classified as a Linear and Non-Linear control system. Each control algorithm has its pros and cons. Some of the controller designed for AGV system has been discussed below.

4.2. Proportional integral derivative (PID)

The PID controller considered as the widely applied controller and applied for broad range of controller in control system applications. It is considered as a simplest controller to design and implement since the gain parameters are easy to adjust. However, some major challenges involve the non-linearity, imprecise and inaccurate parameters of the model. Therefore, PID controller limits the implementation design of system and its performance. Li et al. used PID with fuzzy logic controller to enhance the static and dynamic performance of AGV as well as improve the performance of PID controller [24]. They use Kalman filter to determine the pose of AGV. Gomes et al. developed a control algorithm for AGV model to follow the predefined path by line avoiding oscillation on its movement. Cameras were used inside PID control loop to track path [25]. Kim et al. [26] have designed the obstacle avoidance system for AGV by using fuzzy logic control with PID control. They controlled the rotation angle and moving velocity by fuzzy-PID controller. Al Zaher et al. developed the AGV for lane tracking, detection and obstacle avoidance. The system employs camera for collecting data in real time and images captured by camera were used to recognize the lanes lines and obstacle dimension. A PID controller used to predict the vehicle-heading angle [27]. Wan Rahiman designed PI controller for velocity control of a mobile robot. A loop of PI controller is designed to provide a stable velocity to the mobile robot system [28]. Pan Zhao et al. presents the control system architecture by developing the new adaptive PID controller called" Intelligent Pioneer" for navigation of mobile robot in an unknown environment. Two-degree freedom model is presented for the formulation of state space [29]. The results were presented in Future Challenge of China and stood out as number one. Figure 5 shows the general block diagram of a PID controller for autonomous guided vehicle.

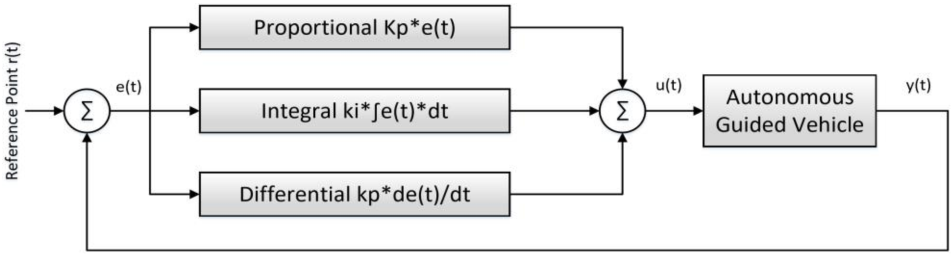


Figure 5. Block diagram of PID controller for autonomous guided vehicle

4.3. Fuzzy logic and neural network

Intelligent control algorithms have several artificial intelligence techniques, and some are biologically inspired for controlling a system. This includes fuzzy logic, neural network, genetic algorithm and machine learning. They are considered an efficient way to deal with the intelligent system but involves mathematical complexity and uncertainty. This also increases computational complexity for usage of intelligent system. There are many intelligent control systems, but fuzzy logic and neural network are considered as most widely used and applied control system. Fuzzy Logic strategy was implemented for control and trajectory tracking for an autonomous unicycle robot. A back-stepping approach implemented in Fuzzy Logic Controller to acquire the asymptotic stabilization of the robots pose around the desired trajectory [30]. The Mamdani Fuzzy Inference system with IF-THEN rules has been implemented to construct the controller. Input velocities and torques were given the linguistic variables and centroid method area was used for defuzzification process. Simulation results were also carried out to illustrate the performance of Fuzzy logic controller. The kinematics and dynamics of vehicle were also studied. Tso et al. have highlighted that the performance of AGV can be measured and calculated by errors in their position and orientation [31]. They presented the fact that sometimes errors in robot pose are not measured and feedback system is essential to employ to obtain position error. A linear controller is implemented which was further improved by the implementation of Fuzzy logic. Two fuzzy logics were created. Opto-sensors are present in a linear array. The Popov criterion, the phase-plane method, and the Hurwitz criterion demonstrate the stability of the system. Similarly, for neural network approach many authors have worked, and solved problems related to AGV. Singh et al. designed a multilayer feed forward neural network to control the steering angle of robot in static and dynamic environment. The obstacle distances are feed as input and the steering angle of AGV is the output [32]. Zhan et al. presented the intelligent coordination control scheme for AGV steering system by the help of fuzzy control, bang-bang control and neural network. Least square method used for the AGV system identification. The dynamic model for AGV steering system is expressed using orientation angle error and distance error [33]. Motlagh et al. propose the obstacle avoidance and target seeking behaviour of AGV using neural network [34]. Medina-Satiago et al. considered path planning of pattern classification [35]. They developed a path planning algorithm using multilayer perceptron and back propagation of ANN which was experimented on a differential drive mobile robot. Figure 6 shows the block diagram of a Fuzzy logic controller.

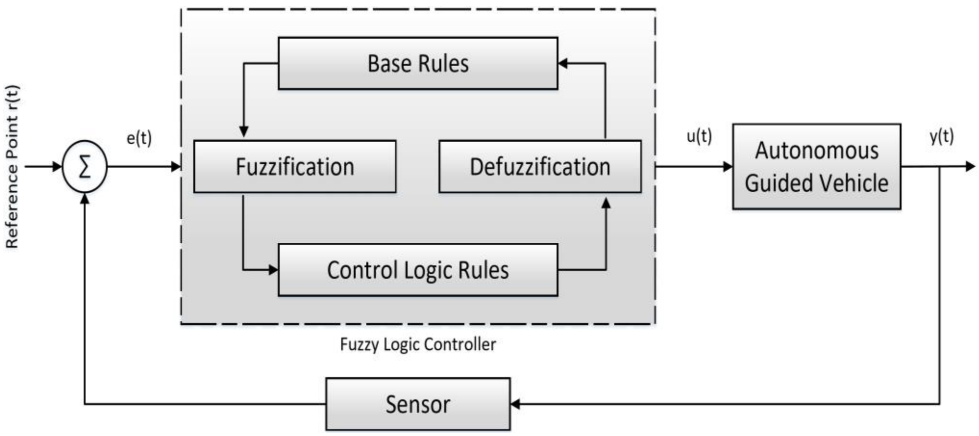


Figure 6. Block diagram of fuzzy logic controller for autonomous guided vehicle

4.4. Backstepping controller

Backstepping controller, considered as the most important technique for stabilizing a nonholonomic system. It is a recursive procedure, which breaks the design problem of controller into sub design problems and progressively stabilizes sub design system. It requires less computational time and converges fast with less disturbance in nonlinear system, but the algorithm robustness is not efficient [25]. While, Partama et al. have proposed a trajectory tracking algorithm for AGV system using backstepping controller unknown wheel radii. A lyapunov function helped in kinematic modelling and achieving system stability [36]. Another backstepping controller for Wheeled Mobile Robot has been developed by Dumitrascu et al. [37] based on robot's kinematics. The controller performance is evaluated in real time and through simulations. The backstepping controller is also used to keep the vehicle on track. Fan et al. developed 4-wheeled steering automatic guided vehicle (4WISAGV) and control the steering of each wheel independently by demonstrating the vehicle track and reducing the 4-wheeled vehicle to 2-wheeled vehicle by aligning wheels in center of vehicle [38]. Backstepping controller used to keep track of vehicle path and at last simulation results proved the successful trajectory.

4.5. Sliding mode control

SMC is a non-linear control algorithm, considered as effective approach and solution due to its easy implementation, robustness in parameters variation, fast dynamic response, and good tracking ability. In a different development, SMC was considered by some researchers [39, 40]. The algorithm works when a discontinuous signal applied to a control signal of system to command it and slide it to prescribed path. Wang et al. developed trajectory tracking control system for AGV by incorporating VDC, vehicle dynamic control with it. The control system depends on two levels: a desired yaw rate generator based on kinematics and yaw rate controller based on tire dynamics of AGV [41]. Ertugrul et al. modelled AGV system using kinematics and dynamics response and using variable structure system technique [42]. They developed a sliding mode controller using Lyapunov method to eliminate chattering. The simulation proved the results. Thanhphuong et al. designed a non-linear controller for AGV system. The controller helps AGV to follow the desired path with constant velocity and encoders help to estimates the position of AGV. Lyapunov method helps in improving the system stability [43]. Soysal et al. proposed the tracking control method for AGV, using sliding mode controller. The SMC used to control direction angle and velocity of vehicle to keep it on desired path. The controller applied a continuous signal instead of a discrete signal. It occurs due to discontinuity of control signal [44]. Figure 7 shows the general block diagram of a sliding mode controller for autonomous guided vehicle.

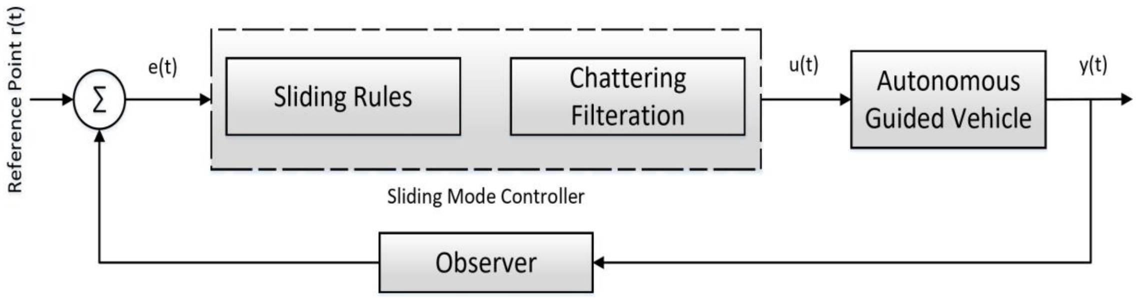


Figure 7. Block diagram of sliding mode controller for autonomous guided vehicle

4.6. Adaptive control

Adaptive control algorithms are prone to adapting parameters in system. These parameters are either varying or uncertain with time. Non-linear adaptive controller was presented for autonomous guided twowheel vehicle for automatic overtaking manoeuvre in [45]. Using robotic nomenclature for translational and rotational velocities and kinematics model of robot used in developing relative inter-vehicle kinematics. Hidaka et al. proposed a path control AGV that can steer in all directions [46]. They developed an adaptive path control for omni directional and holonomic AGV by assuming that design parameters cannot be decided in control system. Numerical simulations proved the validity of result. Figure 8 shows the general block diagram of an adaptive controller for autonomous guided vehicle.

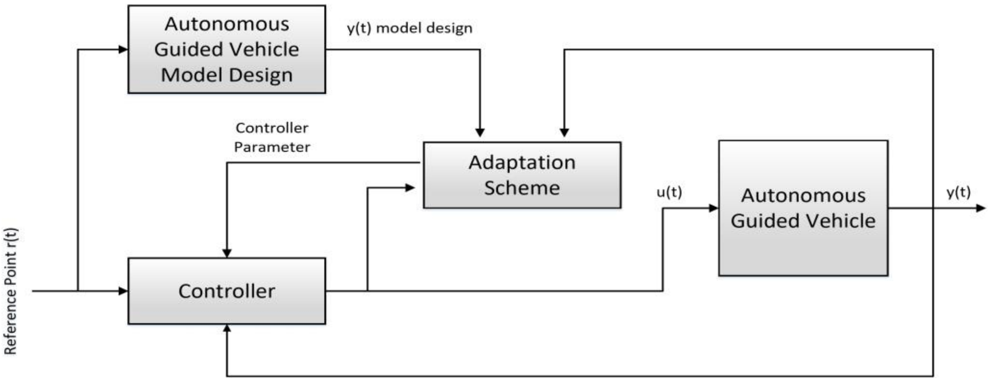


Figure 8. Block diagram of adaptive controller for autonomous guided vehicle

4.7. Linear quadratic regulator

The LQR control algorithm runs a dynamic system by optimizing the cost function. It is considered as powerful technique for both linear and nonlinear system. Li et al. proposed the trajectory tracking control for AGV system. Newton second law used for vehicle lateral motion and lateral tire forces. The linear quadratic regulator then used for path tracking control [47]. MATLAB and CarSim used for simulation purpose. System performance is also countable parameter when designing a control system for any vehicle. For small system, lesser state space variables are required and the conversion of the performance index from scalar form to matrix form is considered simple and easy for implementation whereas for larger system more appropriate design, controller and state variables are required. Tchamna et al. used linear quadratic regulator to design a technique for large system, which do not require the redesigning from beginning and make it easy for implementation for any new implemented system [48]. The method was used to control the attitude of vehicle in cornering. Figure 9 shows the block diagram of linear quadratic regulator.

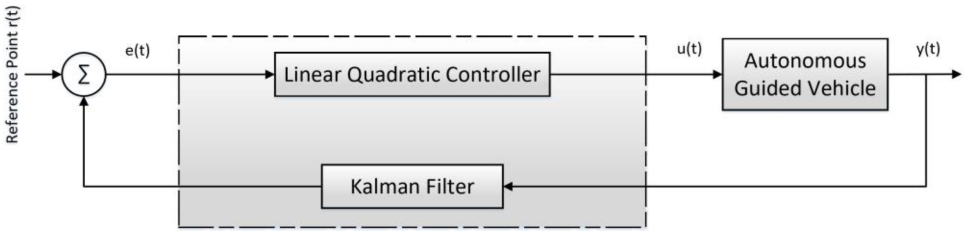


Figure 9. Block diagram of linear quadratic regulator for autonomous guided vehicle.

4.8. Hybrid control algorithm

It has been observed that linear or non-linear algorithms had their own limitations and cannot provide desired output and no single controller provide give required performance. So many researchers have integrated different controllers together to enhance system performance. The scheduling and routing is considered as important problem for AGV [49]. A hybrid simulated annealing and Dijkstara algorithms have used to solve routing problem. Then hybrid algorithm and simulated annealing algorithm were compared to check the performance. Mousavi et al. presented fuzzy hybrid Genetic algorithm and particle swarm optimization algorithm to solve the scheduling problem of AGV. The obtained results showed that hybrid system take less computational time when compared with GA and PSO algorithms itself [50]. Table 2 shows the comparisons of different algorithms based on their performances.

Table 2. Comparison of control algorithms for AGV

Algorithms	Robustness	Optimal	Intelligent	Tracking ability	Simplicity	Precision
PID	Low	Low	Low	Satisfactory	High	Low
Fuzzy logic	Low	Low	High	Low	Low	Low
Neural Network	Low	High	High	Low	Low	Low
Backstepping	Satisfactory	Average	Average	High	Average	Satisfactory
Sliding Mode Controller	Average	Average	Satisfactory	High	Average	High
Adaptive Control	Satisfactory	Average	Average	Average	Low	Satisfactory
Linear Quadratic Regulator	Low	Average	Low	Average	Average	Low

5. STRENGTH AND WEAKNESS

A total of 50 articles were discussed in this study, encompassing the different control algorithms related to automatic guided vehicle. A brief report was made between most known control algorithm engaged in path planning. After deliberation the researchers has drawn a conclusion that hybridization of techniques is most popular and useful. Control algorithms has numerous elements to be taken in account for generating the best solution which involves stability, navigation route and safety of vehicle. In the beginning researchers worked with single controller to minimize the errors via generating desired output, as the technology and research grew it has been noticing that working with single controller does not produce the required results. To generate the best results or to enhance the working of any controller requires the integration of controller/algorithms which has good precision, response time and how intelligently it responds to the system errors produced in algorithms. As controllers are difficult to handle therefore hybrid systems do not assure the best performance. Therefore, a balance and trade off is required among controllers. To find the best match of controller's capabilities a desired output can be generated. The authors are still evaluating different algorithms for finding the balance in overall performance. Hybrid approaches that has the capability exploit the benefits and reduce the constraints of each of the technique involved can be considered to obtain better results for path planning and obstacle avoidance task. Still, attempts should be made for implementing these proposed algorithms in real robotic platform where real time conditions can be meet. Implementation should also involve both indoor and outdoor environments to meet real conditions required for autonomous guided vehicles. Table 3 shows the strength and weakness of algorithms.

Table 3. Summary of advantages in control techniques

Control Algorithm	Strengths	Challenges
PID	(a) Productive when combined with different algorithms	(a) Difficult to produce robust and efficient results
Fuzzy Logic &Neural Network	(a) Real time experiments can be performed (b) Tuning membership functions ispossible	(a). Had difficulty in handling the buriedlayers in neuron system (b). By adding more layers increase thecomputational complexity
Back Stepping Controller	(a). Provide good result in simulations (b). Less computational complexity (c). Fast convergence as compared to Fuzzy logic	(a) Performance analysis is difficult
Sliding Mode Observer	(a). Can produce efficient results in simulation (b). Good optimization capability(c) Gives good result when integrated with different algorithm	(a). Handling in complex situations isdifficult (b). Produce oscillations in system
Adaptive Controller	(a). Give effective results in simulations (b). Easy to implement (c). Require less control parameters(d) Combine well with different other algorithm	(a) Slow convergence
Linear Quadratic Regulator	(a) Produce good results in simulations (b) Can run in dynamic environment (c) Combine well with different another algorithm	(a) Difficult to control

6. CONCLUSION

This survey gives a step ahead for future work related to automatic guided vehicle. The paper mainly focuses on control algorithms that helps AGV for giving better performance. After reviewing several algorithms, it is quite evident that very few algorithms work alone or presents required features. It is seen that hybrid control scheme has been used popularly where two or more algorithms are combined to give better results in control performance and enhances the AGV performance. The hybrid control schemes depend on the best combination of tracking ability, robustness, fast response, adaptability and noise rejection. Still, integrating different control algorithms do not promise the required performance for control system. Authors are still looking out for best suitable mathematical model which will give overall satisfactorily performance. Moreover bio-inspired optimization algorithms are the most researched area, the integration of bio-inspired technique with controllers can be proved beneficial in increasing performance. The stochastic optimization is another area which can also be proved fruitful.

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BIOGRAPHIES OF AUTHORS

Faiza Gul is a postgraduate student at School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM), Engineering Campus, Penang, Malaysia. She has worked on the development of LIDAR systems, autonomous guided vehicle and non-linear system.

Syed Sahal Nazli Alhady Syed Hassan is currently a senior lecturer at School of Electrical and Electronic Engineering Universiti Sains Malaysia. He obtained his Bachelor of Engineering at Universiti Teknologi Mara and completed his M. Sc and Ph. D at Universiti Sains Malaysia. His specializations are in neural networks, biomedical, embedded systems, and intelligent system

Wan Rahiman gained BEng degree from Cardiff University, UK specialising in Manufacturing Engineering and completed PhD in control-engineering study from University of Manchester, UK. Dr Wan Rahiman joined as a senior lecturer in School of Electrical and Electronic Engineering, Universiti Sains Malaysia in 2009. He is currently Head of Cluster of Smart Port and Logistics Technology (COSPALT). His research interests lie in the area of modelling nonlinear systems and their controller algorithm on a wide range of development industrial projects, particularly, in drone and autonomous vehicle technologies. He endeavours to develop smart electronics with Internet of Things (IoT) solution that could widely applied in the medical industry.