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REVIEW ARTICLE

Control of truck-trailer mobile robots: a survey

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Abstract Mobile robots with trailers and its control is one of the most challenging problems in service robotics. Since, these kinds of robots can accomplish the given task in a faster and cheaper way than an individual robot, they find applications in many areas. However, the backward movement of a truck-trailer mobile robot is more complex as the complete system is highly non-linear and unstable. The practical advantages of this system in the transportation industry have led to significant research in this area. Various studies have been conducted in this area for exploring more on the subject of non-linear control. This paper presents a survey on the various control strategies developed in the backward motion of mobile robot with trailers. The existing studies in this field are analyzed to identify unsolved problems.

Keywords Mobile robot · Non-holonomic · Trailers · Backward tracking

1 Introduction

Wheeled mobile robots (WMRs) are the simplest and the most widely used mobile robots for research. The concept of non-holonomy has also brought more research interest into this area. Hooking up a passive trailer with a mobile robot is more useful in accomplishing a complex task than a single robot, as it can be used for tasks such as floor cleaning, material removal processes, load haulage, etc. The operational cost of using a mobile robot with trailer is very less compared to deploying multiple individual mobile robots. However, WMR with a passive trailer is one of the most complex systems as the complete system is under-actuated. When the trailer is hooked as off-axle, it is a very complicated non-linear system. It involves complex kinematics.

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Recently, there has also been another challenge of developing control strategies for the formation control of multiple WMRs with trailers. Multiple WMRs with trailers are very useful for achieving cooperative tasks. These robots need to maintain a formation to accomplish such tasks. The relative position and orientation of the robots are controlled so that they move in a group and shape as required. This is called as formation. There have been numerous researches on this area to achieve a better formation control between the robots and reduce error dynamics.

WMRs are classified as non-holonomic systems according to non-linear systems. Due to this property, motion control of WMRs is a difficult task and for the past two decades, many researchers have been conducted in this concept. Recently, auto industries are also focusing research in this area so that new and better motion control strategies, technologies can be introduced to bring practical implementation of automated high-way system and driverless cars. So, researches on better and rugged control strategies for non-holonomic systems will have great impact in both robotics as well as auto industry.

A four-wheeled robot (car-like) with a trailer is treated as a non-holonomic system with 4 dimensions and motion control for such system is very hard compared to a single robot. The degree of the non-holonomy increases depending upon the number of trailers added to it. Backward movement of this system is a great challenge in the area of non-linear controls. Presently, there are so many research works going on this area and effective controllers are being proposed. Many practical problems such as parallel parking, jack-knife phenomenon, etc. can also be addressed, if a robust motion control strategy is proposed for these systems.

This article presents a review on the motion control strategies used for truck-trailer mobile robots (TTMR) or articulated robots for path planning, path tracking and backward tracking. Most of the controllers designed so far have relied on non-linear control theory. Considerable amount of work is also done in this area using modern control strategies such as neuro-fuzzy logy and control learning approaches. Emphasis is also done based on whether the trailers are hooked as off-axle or on-axle. This paper also addresses the problem on papers which have worked in the presence of dynamic obstacles, in case of path planning. Some of the papers which proposed better controls for parallel-parking issues of the truck-trailer robots have also been discussed. This paper reviews all the approaches that have been adopted from path planning of a truck-trailer robot to the formation control of a group of truck-trailer robots. But, the main focus of this work is to survey the control strategies used for backward motion of truck-trailer mobile robots.

The paper is described as follows. The first section gives an overview of non-holonomy concepts and the practical problems to truck-trailer mobile robots. Path tracking and path planning of these robots are reviewed in Sect. 4. Section 4 presents a survey of the major type of controllers employed by various researches. Section 5 gives an overview of formation control of truck-trailer robots, papers that have addressed parallel-parking issues and also about obstacle avoidance in a dynamic environment. The final section discusses about the open problems and the work contributed in recent years.

2 Background and overview

Non-holonomic path planning is considered a research problem that includes researches from control theory, differential geometry and classical mechanics area. It is one of the most challenging researches for control engineers. In this section, we shall begin with the basics of non-holonomic constraints and how it restricts the motion of the system. The practical problems caused, with respect to mobile robots with trailers have also been mentioned.

2.1 Non-holonomic constraints

Non-linear systems are classified into holonomic and non-holonomic systems. A system is said to be holonomic, if it is possible to write all the constraints of the system as $f(q,t) = 0$, where q is the system coordinate with respect to the reference frame and time t. But, if the constraints of a system are expressed as $f(q,\dot{q},\ddot{q},t) = 0$ and cannot be reduced to $f(q,t) = 0$, then it is called non-holonomic. By definition, it refers to the set of non-integrable differential equations which describes the restriction on the motion of the system, or in simple words, the total degrees of freedom are greater than the controllable degrees of freedom [73].

2.2 Wheeled mobile robot

A two-wheeled differential drive mobile robot is the best example for non-holonomic system. The kinematic model is given as,

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{v} \\ \omega \end{bmatrix} \tag{1}$$

Reducing this equation, gives $\dot{x}\sin\theta - \dot{y}\cos\theta = 0$ which is a non-integrable equation. If the system is assumed to be a rolling contact then this denotes there is no-side slip condition and so this system is uncontrollable. But from experience, we know that the two wheeled robot or car can be controlled in a 3D space but in reality there are only two inputs. According to Brockett theorem [67], such systems cannot be stabilized to a desired posture via differential or state feedback. So, alternative approaches such as discontinuous feedback, smooth time-varying feedbacks, etc. has been proposed. Similarly, a multi-body (articulated) mobile robot (truck-trailer) is termed as a non-holonomic system. This is because of the rolling constraints of the wheel which contributes more degrees of holonomy making the system under-actuated. For a system with n trailers, there are two velocity inputs but $n+3$ generalized coordinates. Because of this, motion control of truck-trailer robots is also uncontrollable. Backward motion of this non-holonomic trailer system makes it an open loop unstable. The trailer skids and goes off the track ending up with jack-knifing with the WMR.

2.3 Jack-knife phenomenon

Truck with passive trailers or articulated vehicles experience a motion control problem during sharp turning, backward movements and faster speeds. This is due to the passive trailer being pulled by the truck using a physical link, whose motion cannot be controlled by the truck. The trailers usually skid under these conditions and end up hitting with the truck. This phenomenon is called as jack-knifing. The motion control problem is challenging because it is a 4 degree non-holonomic complex system and the kinematics are hard to compute. As mentioned earlier, it is an unstable dynamics system and the input constraints drive the robot to jack-knife with the trailer, even if we make it to move in a straight line. Figure 1 illustrates this. Even though there are so many research works going on this area for the control of non-holonomic WMRs with trailers, an optimized controller have not been proposed yet.

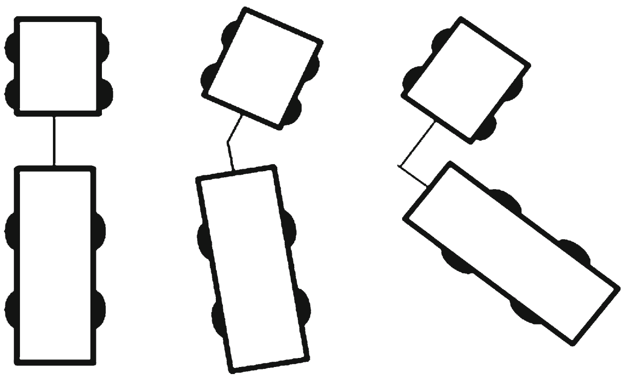

Fig. 1 Jack-Knife phenomenon

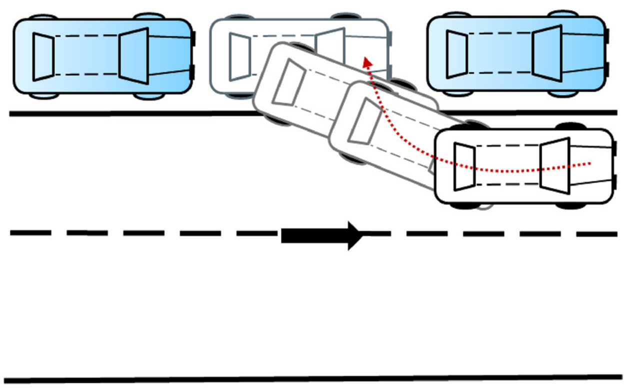

Fig. 2 Parallel-parking problem

2.4 Parallel parking

As it is seen from above, maneuvering of articulated vehicles or robots in a constrained environment is a trivial task. Parallel parking of such vehicles in congested road needs a series of back and steer motions to drive the robot into the parking space safely and correctly as shown in Fig. 2. It also needs to carefully plan the path by already calculating the parking space and the position of the car in it. Many auto-giants carry out research in a prototype model of their vehicles or robots and try out their steering controller in such models. Hence, a motion controller design can also help in addressing this problem which is a critical one, faced in the automotive sector.

3 Truck-trailer mobile robots

To be specific, truck-trailer mobile robots have a steerable car-like robot with a passive trailer or more number of trailers. The trailer is connected with the tractor robot with a physical link which can be off-axle or on-axle. Truck-trailer mobile robots (TTMR)s are more useful than using a single robot because exploitation of passive trailers provides practical applications.

A brief overview of the early research conducted in the area of non-holonomic mobile robots that was extended to application in car-like robots with trailers has also been discussed here. Many papers have successfully addressed the path tracking and motion planning of TTMR in the forward direction. There has been a great advancement in this area from early 1990s by Sampei et al. [1], Saeki et al. [24] and many others especially on the backward motion of the system. There has also been considerable amount of work done to address issues like obstacle avoidance and parallel parking of the trailer system.

3.1 Early researches on motion planning in NMR

Research in the area of non-holonomic mobile robots has been more than two decades old. In-depth research on path planning and motion control of non-holonomic mobile robots (NMR) was first conducted by Laumond in late 1980s [70,99]. Path planning is defined as finding a collision-free path for the robot to navigate in a known environment. In 1987, Laumond [69] proved that an NMR is controllable, when the steering angle, which is considered as an inequality constraint, is limited. The work is on a single non-holonomic constraint in the presence of obstacles. In 2002, Laumond extended this paper to prove the controllability of a general n-body system in [30]. He derived kinematic equations for a unicycle, two driving wheels vehicle, real car and the first two bodies. Usually research in this area has led to research using trailers for NMRs. Laumond and Simeon [68] extended this work on NMRs to mobile robot towing a trailer by showing the existence of path connecting initial and final configurations with two constraints.

Barraquand and Latombe [26] developed a path planner algorithm that can handle any set of non-holonomic constraint among obstacles. This approach involves two steps. Discretization of the workspace and the configuration space of the robot is done. Then, a dynamic programming search is performed in this discretized configuration space. The planner checks for the distribution of obstacles irrespective of the size and number of the obstacle in this workspace. This planner is also implemented for car-like and trailer-like robots and has been proved for controllability using general results from differential geometry and non-linear control theory.

Later, Laumond et al. [35] addressed this problem of motion planning in a new perspective compared to the classical Euclidean one. A new metric is introduced in the configuration space of the system, which is expressed as the length of the shortest paths in the absence of obstacles in [27]. However, the resulting planner has problems like: there still can be the presence of potential wells (between two consecutive sub goals) and limit cycles can appear as part of the trajectory. But still this method can be used in some cases. Hence, this planner is applicable to specific robots whose configuration spaces have small dimension. Simulation work has been tried on car-like and trailer-like robots for this algorithm.

This was the first early research conducted in this area which led to many other research topics like robots with trailers, space robots, non-holonomic manipulators, multi-fingered hands, one-legged hopping robot, etc.

3.1.1 Conversion into chained/sinusoid forms

After Laumond showed the controllability of non-holonomic mobile robots by limiting the steering angle, many control theoretic approaches were made based on differential geometric framework. One such method was to convert the kinematics equations into chained form system proposed by Sastry and Murray in 1990. The method of converting into chained canonical forms draws inspiration from Brockett's work [67]. Optimal steering controls for a set of canonical systems were derived. Here, the input vector fields and first order Lie Brackets, (whose control algebra are Heisenberg algebra), span the tangent space to the configuration manifold. Later, sinusoidal inputs were used to steer certain classes of non-holonomic systems in [28] by Sastry and Murray. This method is comparatively very complex and can be used to robots with specific connecting form. Later, Sussman et al. improved this method by introducing few set of tools for steering general drift-free control systems using sinusoids of asymptotically high frequency and amplitude, whose Lie algebras are not necessarily nilpotent.

Using these results, Sastry et al. [29] proposed a chained form, which is a canonical form for a class of drift less non-holonomic systems that can be a mobile robot with n trailer system. Based on Fourier series techniques, sinusoidal inputs at integrally related frequencies were used to steer this chained form system step by step to their desired values of the trajectory. As this steering of sinusoids can be done only for chained form systems, sufficient conditions for converting into chained form were also presented. Hence, this was applied for a car with one trailer system and the convergence properties of the system were found to be satisfactory. But the algorithm failed when additional trailers were added. This is because each trailer adds one dimension, i.e., its angle to the inertial frame and one holonomic constraint, apart from the general system of the car (truck) robot which has two degrees of freedom.

To overcome this problem, Sordalen et al. [4,62] shifted the coordinate frame to the last trailer and so the coordinates of the complete system is given by the position in the last trailer. Hence, the transformation of the coordinates enabled the chained form conversion as global in the position of the system and local in the orientations of the trailers. For stabilizing the chained form system, a time-varying feedback control law was introduced. This result proved positive as the system obtained asymptotic stability with exponential convergence to any desired configurations and the simulation results were provided for a car with 3 trailers.

In 1998, Petrov [11] developed a hybrid dynamic controller for stabilization of the same. The chained form equations are converted to control laws using integrator backstepping recursive scheme for multi-input chained systems. A dynamic feedback law is derived for this system. The hybrid strategy which is developed in this system uses the trajectory tracking control law till the configuration coordinates reached a desired small magnitude near the origin. Later, it switches over to a time-invariant stabilizer near the origin. Simulations were carried out using MATLAB.

Many papers worked on the stabilization problems of such systems, Zhong et al. [41] developed a recursive technique for semi-global tracking control of non-holonomic systems which is based on integrator backstepping. All these papers assumed that the robot states are available using sensor measurements. But in reality, there exists non-certainties such as noise and external disturbances, modeling errors, mechanical limitations, unknown parameters, etc. So, in 2011, Zhen-Ying and Chao Li [23] addressed non-holonomic systems with uncertain chained systems. These models were different from the earlier models and they do not satisfy triangularity conditions. Recent developments in terms of uncertain chained models, control methodologies like adaptive stabilization, exponential stabilization and finite settling time stabilization and their results were also provided. Finally, a new two-step technique with novel time varying controller is presented to stabilize the uncertain chained form system depending upon the robot type.

3.1.2 Goursat normal form

Path planners for the chained form were proposed by Tilbury et al. in [34] which stated that the multi-trailer system can be expressed as Goursat normal form, which is a dual to the chained form. Motion planning using Goursat normal form is done by converting the kinematic equations into chained form coordinates and steering the chained form coordinates from an initial to final position. Then the trajectory is converted back into original coordinates. The paper also discussed using sinusoidal inputs instead of the time-consuming sinusoids used earlier. Other choice of inputs like piece-wise constants and time polynomial were also analyzed. Piece-wise constants can steer chained system exactly as chained system are nilpotent. Major advantages for using Goursat normal form are: Conversion is straight forward and an algorithm is provided to help in finding the necessary coordinate transformation.

3.1.3 Power form

Power form is another canonical form proposed in [71] by Pomet and Samson. It is mathematically equivalent to chained form and it can be easily transformed in it. Explicit smooth time-varying feedbacks can also be derived for this form as shown in by Teel et al. [72]. However, as mentioned by Samson [36], both the forms have complementary advantages and drawbacks. In his work, he explains a slightly different form of chained form, a skew-symmetric chain form to which Lyapunov techniques are applied to analyze the feedback control design. A two-way approach is derived which achieves asymptotical stabilization of the origin of an n-dimensional chained system. Applications like path following and point stabilization with a car pulling trailers has also been shown in this work.

A tracking control strategy that does not involve any state or input transformations was also derived by Maciej [8] for off-axle trailers. The approach is developed using the vector-field-orientation control method which is applied to the last trailer. The final results show that the system is asymptotically stable as the error dynamics converge to zero.

4 Path planning of a TTMR with obstacle avoidance

When path planning of a TTMR is addressed, many papers did not propose special ideas for dynamic obstacle avoidance for the ease of the path planning control. But many others have used different approaches to address this problem specifically because the efficiency of the path planner depends on how well the obstacle is avoided and subsequent effect on the controller. Moreover, the robot cannot exactly trace the path planned due to the dynamic environment and imprecise localization methods. Subsequently, obstacle avoidance algorithms used for non-holonomic mobile robots cannot be used for TTMR system due to the complexity in multi-body system. Some of the methods below help to understand in detail the ideas handled by various researchers.

4.1 Probabilistic path planner

Svestka and Vleugels [21] first constructed an efficient motion planner using closed form solutions of the kinematic parameters of the TTMR. This motion planner worked well in the absence of obstacles, but integrating this into a probabilistic global planner so that it can be used in the presence of obstacles did not succeed all time. Moreover, this path planning algorithm did not work in cases like more than a single trailer. This is due to the manner in which the paths are constructed which does not provide probabilistic completeness. So depending upon the efficiency of constructing paths, the planner works in presence of obstacles. An iterative trajectory tracking scheme was proposed by Lamiraux and Laumond [39] in 1998 to drive a truck-trailer robot from an initial configuration to a given goal. Motion planner which was described in [45,61,100] by Sekhavat et al. was used as input to avoid obstacles. This planner helps to make the control strategy robust due to its topological property of the steering method. Experimental results seem to be very precise, though the robot did not converge exactly with the goal.

Path planning of a Hilare (two-wheel drive) robot with a trailer was done by Lamiraux et al. [45,61] in 1997. An integrated approach was developed with three tasks: 1. Computing a collision-free feasible path–a random path planner which is probabilistic complete is used and new steering method based on differential flatness was proposed for the non-holonomic systems. The planner mentioned in [35] was used for approximation in any constrained environment. 2. Dynamical constraints of the system are included to transform the path into a trajectory-This path planning was done without any approximations on robot parameters. 3. Tracking of the trajectory is done—only in forward direction via geometric transformations. Later, Laumond et al. added non-holonomic constraints step by step to for path planning of a TTMR in several levels. The algorithm was based on the concept of geometric approximation. But the complexity of this planner increased when the number of trailers was more.

4.2 Concept of equivalent size

In path planning, system radius (SR) of the robot is defined as a circumradius about which the obstacles in the robot path can be enlarged. This is done to shrink the robot to a particle in order to navigate easily without colliding with obstacles. However this was difficult when applied to TTMR as it is a multi-body system and leads to the following problems like: expanding obstacles in the map causes to lose some search path and so an expensive path is found. The obstacles are expanded depending upon the SR of the truck but in reality the trailers may or may not follow the truck path. Angle constraints between the two bodies must also be taken into account. Hongchao et al. in 2001 [13,51] developed a new concept of equivalent size (ES) instead of SR and this addresses all the problems caused by the latter. ES is a dimension used for expanding the obstacles and for restricting the curvature of the path planned for the robot. So the obstacles are enlarged using ES and the robot is reduced to a particle. By doing so, the complexity of path planning amidst obstacles is reduced to the path planning for a single robot. Since ES is smaller than SR, the loss of feasible space is reduced here. The detailed description and calculation of ES is found in by Hongchao et al. [50].

The concept of band-path was also developed by Hongchao and Li [97]. In these works, the size of expanding obstacles and path planning affected one another. Since the proper expanded size is not appropriate, there is a loss of free space. Qiang et al. [52] gave a new method to generate the size of the obstacles and path planning algorithm so that the best expanded size can be found. For this, various trajectories are given to the TTMR to analyze the width of the system. Based on this, a new concept of Global-width is defined and calculated. This is the maximal width the robot can have when tracking a certain path and this idea was implemented in the existing algorithm and the modified algorithm is called PRM algorithm.

4.3 Reactive path deformation

A collision-free path which is planned initially may change due to dynamic environment. For path planning in such circumstances, Shiller [101] developed a new concept of velocity obstacles in which a set of forbidden velocities are defined depending upon the velocity of the obstacles. Large et al. [102] used this concept to achieve obstacle avoidance based on goal-orientation. However, this algorithm can be used only with simple environment and not in a clustered one where multiple robots are used. So, to specifically address the problem of dynamic obstacle avoidance, Lamiraux et al. [57] proposed a generic framework which allows modification of the initial path even after planning is done according to the obstacles sensed. The path deformation algorithm is modeled as a closed loop controller. The input to the infinite-dimensional dynamic control system based on the present path by avoiding obstacles at that instant is computed. In simple words, the path is iteratively deformed till the path is collision-free and then implemented. This algorithm was experimented successfully on the mobile robot ATRV Dala with a trailer in the LAAS-CNRS building.

4.4 GA based

As mentioned earlier, in 1995, Tanaka and Yoshioka [37] found a semi-optimum path from a given point to the goal point without obstacle avoidance using GA. Simulation results were carried out by implementing the trajectory control which was derived earlier using fuzzy control.

5 Path tracking control: forward and backward for TTMR

Though there has been a significant accomplishment in forward movement (path tracking) control of TTMR, it is the backward movement control which is more complicated. Backward movement of the trailer is important when parking in constrained spaces, the sudden approach of dynamic obstacle obstructing all possible forward movements, loading docks, etc. Since this is very interesting subject of advanced non-linear control theory, most of the controllers involve design of a non-linear control system design. Others include new concepts in differential geometry, fuzzy logy, neural networks and linear algebra. We look at each of the methods separately and the different approaches within each method, dealt by the authors.

5.1 General non-linear control system design

As mentioned, path tracking of a TTMR was done as early as in 1991 by Sampei et al. [1]. A tracking controller is designed for the trailer using input/state linearization method and time scale transformation. To achieve this, a dynamic model of the robot is derived using state equation with the distance along the desired path as time scale. The state equation is then linearized with state transformation. A linear controller is designed for this linearized state equation system with a feedback controller of regulator and servo controller type. Further time scaling is done to get a desired velocity-dependent controller. However, this method cannot track circular arc more accurately as the path is approximated as a sequence of straight lines. This was later carried out using radio controlled vehicle and CCD camera for backward driving of the trailer in Sampei et al. [84]. However there was no path planning in this. Both these methods had the assumption that the joint of the tractor and the trailer is located at the middle point of tractor's rear wheels. If this assumption is not satisfied, the input state linearization method cannot be used. Hence, a partial linearization technique along with time scale transformation was proposed by Sampei et al. [85] in 1994 for car-caravan type articulated vehicles. Nakamura and Yuta [33] in 1993 formulated a control algorithm for a TTMR to move in both forward and backward directions in straight line as well as circular arc curve. The algorithm is based on linear approximation of the system. This work was inspired by Li et al. [44] to develop an index to estimate the manipulative difficulty of towing and pushing multiple trailers like the number of trailers, the length of each trailer or the relative position of the joints. The index is measured by applying an impulse disturbance to the system in straight line motion only.

Later, Divelbliss and Wen [89] in 1997 worked on path tracking using 3-step method: the trajectory is generated for satisfying the non-holonomic constraints and the linear kinematic model of the car and this trajectory is stretched till the maximum velocity constraint is satisfied.

In 1998, Doh-Hyun and Jun-Ho [96] devised a globally asymptotically stable (GAS) tracking control law for the trajectory tracking of the trailer. This work was further modified by them in [3] for backward movement of the trailer system. Altafini [20] designed a control scheme that consists of a switching controller that can switch between two different modes, backward and forward. Each of the modes is governed by a linear state feedback control law which is based on linear quadratic techniques on the Jacobian linearization. The switching is an additional feedback loop enclosing the two different closed loop modes that works depending upon the movement required.

In 2002, Martinez et al. [10] have used a pure geometric technique for path tracking of mobile robots. This technique is an extension of an efficient path tracking method employed for non-holonomic mobile robots to a TTMR. This avoids problem for cases where tracks are employed instead of wheels or when working with irregular terrain. This technique is simpler as it does not involve conversion of complex kinematic models into control laws. But the backward movement problem has been addressed only by limiting the demanded curvature and dynamic effects when working with heavy loads are also not considered.

Cantos and A. Ollero [104] has extended their work [31] in 2009, an optimal two level control system. Orientation controller is used for the lower level tracking which is of pure-pursuit strategy. The error between the vehicle and a goal point selected on the path at a given look-ahead distance L is first computed and the controller calculates the orientation angle which is the reference for the second level. Look-ahead controller is for the higher level for tracking backward path. This level computes the control u of the vehicle's steering actuator. This makes the vehicle reach the desired orientation in the referenced path. Stability of this system is guaranteed by applying non-linear dynamics.

5.2 Fuzzy and neural networks

Mostly, all the works which employed fuzzy and neural networks was analyzed in simulation and not through experimental work.

In 1989, Nyugen and Widrow [78] proposed a self-learning technique using neural networks to achieve non-linear controller design. Here, it addresses the backward movement of a truck with trailer by controlling the steering angle of the truck from an arbitrary initial position. This approach involves two stage learning process; first one is to train the emulator and the second one is to train the controller using emulator. Training of the two layered emulator is done to make it understand how the real truck-trailer behaves. A wide range of positional states and steering angles are given to the emulator so that it generates the next positional state vector by learning. Later, training of the controller is done using a supervised back-propagation algorithm as mentioned in Hougen et al. [38]. The problem with this approach was it involved thousands of backups to train the network and all the earlier control decisions made by the controller had significant effects upon final results.

Later in 1992, Kong and Kosko [63] developed an adaptive fuzzy controller to address this problem. The supervised back-propagation algorithm trained the neural system. Error nulling intuitions and common-sense were used to generate Fuzzy-associate-memory (FAM) rules. The speed with which the DCL clustering technique recovering the underlying FAM bank and the robust performance of the system even when 50 % of the FAM rules removed showed that such method can be used for controlling more complex higher dimensional problem.

In the same year, Tokunaga and Ichihashi [79] proposed a neuro-fuzzy optimal control which is based on the mathematical model of the system. The trajectories of the truck-trailer system are represented by a fuzzy model with Gaussian Membership functions. An optimized controller is developed for backing up a trailer to a loading dock. Later in 1994, Tanaka and Sano [80,81] stabilized this system using fuzzy control.

In 1995, Tanaka and Yoshioka [37] developed a fuzzy controller for backward trajectory tracking of a truck with five trailers. Depending upon the dynamics of the system, a fuzzy model was derived using fuzzy approximation method. Later fuzzy rules were calculated by parallel distributed compensation (PDC) method. A trajectory fuzzy controller is designed using these rules and feedback gains. This paper also discussed on obstacle avoidance which is discussed later in this review. Tanaka et al. [40] in 1998 further extended this work for a mobile robot with ten trailers. The stability condition is based on Lyapunov approach, which is expressed in terms of linear matrix inequalities (LMIs), so that the problem is just to find a common Lyapunov function for a set of Lyapunov inequalities. Stable feedback gains are found using convex optimization techniques. Simulation results showed that the fuzzy controllers successfully backed up the trailers even in a difficult initial position and the fuzzy model developed imitated the dynamics of the original models. This work was the first one to work on more than three trailers.

Later, Cheng et al. [16] designed a fuzzy control with a line of sight (LOS) guidance method to address this complex system. Here, the motion planning of the system is done by denoting the line segments (path) as way points. The "way point trajectory system" helps in driving the TTMR with reference speed, when the path cross track error is least. A LOS vector is taken along with the reference position. When the TTMR moves, these values are updated. For the trailer to follow the LOS vector, a fuzzy logic controller is designed, thus reducing the complexity of using a trajectory control.

5.3 Connectionist control-learning system

While most of the studies on fuzzy and neural like cerebellar model articulated controller (CMAC) [64], adaptive fuzzy systems [63] were conducted as simulations; Hougen first tried implementing in real robot. Unsupervised control learning was employed to find a solution to this problem, when Hougen et al. [65] in 1996, first developed a new connectionist system with terminal feedback. Previously, he proposed the use of SONNET, Self-Organizing Neural Network with Eligibility Traces, which performs real-time classification of temporal patterns and makes use of response learning through inter-neural cooperation for controlling a real robot. Hougen et al. [65] introduced ROLNNET (Rapid Output Learning Neural Network with Eligibility Traces which is easier than SONNET, except that the network here learns rapidly by partitioning the input space by problem specification prior to learning. Results showed that the robot was able to back the truck successfully by learning quickly compared to other systems and with less computation time. Works were also carried out by Hougen et al. [66] with ROLNNET for backing up a robot with two trailers.

5.4 Differentially flat systems

Fliess et al. [47] in 1993 first studied about systems that exhibited the property of differential flatness or linearizing output. A control system is said to be differentially flat if there exists a finite set of differentially independent variables, which are differential functions of the system variables and vice versa as defined by Ryu et al. [12]. Flatness can be considered as a non-linear extension of Kalman's controllability. These systems can be linearized via a special type of feedback called endogenous. Rouchon et al. [32] devised an open loop generation strategy such that the general n-trailer system is flat. With the use of Frenet formula, this strategy was successful and the linearizing output is taken to the middle of the axle of the last trailer. The path planning problem without obstacles is easy when the linearizing output is determined. This is because the reference trajectory and the open loop control are expressed in terms of linearizing output and its finite number of derivatives. Lamiraux and Laumond [48] also proposed a new steering system for path planning that can be used with any differentially flat drift less system with two inputs. The method was devised such that the system satisfies topological property, which can account for small-time controllability of the system. By doing so and implementing on Hilare robot with trailer, it was found that unlike sinusoidal inputs, this method did not have unnecessary cusp points.

6 Mechanical structure of TTMR

In this section, the impact of the physical structure of the TTMR on jack-knifing and parallel parking is studied. Some papers have also designed new TTMRs that cannot jack-knife, while others have used omni-directional wheels while some others have looked in to the type of hooking between the truck and trailer. Jaehyoung et al. [17,49] compared the mechanical structure and kinematics of three types of trailers—direct hooked, off-hooked and three-point trailer. Stability analysis showed that though the kinematics of an off-hooked trailer is complicated, but the mechanical structure was simpler and the trajectory tracking performance seemed to be better. It concluded that off-hooked trailer system is more advantageous despite the complicated equations.

6.1 Off-axle TTMRs

On-axle trailers have the trailer joints located on the center of the rear axle of the truck/preceding unit. But, if the trailer joint lies in a point away from the rear axle, it is called as off-axle hitching. Most of the papers discussed so far had trailers towed as on-axle hitching with trucks. There are also considerable amount of work done on trailers which are hooked off-axle. Moreover, off-axle hitched trailers find more practical applications in industrial sectors than on-axle ones despite the fact that it is a highly unstable system. As seen in [32], truck-trailer system with off-axle hitching is also differentially flat. It can also be converted to chained form system as tried by Tilbury et al. [5] and Bushnell [9] for a fire truck with three inputs. However, the derivation to find the chained form functions is very difficult and was not presented in [9]. Alternatively, DeSantis [6] worked on path tracking of off-axle hitched robot using linear control techniques in 1994. Higwe et al. [74] used linear parameter varying (LPV) technique to design a lane following controller for a truck with off-axle hitched trailer. There were also other researchers who worked on backward driving control of these systems and employed non-linear control methods like [74,75,77,83]. Petrov [22] in 2010 presented a non-linear path controller for TTMR with off-axle hitching using high-gain design techniques based on reduced order of the system. State space approach is used for asymptotic convergence of the error coordinates. The stability of the system is analyzed using Lyapunov stability theory.

Myoungkuk et al. [54] showed that a robot with n passive trailers can be controlled in backward direction by treating it as a trajectory-following problem. The advantage of this method was that it can be employed for any multi-axle mobile robot. From the kinematics of such system, the control inputs can be obtained by coordinate and input transformations. In 2009, Stergiopoulous simulated a multi-trailer truck but with an active sliding off-axle free joint instead of a fixed kingpin. The controller regulates the sliding velocity of the kingpin sliding joint during backward movement to stabilize the system. This control law is also used in forward motion by stabilizing the system during off-tracking movement of the sliding pin.

6.2 Physical design of a TTMR

As seen, there are discrepancies and errors in the path tracking of trailers due to the physical dimensions of the robot. All the controllers have tried to fit into the truck-trailer parameters, but have resulted in some deviation in tracking. So, there are some papers which worked on the physical design of trailer systems that can satisfy both mechanical constraints and controllability. These works are motivated by Laumond's [69] work which proved that the car-like robot can be controllable by limiting the steering angle. One of the first papers that tried to bridge the gap between non-holonomic trailer systems and the mechanical design of trailers with good tracking performance was by Nakamura et al. [46]. The paper created a new steering design mechanism that has chained form compatibility and good tracking. Various kinematic models of trailer systems with and without steering were studied. A three-point model is designed for steering the trailer system such a way that the system is differentially flat and can be convertible into chained form. Path following stability was compared with the standard industrial trailer designs like ITS and Yamamiya with the optimal three-point model prototype and was found to be more stable than the other two.

When path planning for TTMR is considered, the number of trailers varies depending upon the requirement and this property is called variable structure. None of the papers mentioned above proposed ideas that can satisfy this property and also have optimized physical parameters for path planning. This new idea of designing a physical structure for TTMR with variable structure was proposed by Jing and Yalou [55]. Various features of the deviations and transient motions of the trailers in the trajectories were analyzed to compute the connecting parameters that can be used to design an optimized structure. ES and other path planner parameters will not vary even if the connecting parameters are adjusted according to the path planner and this avoids repetitive path planning.

Apart from modifying the physical design of the tractor, Martinez et al. [58] proposed limitations in the steering of the tractor to avoid jack-knife during forward motion of the vehicle. This control was applicable for both on-axle and off-axle joint vehicles. The method has been validated experimentally using Auriga-alpha robots. Steering mechanism was designed and controlled by Nakamura et al. [98] in order to control non-holonomic trailer systems.

6.3 Virtual trailer

Few other papers looked in to the path tracking problems of trucks with passive trailer system with a different approach. They involved autonomous vehicles in the place of the passive trailer. Ng et al. [18], proposed a virtual trailer link model that tracks the leader vehicle. The model has been designed based on the off-hooked, single-trailer configuration that boasts of having better tracking errors compared to the traditional approach. An approach similar to this method has been adapted by David et al. [105] by means of a virtual link model. In this approach, two autonomous vehicles/robots are treated as a truck-trailer robot. The space in between them which is the linear separation distance is considered as the virtual link which is varied by the trailer to avoid collision between the two robots.

Both these methods address the problems of truck-trailer robots successfully. However, this system is expensive because of employing two mobile robots/vehicles in place of a single robot with passive trailer.

7 Articulated vehicles

Transportation industry started to show much interest in the area of control of mobile robots due to the fact that the practical motion control problems can be first tested on a scale-down model of the articulated vehicle or a mobile robot and then tried on their vehicles. We take a look at few of the papers that dealt with jack-knife problem in articulated vehicles.

Altafini et al. [60,83] proposed a hybrid (hierarchical) control for a scaled down vehicle with a truck and a two-axle trailer. It involves three different low-level control strategies depending upon the track: backward driving along a line, backward driving along an arc of circle and forward driving of the vehicle and there is a switching of the controls between them depending upon the requirement. This was implemented to stabilize a Dubins vehicle, which is a radio controlled and a 1:16 scale of a commercial vehicle with an off-axle. Hence it represented a full-scale truck and trailer in terms of steering angle and relative angles between the truck and trailer. The results also proved to be asymptotically stable. Saeki et al. [24] came up with an idea of a fully flexible path following control system. His earlier work on the same topic had substantial results. The controller has a hierarchical structure with two levels; the lower level being a control law which makes the articulated vehicle to behave like a single vehicle to avoid jack-knifing. The higher level consists of a control law which helps in steering backwards for path tracking control. The control laws are a set of differential equations derived from basic kinematic models of the articulated vehicle. Control laws were designed by Astolfi et al. [14] for stabilizing control laws for the path tracking of an articulated vehicle with two bodies using Lyapunov techniques. This paper successfully eliminated the limitations on steering angle during tracking. But it did not guarantee the convergence of any arbitrary initial configuration. Only four known configurations like forward/backward and rectilinear/circular are considered here.

Jorge et al. [57] devised an approach which limits the steering commands for articulated vehicles so that the tractor can be controlled effectively as if there is no trailer attached. It was assumed that the curvature control loop of the tractor has an over-damped response. However, this approach dealt only with forward driving but can be used with any combination of on-axle and off-axle hitches. The limitations are introduced based on the kinematics of collisions between the bodies. Later, Matsushita et al. [25,76] extended Saeki's [87] work to double trailers in 2006. When the steering controller which was based on the observer and Lyapunov function of Saeki was used for two trailers, the tractor oscillated. So a new steering controller based on backstepping was designed and the controller was verified using numerical results. The LMI conditions that was implemented for TTMRs by Tanaka et al. [40] was extended to articulated vehicles with three trailers in [86]. Simulation and experiments were carried out and the controller proved successful without the jack-knife phenomenon.

Roh and Chung [59] proposed driver assistance system (DAS) which focuses on manual control by the driver. The main idea used here is to look at the control problem as a pulling motion rather than pushing motion by changing the connecting configuration of the vehicle. It makes use of rear view camera and image display, electrical power steering, joint angle sensors at revolute joints between trailers and a keypad to receive steering command. This DAS can be successfully implemented in practice by means of a minor hardware modification.

8 Parallel parking

The studies on motion and path planning of car-like robots have given rise to research in car-parking problem. Some of the motion planners which have been discussed earlier contributed to certain extent in this area. Parking maneuver is a typical problem of path planning of non-holonomic vehicles. Parking of a robot involves two phases: first, various sensors equipped in the robot scan the parking area to get the estimation of the parking space lot. Subsequently final position and collision-free maneuvering paths are generated in reference to the surroundings. Then the robot moves to the required position by sequence of backward and forward maneuvers depending on the requirement.

This research derives inspiration from the general motion planning of non-holonomic robots. Research interest increased more in the late 1990s, because these controls can also be integrated to automobile industry. Articulated vehicles experience serious parking problems as it involves a number of maneuvers to drive the vehicle to the parking lot. As seen from above, the control algorithms used for backward movement of a TTMR can be used to address this problem. But in case of a TTMR or articulated vehicle or a car-like robot with a dedicated parking guiding device, it is difficult to apply these algorithms. So, there are few papers which have dedicated strategies for parallel parking of a car, TTMR and articulated vehicles. Some papers dealt with building a complete automatic parking system. Others have targeted on dedicated parallel-parking controllers using fuzzy and neural networks, while others have tried to employ the existing path tracking controllers for this problem.

One of the early studies that addressed parallel parking for a car-like vehicle was done by Paromtchik and Laugier [88]. As mentioned, this was an extension of the available motion planning algorithms. Here, the motion of the car is modeled using sinusoidal reference function and the parking space is scanned using ultrasonic sensors. The path planner computes a path in accordance to the non-holonomic constraints of the robot. But no proper functions to predict the collisions between the parking space and the vehicle were discussed especially during reversing of the vehicle. Later, Jiang and Seneviratne [42] developed an automated planning strategy to overcome this collision problem. Explicit relationships were found to predict possible collisions and a forbidden area is calculated. Now the path planner is produced in real time with the robot and parking space dimensions so that the robot avoids the forbidden area and goes to the goal position. Yamamoto et al. [93] proposed an optimization method that can be used in dynamic environments in the presence of obstacles. It is based on receding horizon control that satisfies the non-holonomic constraints of the car-like vehicle. Some works on fuzzy logy and descent methods were done by Miyata et al. [90,91] to control an AGV for this problem, but this worked on the assumption that the path is predefined or known.

Parallel parking of a TTMR was also achieved by means of a fully automated fuzzy controller in [94]. The controller has two inputs: difference between actual and desired trailer angle and the speed of the truck, where the first input is calculated using another sub-fuzzy control. Simulation was done in MATLAB and the results seemed to be satisfactory with drawbacks caused due to hardware and digital to analog system. In 2004, autonomous electric vehicles like ROMEO-3R and ROMEO-4R, developed at the University of Seville was used by Cuesta et al. [56,92] to implement parallel-parking maneuvers for car-like and tractor trailer robots. Existence of collision-free path is computed based on fuzzy system. Morteza et al. [95] devised an intelligent parking method for the TTMR system in the presence of dynamic obstacles using fuzzy approach. It had two separate fuzzy controllers for finding the obstacle and avoiding the obstacles. MATLAB simulations were carried out that showed smooth movement of the trailer with the presence of obstacles.

9 Formation control of truck-trailer mobile robots

Research has also been conducted on the formation control of TTMRs. Combining both the problems of formation control and control motion of TTMR is one of the most challenging problems. In [19] and [103], a scheme for planning and control of UGVs with trailers has been addressed by Hao and Agarwal. So this paper addressed two problems: (1) on-line planning, changing and optimizing the formation; (2) trajectory tracking of individual TTMR. Online path-planning of the formation is done using A* search algorithm and can be changed dynamically to avoid obstacles. This paper deployed the concept of differential flatness to plan the trajectories of the mobile robots. Way points are chosen from the algorithm and the trajectory is generated. Tracking controller is chosen to satisfy conditions based on Lyapunov theory. This algorithm was validated for computer simulated models of John Deere Vehicles and experimental work for iRobot Magellan Pro robots. These results showed that the trajectory error will increase with the number of trailers attached to the vehicle and also involved long computation time.

Another paper which involves formation control and TTMR was studied by Morbidi and Prattichizzo [15]. Leader-follower formation is controlled using sliding mode control, where the leader is a tractor pulling trailer and the follower is a car-like robot. The advantage of using sliding mode control is that it is insensitive to external disturbances and uncertain parameters. Hence, in this paper, the desired formation is allowed to vary arbitrarily. A formation tracking control framework using sliding mode and non-linear observers are designed in this paper. Observers are used for the estimation of the altitude angles of the follower and the leader.

10 Open problems

This research area is more than 25 years old and the authors have tried all possible approaches for improving the controller in terms of stability and reliability. From the review of the literature, it is evident that a significant amount of work has been done on the path tracking of truck-trailer robots and the challenges and problems have been worked well. However, there has hardly been any research in the dynamics and control of such systems. Regarding the works on path planning and path tracking, very few controllers seem to be promising and others have only partial answers to many questions, especially on the reliability and real-time implementation of the system, so a complete analysis is yet to be performed. There are very few other works on the physical design of the truck-trailer robots to avoid jack-knifing, but how far that is possible in real-time design is still a question. Extension of the present algorithm to parallel parking of such systems is also important. Some of the open problems, which can have attention in the immediate future, are as follows:

1. *Dynamics and control* Study of the dynamic behavior of the truck-trailer robot or for the vehicle is not considered in any of the researches. Dynamics can be ignored when working with mobile robots in more certain conditions. But when considering more dynamic and unknown environment, it is very important to consider the dynamics of the system.
2. *Advanced controls* Specialized advanced modern control strategies that can exploit the non-holonomic behavior and can control the system can still be studied. Study on the derivation of theoretical results regarding controllability and observability issues are also not focused.
3. *Stability of the controller* Exploration of redundancy or singularities in the controller is not studied in detail by most of the papers. After the implementation of the controller, it is also important to study the stability of the system to avoid singularity conditions.
4. *Design of the system* As we have seen, though there are papers working on the physical design of the truck-trailer robots to avoid jack-knife phenomenon, an optimal design has not been studied so far.
5. *Experimental study* Research involving fuzzy and neural networks has been done only in simulation. This is also the case with working with scaled-down model of a car. Experimental verification of such controllers will open up research in a more wide area.

11 Conclusion

In this paper, a review of the literature on the works on the path tracking and path planning of truck-trailer robots has been presented. It also details on the different control methodologies of truck-trailer robots, grouping them and highlighting the advantages and disadvantages of each methodology. All the open and unsolved problems in this area which will have impact on the applications have been listed. Though the main focus of this article has been the path tracking and path planning of truck-trailer robots, other problems caused due to non-holonomy are also discussed. This includes parallel parking of the truck-trailer system, obstacle avoidance and off-axle trailers. The root causes and basic methods that are adopted by researchers for solving such problems are also shown.

Though this problem is studied for more than two decades, the recent revolution in the area of hybrid controllers, technological advances and complex computations will pave way for the solution to this problem in the near future. In addition, the new problems that arise due to implementation of such systems in real-time have to be understood and solved. This will make the system more effective in application areas where their performance can be fully exploited. As the field of mobile robotics is more dominated by wheeled mobile robots, effective controller to address the problems of non-holonomy will be a major breakthrough not only in the area of robotics, but also in the area of automobiles.

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