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Path following hybrid control for vehicle stability applied to industrial forklifts

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HIGHLIGHTS

- Novel closed-loop hybrid controller for smooth path following problems.
- Path following of an industrial forklift carrying heavy loads at high speeds.
- Real-time path generation guarantees stability conditions against tip-overs.
- Path generation considers vehicle stability, safety, slipperage and comfort.

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ABSTRACT

The paper focuses on a closed-loop hybrid controller (kinematic and dynamic) for path following approaches with industrial forklifts carrying heavy loads at high speeds, where aspects such as vehicle stability, safety, slippage and comfort are considered. The paper first describes a method for generating Double Continuous Curvature (DCC) paths for non-holonomic wheeled mobile robots, which is the basis of the proposed kinematic controller. The kinematic controller generates a speed profile, based on "slow-in" and "fast-out" policy, and a curvature profile recomputing DCC paths in closed-loop. The dynamic controller determines maximum values for decelerations and curvatures, as well as bounded sharpness so that instantaneous vehicle stability conditions can be guaranteed against lateral and frontal tip-overs. One of the advantages of the proposed method, with respect to full dynamic controllers, is that it does not require dynamic parameters to be estimated for modelling, which in general can be a difficult task. The proposed kinematic–dynamic controller is afterwards compared with a classic kinematic controller like Pure-Pursuit. For that purpose, in our hybrid control structure we have just replaced the proposed kinematic controller with Pure-Pursuit. Several metrics, such as settling time, overshoot, safety and comfort have been analysed.

1. Introduction

Safe and comfortable driving implies taking into account aspects such as normal and tangential accelerations and their corresponding derivatives, the jerks. It is well known that safety and comfort increase when generating continuous curvature paths. These kinds of solutions can be applied on the industry in situations such as transportation of goods and materials in hostile environments in the safest possible manner. This is the case where the kind of material that is being transported must be handled with caution, because it is fragile, hazardous or explosive or because the area where the vehicle moves contains potentially danger aspects such as explosive area or gas pipelines.

Path following problems have been studied intensively in the past and can be applied on different approaches, covering a wide spectrum of applications such as vision-based line following, path generation for overtakes, lateral tracking, and parking. One classic approach is to generate a path that converges to a ground painted line, based on direct data from a vision system (vision-based control). Another classic application is to estimate the road profile and to provide a curvature control law that keeps the vehicle within the lane bounds.

The main contribution of this paper is to provide a new closed-loop hybrid controller (kinematic and dynamic), where aspects such as vehicle stability, safety, slippage and comfort are considered. In particular, the kinematic controller generates generic continuous-curvature paths, coined as Double Continuous-Curvature paths (DCC), used in path following problems for

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non-holonomic vehicles. The controller applies a curvature profile to steer the vehicle to converge to a path. Through the paper, it will be shown that the proposed continuous-curvature method uses combinations of clothoids, line segments and arcs to cope with generic curvature profiles. The method can generate paths between two arbitrary configurations (current pose and target) composed by positions, orientations and curvatures. The type of provided solutions gets benefit from higher comfort and safety and constitutes a set of "natural" paths with the shortest possible length. In addition, a speed profile is also proposed to cope with human-like driving based on "slow-in" and "fast-out" policy. In addition, the dynamic controller guarantees dynamic stability conditions in order to avoid lateral and frontal tip-overs using only odometry and inertial data. For that purpose, lower and upper bounds on sharpness and maximum curvature constrain generated trajectories. Compared to standard dynamic controllers, one of the advantages of the proposed method is that it does not require to estimate complex parameters such as inertial, torques and frictions. In this work we use a clothoid-based approach because they have an explicit relation with jerks (at constant velocity), so designing clothoid-based paths implies planning paths with limited jerks, which also has direct impact on comfort and safety. Other curves such as Bézier or Splines can also provide smooth curvature profiles, but their derivatives are not limited, unless explicitly stated.

In [1,2], the authors already introduced the DCC path generation method which constitutes the mathematical background for this paper. The new contribution of the paper with respect to our previous work [1,2] is to provide necessary conditions for vehicle stability with an industrial forklift carrying a heavy load at high speeds and to provide an exhaustive analysis to evaluate the performance of the new method with respect to classic ones. Moreover, we provide several examples and videos showing the advantages of the proposed method (see Appendix D).

1.1. Related work

During the last years, path following problems, whose goal is to generate a path and follow it with a kinematic control law, have been studied intensively because they can be applied in vehicle applications such as: parking [3,4], overtaking and lane changing [5–7], and vision-based line following [8,9]. In that sense, the well-known Pure-Pursuit method determines appropriate vehicle's curvature and velocity that guarantee convergence to a specific path or trajectory based on current robot pose [10–12]. However, applications such as path following or kinematic control differ from motion planning and obstacle avoidance methods, since they do not generally take obstacles into account, neither solve the global path planning problem. For a complete reference on motion planning and obstacle avoidance methods see [13].

Most kinematic controllers are based on current robot and target poses, but they do not take into account curvature continuity, which might affect seriously to comfort when transporting people, and safety when transporting dangerous goods. These aspects can affect load stability in transportation systems and they can even affect wheels slippage and therefore odometry errors. In order to generate continuous-curvature paths in mobile robotics, some researchers use clothoids to generate paths in navigation problems [14–17] because of their "nice" geometric properties including a close relation between physical phenomena (normal acceleration and jerks) with the clothoid scaling parameter. In [18], Elementary paths were first introduced, a combination of two symmetrical clothoids with the same homothety factor. These ideas were extended in [19], by introducing the concept of Bi-Elementary paths, combinations of two Elementary paths. In Bi-Elementary paths the initial and final configurations are not necessary symmetric, but the loci of the intermediate configuration is restricted to a circle with specific orientations to ensure that each Elementary path contains symmetrical clothoids. Obviously, the solution space is significantly limited in those cases and Elementary and Bi-Elementary paths might not be appropriate to solve specific problems, specially the obstacle avoidance problem or the line following problem with bounded sharpness and curvature. Dubins' curves [20] were the inspiration in [21] to create the SCC-paths (Simple Continuous-Curvature paths) and thus simplify the problem of finding optimal paths for vehicles that can go only forward, while keeping curvature continuity. They replaced the circular arcs of Dubins' paths to the called CC-turns, in order to perform paths defined as a combination of clothoids, circular arcs and line segments. The authors of Fraichard and Scheuer [22] used RS-paths [23] to extend SCC-paths by creating continuous-curvature paths that ensure continuity for vehicles moving both forward and backward.

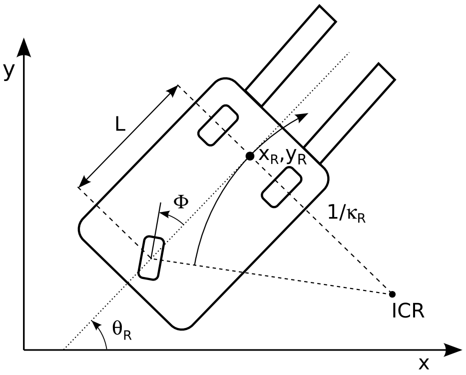

Fig. 1. Vehicle $\mathcal{R}$ in tricycle configuration with back steering wheel.

In order to increase driving safety and comfort, many studies have been done to determine appropriate values for super-elevation and side friction factor for horizontal road alignment [24,25]. These studies also establish appropriate values for clothoid sharpness in transition curves. Moreover, in mobile robotics some efforts have been done to improve stability and to avoid robot tip-over by providing the ability of load reconfiguration for robots with manipulators carrying loads. For instance, there are some analysis of the stability of vehicles carrying heavy loads, establishing dynamic models and guidelines to follow in order to avoid accidents [26–28]. Other works use mobile manipulators so that the centre of gravity can be repositioned to avoid roll-over when travelling on slopes or on uneven terrains [29–31].

2. Smooth curvature path generation

2.1. Problem statement

Let $\mathcal{R}$ be a non-holonomic wheeled robot moving on a 2D plane with extended state space $\mathbf{q}_R(t) = (x_R(t), y_R(t), \theta_R(t), \kappa_R(t))^T \in \Re^2 \times \mathcal{S} \times \Re$ containing the robot Cartesian positions $x_R(t)$ and $y_R(t)$, the robot orientation $\theta_R(t)$ and the curvature $\kappa_R(t)$, which is the inverse of the radius of the robot instantaneous centre of rotation (see Fig. 1).

The kinematic model for $\mathcal{R}$ is:

$$\dot{\mathbf{q}}_R(t) = \begin{bmatrix} \dot{x}_R(t) \\ \dot{y}_R(t) \\ \dot{\theta}_R(t) \\ \dot{\kappa}_R(t) \end{bmatrix} = \begin{bmatrix} v_R(t)\cos\theta_R(t) \\ v_R(t)\sin\theta_R(t) \\ v_R(t)\kappa_R(t) \\ v_R(t)\sigma(t) \end{bmatrix} \tag{1}$$

being $v_R(t)$ the robot linear velocity and $\sigma(t)$ the sharpness of the path.