

Investigating Control of Vision Based Autonomous Navigation in the Image Plane

2010-01-2005

Published
10/05/2010

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ABSTRACT

This paper develops a novel integrated navigational system for autonomous vehicle motion control. Vehicle control is defined in terms of the required vehicle steering angle, rate of steering change and speed. This paper proposes predictive control in the image plane. The proposed predictive control enables the navigation on the desired path, reduces the control complexity and increases the application space for multiple types of vehicles. The paper investigates vehicle control stability; especially in scenarios containing varying curvature turns and variable vehicle speeds. The primary emphasis of this paper is on vehicle control rather than scene analysis. To demonstrate the proposed vehicle control, a computer vision based multi-lane detection algorithm is introduced. The control strategy is applied such that the vehicle maintains position within the lane boundaries. Stability of the control algorithm is tested and demonstrated in multiple scenarios using 3-D simulation results.

I. INTRODUCTION

“Autonomous vehicles” are not a new concept. They potentially provide improved convenience, ease of life, and safety; both in civilian and military applications. If there is not an immediate need for fully autonomous vehicles, there is surely for active safety assistance features.

Autonomous navigation has many aspects: determination of navigable regions, detection of other vehicles/obstacles, etc. To extend autonomous navigation to urban settings, it is required to factor in additional constraints such as detection of signs, intersections, exits, etc. In day-to-day life, humans take visual navigational capabilities for granted and many tasks (such as detecting the road/navigable regions, merging/changing lanes, following traffic rules, and most importantly avoiding collisions) become second nature to

experienced drivers. Thus, an autonomous system must have complete awareness of the entire scene in order make correct navigational decisions in urban, non-urban, or off-road dynamic scenes.

The most important component of an autonomous vehicle application is the immediate and synergistic control action. Therefore, all scene information must be converted into vehicle control parameters. The control system consists of different system components such as speed control, braking, steering motion control, etc. Taylor et al. [4] systematically compared different control strategies (lead-lag controller, full-state feedback and input-output linearization) for vision-based autonomous driving and concluded that all three strategies give comparable performance and the performance improves by curvature feed-forward component. Road parameters such as curvature are dynamically changing, and thus feedback gains in any control strategies should be changed dynamically as a function of road parameters. As we are dealing with a vision based approach, the perspective transform changes the coordinates from ground plane to image plane and thus the major challenge is to come up with a control algorithm, which will determine the correct control for every component of the integrated navigational system concurrently from image plane parameters. Graefe [1] discussed sensor fusion and multi-processor architecture for autonomous mobile robots. They suggested a highly modular vision system with a minimum intermodule communication maximizing the time available for computation. They designed some fast acting autonomous robots with the suggested architecture to prove that this hierarchical modular design is realizable. Graefe's work suggests an architecture which can be extended to a truly universal vision system for autonomous robots. Graefe, however, did not address the compatibility between vision information and vehicle control explicitly. Dickmanns [5] explained a dynamic motion model for road vehicles and further used that model for the control

of the autonomous vehicles in his book “Dynamic Vision for Perception and Control of Motion.” The controls explained by Dickmanns are in ground co-ordinates. O'Brien et al. [3] addressed modeling and control of lateral motion of a highway vehicle and designed a steering controller to track the center of the present lane on both curved and straight highway sections using an H_∞ controller. They dealt with vehicle dynamics and external factors such as wind gust, icy conditions, etc. to design the lateral controller. However they assumed the knowledge of required steering angles in ground coordinates making the control algorithm difficult to integrate with the image based lane detection algorithm.

Unlike the control algorithms presented in the literature, this paper proposes Predictive Control in Image Plane (PCIP.) PCIP determines the control for the vehicle depending on the road parameters in the image plane (considering a forward looking camera) without the transformation to the ground plane co-ordinates making it more flexible to integrate with image based road/lane detection algorithms. The architecture of the integrated navigation system presented in this paper is inspired by Graefe's work such that speed, steering and other motion components of the vehicle can be controlled independently. While these systems are controlled independently, they act as an integrated system, which realizes a stable motion control.

This paper explains the design for the controller mathematically based on only the parameters in the image plane co-ordinates determined by our vision-based multi-lane detection algorithm [6]. The controller design suggested in this paper determines the steering angle, rate of steering change and speed for the autonomous vehicle simultaneously. Additionally, the design takes into consideration that the control must be robust and stable to achieve reliable autonomous operation for the safety of the vehicle, pedestrians, cargo, drivers, passengers, etc. This paper also investigates vehicle control stability proving that predictive control based on image plane parameters is realizable.

This paper is structured as follows: Computer vision based multi-lane detection algorithm is introduced in section II. This algorithm thus decides the road/lane to follow. Mathematical foundation for the proposed control strategy in image plane for the vehicle that maintains position within the lane boundaries is explained in Section III. Section IV is about stability analysis to include all of the vehicle motion components together (speed, braking, and steering system). Simulation results and stability analysis of the control algorithm are also part of Section IV demonstrating that the vehicle control is robust to on-road and off-road driving scenarios, and thus can be extended to applications in urban lane following and off-road navigation in military operations. This is followed by the conclusion in Section V.

II. VISION BASED MULTI-LANE DETECTION

Fig. 1 illustrates the projective geometry of the imaging system and result in the relationship between ground and image plane coordinates: Eq(1) and (2). Parameters are illustrated in Fig. 1. This figure is a modification of the camera configuration figure in [6].

$$y = f k_y \frac{(Z \sin \Theta - H \cos \Theta)}{(Z \cos \Theta + H \sin \Theta)} \quad (1)$$

$$x = f k_x \frac{X}{(Z \cos \Theta + H \sin \Theta)} \quad (2)$$

where k_x and k_y are the camera resolution in pixels / meter in x and y direction respectively.

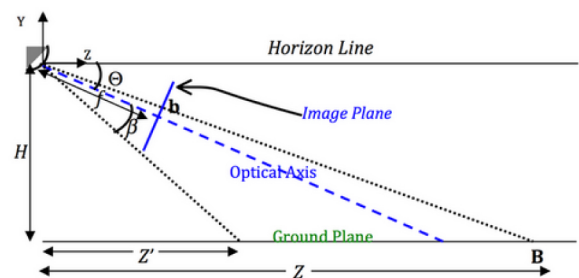
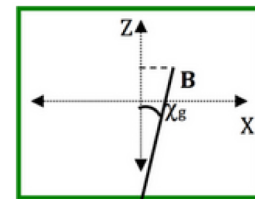
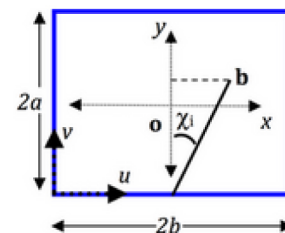


Fig. 1. Camera configuration



(a). Top view of the ground plane.



(b). Image Plane

Fig. 2. Image Plane to Ground Plane.

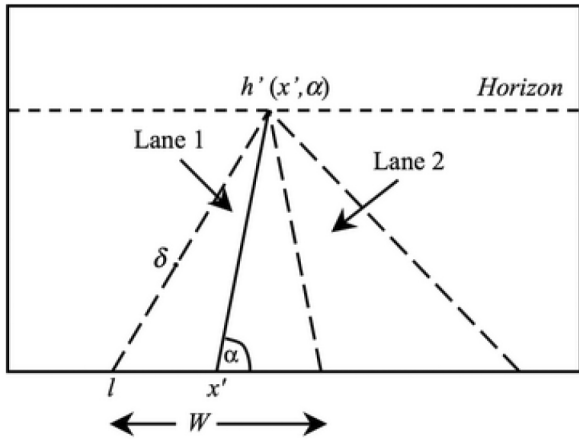


Fig. 3. Figure showing the possibility that two lanes are visible in an image. Lane edges are drawn with dotted lines. The left lane is parameterized by $\{x', \alpha, W\}$ for explanation purpose.

The first step in visual control is detecting lanes with parameters useful for control. The algorithm detects multiple lanes in the scene using the 3-D accumulator A defined in Eq(3).

$$A(x', \alpha, W) = \sum_{\delta \in \partial} \sum_{\alpha_{min}}^{\alpha_{max}} \sum_{x_{min}}^{x_{max}} p(\delta) \cdot f(W_{\delta}, x'_{\delta}, \alpha_{\delta}) \quad (3)$$

Where, $p(\delta)$: Weight representing the confidence that δ is a lane edge ($0 \leq p(\cdot) \leq 1$). (x', α, W) : Lane center, lane angle and lane width, respectively, as illustrated in Fig. 3. Loop over all values of x', α , computing W , and incrementing the point $A(x', \alpha, W)$. Thus every edge point δ in the scene votes in the accumulator A , with a value $p(\delta)$, at the 3-D location $(x'_{\delta}, \alpha_{\delta}, W_{\delta})$ representing a lane whose edges it can potentially be part of. If a lane with a parameter set (x', α, W) , then all the points on that lane edge will consistently vote at the same location (x', α, W) in A forming a peak as an evidence of the lane. More details on the vision based multi-lane detection algorithm can be found in [6].

III. PREDICTIVE CONTROL IN IMAGE PLANE (PCIP)

a - Center of the bottom-most row.

p - The current location of the vehicle, (**p** is the projection of **a**, assuming that the camera is installed at the center of the vehicle.)

b(x, y) - Current look-ahead point i.e. the point to be reached by the vehicle.

c - Prediction of next look-ahead point. (x', y') - lane center.

Lane center can be different from the center of the bottom row of the scene as the vehicle needs to not always be at the center of the lane. α - The lane angle, which the lane center makes looking at the current vanishing point.

θ - The angle made by the current vehicle position toward **b** i.e. the required steering angle to track the center of the desired lane from the current vehicle position.

l - Current look-ahead distance i.e. distance in y -direction from the current vehicle position to point **b** in image plane.

Thus, Let,

$\omega_i = \frac{d\theta}{dt}$ - The rate of change of steering angle in the image plane.

$\dot{y}$ - Vehicle speed in image plane.

We hypothesize a point **b** in the image plane toward which the car should move (Fig. 4), where **p** is the current position of the vehicle front, **b** is provided by the lane following algorithm described in [6]. A method is required to choose the steering angle (θ), the rate of change of steering angle ($\omega = \frac{d\theta}{dt}$) and vehicle speed $\dot{Z}$ as a functions of **b** and the sampling rate (dt). **b** is parameterized by the lane detection algorithm in [6] in terms of l and (x', α) shown in Fig. 4.

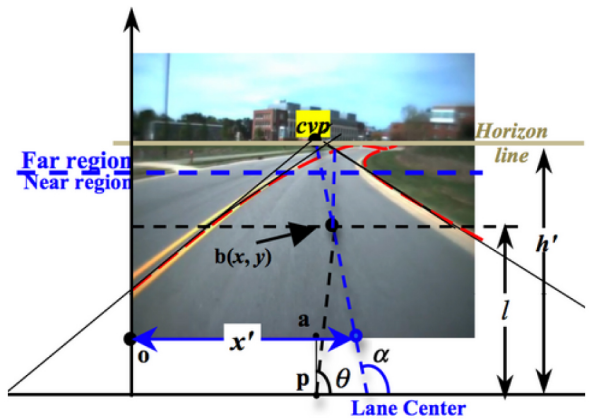


Fig. 4. Urban road scene explaining predictive motion strategy

Other than the fact that there are speed limits in the urban environment, vehicle speed is intuitively controlled by either the speed of another vehicle in front, the bending of the road and sometimes the environment and the road conditions such as icy, rainy, snowy, etc. For the vehicle to follow the road, the vehicle should always point toward the current look-ahead point **b**, assuming there are no additional vehicles. θ is then corrected by using **b**(x, y). The near region in the image plane has a point or a series of points predicting the next