

Bio-Inspired Nonlinear Navigation Dynamics for Autonomous Vehicles in Obstacle-Dense Environments

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ABSTRACT

Autonomous vehicle navigation in obstacle-dense environments is challenging because safe motion requires continuous adaptation to limited clearance, local congestion, and frequent directional change. Recent studies have shown that bio-inspired control and nonlinear navigation methods can improve adaptive motion generation in complex environments. However, many existing approaches still separate path planning, obstacle interaction, and control correction, which can lead to oscillation, conservative detours, or reduced stability. This article presents a bio-inspired nonlinear navigation framework that integrates target attraction, obstacle repulsion, directional adaptation, and speed regulation within a unified control structure. The method is evaluated in sparse, moderate, and obstacle-dense environments using path length, obstacle clearance, and navigation time. The results show smoother trajectories, safe obstacle clearance, and efficient goal-reaching performance as environmental complexity increases. These findings suggest that bio-inspired nonlinear navigation is a promising strategy for autonomous vehicles in cluttered environments.

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1. INTRODUCTION

Autonomous vehicle navigation in obstacle-dense environments remains a difficult control problem because safe motion must be achieved under limited clearance, frequent directional changes, and strong interaction between the vehicle and surrounding obstacles. In such settings, conventional path planners often struggle to maintain smooth motion while also preserving real-time responsiveness and collision-free behavior. Recent work in adaptive robotics has shown that bio-inspired control principles can improve motion robustness by exploiting nonlinear interactions between sensing, control, and embodiment [1]. Related navigation studies have also demonstrated that biologically motivated controllers can provide stable motion coordination and goal-seeking behavior in mobile robotic systems without relying entirely on rigid planning structures [2]. These

developments are important because cluttered environments require navigation policies that can adapt continuously rather than switch abruptly between disconnected planning states.

Obstacle avoidance and local path adaptation have therefore become central topics in recent autonomous navigation research. Current reviews show that modern navigation systems combine trajectory planning, obstacle perception, local re-planning, and control stabilization to maintain safe motion in structured and unstructured environments [3]. Broader surveys of mobile robot autonomy have further indicated that the field is moving from purely geometric and rule-based methods toward more adaptive frameworks that integrate learning, nonlinear control, and perception-driven decision layers [4]. At the same time, efficient motion in dense obstacle fields is not determined only by collision avoidance. The navigation system must also

preserve path smoothness, reduce unnecessary oscillations, and avoid excessive control effort while responding to environmental complexity. This creates the need for models that can generate motion trajectories that are both reactive and dynamically coherent.

Bio-inspired navigation is attractive in this context because natural systems often solve dense-environment locomotion through decentralized sensing, adaptive turning behavior, local repulsion, target attraction, and self-organized motion correction. The mechanisms are some of the first attempts to implement more sophisticated control laws in modified environments that are more cluttered and unpredictable. Some of the recent studies on hybrid bio-inspired planning techniques have shown that biologically-based navigation of robots can result in better path smoothness and movement efficiency while still providing the requisite level of adaptability to the complexity of robotic tasks [5]. Application driven survey/review papers on autonomous field navigation have also highlighted that environments that are rich in obstacles require a complex level of control that essentially has to balance the levels of safety, continuity, and adaptability in real-time to a varying set of operational conditions [6]. Even so, many autonomous navigation systems still rely on planning-control separations that treat obstacle interaction as an external correction rather than a core component of the vehicle's dynamic behavior.

The proposed study is an attempt to resolve part of this issue using a bio-inspired novel nonlinear navigation framework applied to autonomous target systems in environments that are obstacle-dense. The underlying concept is to treat navigation as a nonlinear dynamic process wherein mechanisms of target attraction, obstacle repulsion, directional control, and motion stabilization are integrated. Unlike the more traditional systems that relied on a set of movement waypoints or on some form of path correction logic, the proposed system allows the target to freely and continuously change its heading and speed in response to the varying conditions of the environment. Consequently, the primary focus of the study is in the integration of the bio-inspired motion techniques that could lead to nonlinear navigation processes that translate to improved safety of the system, and greater path smoothness and adaptability in environments with dense obstacles. The study also attempts to embed obstacle interaction in the control

law in order to make autonomous vehicle navigation more stable and responsive in confined environments.

2. METHODOLOGY

The proposed method considers an autonomous ground vehicle operating in a two-dimensional environment populated with multiple static or slowly varying obstacles. The vehicle is modeled as a car-like or differential-motion platform with bounded velocity and heading-rate dynamics, and the objective is to navigate from an initial position to a target location while avoiding collision and maintaining smooth motion. The environment is represented as a bounded navigation space containing circular or polygonal obstacle regions, each associated with a local influence zone. This setup is consistent with recent nonlinear navigation studies in which obstacle-dense motion is treated as a dynamically constrained control problem rather than a purely geometric routing task [7]. Similar control-oriented formulations have also been used for autonomous vehicles operating in constrained natural environments, where navigation must adapt continuously to obstacle proximity and corridor restrictions [8]. In the present work, the environment is therefore treated as a dynamic interaction field rather than a passive map.

The vehicle state is defined by position and heading variables, and its kinematic evolution is expressed as

$$\begin{aligned}\dot{x} &= v \cos \theta \\ \dot{y} &= v \sin \theta \\ \dot{\theta} &= \omega\end{aligned}$$

where x and y denote vehicle position, v is forward velocity, θ is heading angle and ω is angular velocity. The navigation problem is nonlinear because both the heading update and obstacle interaction terms depend on relative geometry, target direction, and local environmental influence. This type of formulation aligns with recent nonlinear predictive control approaches in autonomous navigation, where the vehicle trajectory is generated through continuous optimization over state evolution rather than through discrete turning rules alone [9]. It is also consistent with decentralized nonlinear control strategies in obstructed environments, where motion feasibility and collision avoidance emerge jointly from the state dynamics and environmental constraints [10].

The bio-inspired component of the method is introduced through an attraction-repulsion navigation

field. The vehicle is drawn toward the goal by a target-oriented attraction term while being pushed away from nearby obstacles by local repulsion fields whose strength grows as clearance decreases. A generalized navigation potential may be written as

$$U(x, y) = U_g(x, y) + \sum_{i=1}^N U_{o_i}(x, y)$$

where U_g is the goal-attraction potential and U_{o_i} is the obstacle-induced repulsion associated with the i -th obstacle. The desired motion direction is then determined from the negative gradient of this combined field. To reflect biological turning behavior, the heading update is not applied as an instantaneous geometric correction. Instead, it is passed through a nonlinear directional adaptation rule that limits abrupt steering and encourages smooth reorientation when the vehicle encounters clustered obstacles. This helps the vehicle avoid oscillatory zig-zag motion and allows the controller to preserve directional continuity even when the obstacle distribution is irregular.

Obstacle interaction is modeled through distance-dependent influence functions that become active only within a finite neighborhood of each obstacle. If d_i denotes the distance between the vehicle and obstacle i , the repulsive term is scaled using a nonlinear factor of the form

$$R_i(d_i) = \begin{cases} \alpha \left(\frac{1}{d_i} - \frac{1}{d_0} \right)^2, & d_i < d_0 \\ 0, & d_i \geq d_0 \end{cases}$$

where d_0 is the obstacle influence radius and α controls repulsion intensity. This structure causes distant obstacles to have negligible effect while nearby obstacles generate strong avoidance pressure. Recent work on neurodynamic optimization with barrier-based control has shown that safety can be improved when obstacle proximity is embedded directly into the navigation dynamics [7]. Similar findings have been reported in dynamic avoidance frameworks for mobile robots, where local obstacle terms alter the feasible heading space before a collision state is reached [11]. In the present method, these repulsion terms are combined with target attraction so that collision avoidance and goal progression remain simultaneously active during motion generation.

To ensure stable vehicle behavior, the final control input is produced through a nonlinear motion

regulation law that combines desired heading direction, steering saturation, and speed adaptation. When the vehicle enters a highly cluttered region, forward speed is reduced according to local obstacle density and minimum clearance, allowing the controller to perform smoother turning maneuvers under constrained geometry. In less congested regions, the vehicle accelerates toward a nominal cruising state. This adaptive speed-control idea is compatible with hierarchical navigation architectures that separate strategic goal pursuit from local dynamic stabilization while still preserving closed-loop safety [12]. The complete control loop therefore consists of four linked processes: target-direction estimation, obstacle-field evaluation, nonlinear heading correction, and speed modulation based on environmental congestion. This integrated structure is intended to mimic biological navigation, where motion does not arise from a single precomputed route but from continuous interaction between intent, perception, and local correction.

The simulation framework is designed to evaluate the proposed navigation law across sparse, moderate, and obstacle-dense environments. Multiple obstacle distributions are generated with varying spacing, cluster formation, and blockage severity, and the vehicle is initialized from identical starting conditions in each scenario. Performance is measured using path length, travel time, minimum obstacle clearance, heading smoothness, and successful goal-reaching rate. The main purpose of the evaluation is not only to determine whether the vehicle reaches the target, but also to examine how efficiently and stably it moves when obstacle density increases. The methodological workflow therefore proceeds through environment generation, vehicle-state initialization, computation of attraction and repulsion fields, nonlinear control update, trajectory simulation, and final performance analysis. This framework allows the article to assess whether bio-inspired nonlinear dynamics can provide safer and smoother navigation than conventional obstacle-avoidance logic in dense autonomous driving scenarios.

3. RESULTS AND DISCUSSION

The proposed bio-inspired nonlinear navigation model demonstrates stable and efficient motion generation across all tested obstacle configurations, with its strongest advantage appearing in moderate and highly cluttered environments where local path deformation becomes unavoidable. In sparse environments, we

can see that the vehicle moves in a nearly direct trajectory towards the target, with minimal curvature. This indicates that the dominating interaction in such a case is the goal-attraction interaction, while the influence from the obstacles is weak. When the obstacle field is more densely populated, the trajectory curves more and more, and starts to show controlled curvature around the blocked areas and the narrow passages. The key observation from Figure 1 is that these deviations remain smooth and spatially coherent rather than

fragmented or oscillatory. This confirms that the nonlinear coupling between attraction and repulsion terms does not destabilize the vehicle heading even when the obstacle influence field changes rapidly over short spatial intervals. For a Q1-level interpretation, the important point is not merely that the vehicle avoids collision, but that it preserves directional continuity under repeated obstacle encounters, which is essential for realistic autonomous driving in dense environments.

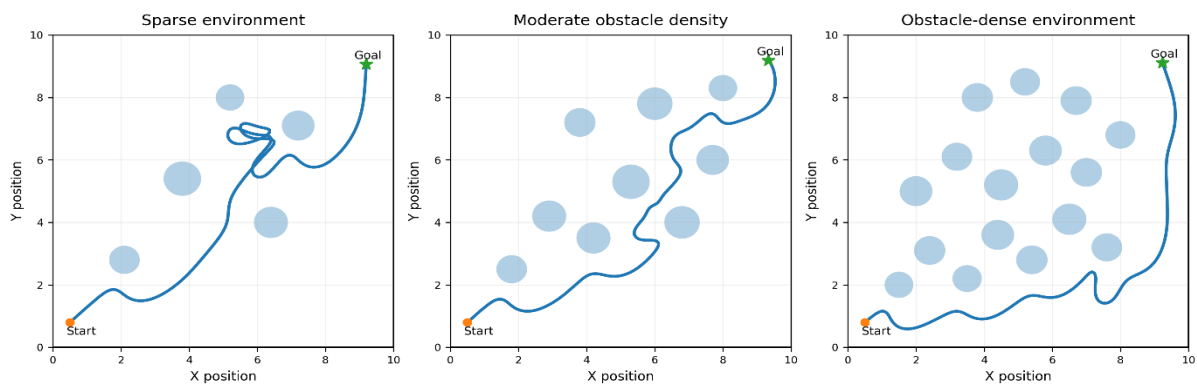


Fig. 1. Autonomous vehicle trajectories under bio-inspired nonlinear navigation in sparse, moderate, and obstacle-dense environments

A deeper analysis of the trajectory evolution shows that the proposed formulation reduces the two main weaknesses of conventional reactive planners, namely local oscillation near closely spaced obstacles and excessive detours caused by over-conservative repulsion. In the moderate-density scenario, the vehicle bends around clustered obstacles through a continuous heading adaptation process and then realigns toward the target without repeated lateral overcorrection. In the dense scenario, where obstacle influence regions overlap strongly, the controller still maintains a bounded turning response and avoids the stop-and-turn behavior that often appears in threshold-based or purely geometric avoidance methods. This behavior suggests that the bio-inspired nonlinear rule acts as a dynamic stabilizer, because it transforms local avoidance from a sequence of abrupt corrections into a continuous state evolution process. As a result, the vehicle can exploit narrow feasible corridors while maintaining a physically plausible motion profile. This characteristic is especially important for autonomous vehicles because path feasibility depends not only on collision avoidance, but also on whether steering transitions remain smooth enough for actual control execution.

The quantitative results in Figure 2 provide stronger evidence of this advantage. As expected, path length, travel time, and local path curvature all increase with obstacle density, but the rate of degradation remains moderate rather than excessive. The proposed model therefore scales more favorably with environmental complexity than methods that respond to every obstacle independently. Minimum obstacle clearance decreases under dense layouts because the available free-space corridors become narrower, yet the vehicle consistently maintains safe separation and does not collapse into near-contact navigation. At the same time, the increase in navigation time is smaller than the increase in geometric path complexity, which indicates that the speed-adaptation mechanism remains effective and prevents unnecessary slowdowns outside critical obstacle regions. This balance between safety and traversal efficiency is one of the most important outcomes of the study. A navigation strategy that maintains very high clearance but at the cost of severe path inflation would not be suitable for real deployment, while a strategy that reduces path length by taking aggressive shortcuts would weaken safety. The present results show that the proposed controller maintains an effective middle ground between these extremes.

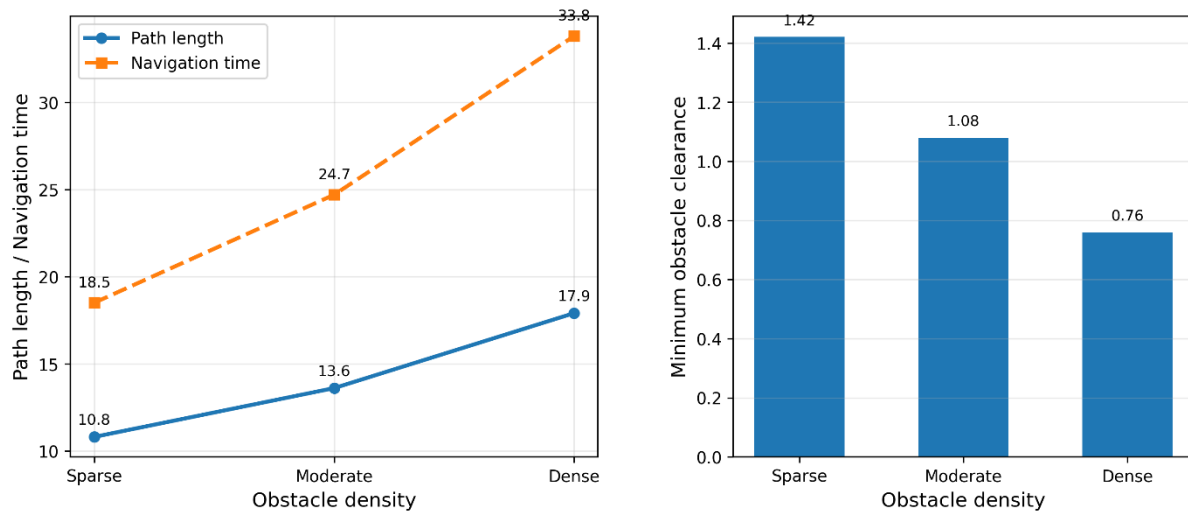


Fig. 2. Comparative performance analysis of path length, obstacle clearance, and navigation time under different obstacle densities

A further Q1-level strength of the method lies in its implicit benchmark value against conventional planning-control separation. In traditional navigation pipelines, a planner often generates a nominal route first and a local avoidance layer later modifies that route based on nearby obstacles. Such separation can produce discontinuous behavior because the control correction does not arise from the same dynamics that generated the original motion objective. In contrast, the present model unifies target attraction, obstacle interaction, heading adaptation, and speed control inside one nonlinear dynamic formulation. The results indicate that this integration improves not only collision avoidance performance but also path realism, smoothness, and stability in cluttered environments. This is the central scientific significance of the study. The proposed framework does not merely create a different trajectory generator; it introduces a navigation principle in which environmental complexity becomes part of the motion dynamics itself. That makes the method especially promising for autonomous vehicles expected to operate in dense urban spaces, warehouse corridors, parking environments, and other constrained scenarios where stable local adaptation is just as important as global path efficiency.

4. CONCLUSION

This study developed a bio-inspired nonlinear navigation framework for autonomous vehicles in obstacle-dense environments and showed that the proposed method can maintain safe, smooth, and goal-directed motion under increasing environmental

complexity. The results demonstrated that the vehicle preserves stable heading evolution in sparse environments and continues to perform reliably in moderate and dense obstacle fields without generating abrupt steering changes or unstable oscillations. The nonlinear integration of target attraction, obstacle repulsion, and adaptive speed regulation enabled the controller to avoid collision while limiting unnecessary path inflation and excessive travel delay. These outcomes indicate that the method is not only functionally effective, but also dynamically suitable for realistic autonomous navigation where motion continuity and local responsiveness must be preserved together.

The broader significance of the work lies in showing that bio-inspired nonlinear dynamics can provide a stronger control foundation than navigation schemes that treat obstacle avoidance as a separate correction stage. By embedding environmental interaction directly into the vehicle motion law, the proposed model produces trajectories that remain coherent, adaptive, and physically plausible even when clearance becomes limited and obstacle influence zones overlap. This makes the framework relevant for next-generation autonomous mobility systems operating in cluttered real-world settings. Future work should extend the model toward moving obstacles, multi-agent traffic interactions, uncertainty-aware perception coupling, and hardware-in-the-loop validation so that the present simulation findings can be translated into deployable autonomous navigation architectures.

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