Collision Avoidance Using Elastic Bands for an Autonomous Car

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Abstract

This paper describes recent work on an autonomous car that is able to navigate through regular traffic being longitudinally and laterally guided by actuators controlled by a computer.

Previously, this autonomous driving capability was purely based on the vehicle-following principle using vision. The path of the leader vehicle was tracked. To extend this capability to general driving situations, a dynamic path planning component is introduced. Several driving situations are identified that necessitate responses to more than the leader vehicle.

The elastic band framework offers the necessary features to cover dynamic driving situations. Simulation results show the power of this approach. Real-world results obtained with an autonomous car agree with the simulation results.

1 Introduction

Collision avoidance has been the subject of extensive research both in the field of robotics and intelligent vehicles. A tremendous benefit is assessed for reducing collisions with automated systems in regular traffic. The detection capabilities of vision-based intelligent vehicles are mature enough to perform such a task (see e.g. [5]).

A popular approach for automated vehicle guidance is to follow a leader vehicle. This intuitive behavior comes to its limitations when other traffic participants interfere with the leader vehicle's path. Dynamic path modification becomes necessary. These dynamic driving situations motivated the work of this paper.

How is this paper organized? Section 2 gives an overview of related work both in the field of intelligent vehicles and robotics. In Section 3 the elastic band framework is introduced. Section 4 describes the necessary adaptations to the elastic band framework in order to tune the avoidance behavior towards that of human beings. The impact of the elastic band framework on the planning and decision stage is described in Section 5. Results are detailed in Section 6. Conclusions and future work comprise the final Section.

2 Related Work

2.1 Potential Field Approaches

The most prominent idea for collision avoidance are artificial potential fields (e.g. [13, 11]). The obstacles are modeled as potentials and the gradient of the superimposed potential field yields the direction command for the mobile robot. Potential fields are an elegant way to model obstacles and can be analyzed globally. A formal verification of the obstacle avoidance behavior is feasible.

Generalized potential fields depend not only on distance to obstacles and can therefore determine irrelevant obstacles pointing away from the ego-path. This method was first applied to velocity-dependent potentials in [13].

A popular approach to avoid local minima, i.e. trapping situations, in potential field applications is the use of harmonic potentials (see e.g. [9], [8]).

2.2 Approaches Using Physical Models

Other physical models besides potential fields are also popular for collision avoidance.

An alternative approach to the potential field methods is presented in [2], where analogies of this problem to hydro mechanics problems are shown. Fluid dynamics equations are used. The fluid starts at the starting point towards the goal point and obstacles obstruct the flow. From the resulting flow field the planned path can be computed.

In [18], an approach to behavioral control of robots is described that uses the model of dynamical systems. The path for navigation and obstacle avoidance is generated solving dynamical differential equations. The approach is rather time-consuming due to the necessary relaxations. For this approach, low-level sensory information as opposed to symbolic obstacle information is used.

Quinlan and Khatib present another approach to obstacle avoidance that uses the model of an elastic band for a robot (see e.g. [15] and [16]). The elastic band framework is used for our application. An initial path has to be supplied. This path is modeled as an elastic band that is subjected to forces, exerted by obstacles which are represented as potential fields. This approach has also been extended to non-holonomic mobile robots [12]. Brock extends that idea to the many-dimensional configuration space of mobile manipulators [1].

Other approaches often include rule-based systems or systems executing behavioral patterns. These systems are not covered here due to space limitations.

2.3 Approaches for Intelligent Vehicles

A potential field application in non-autonomous driving applications is described in [7]. On force-control basis, also vehicle dynamics can be taken into account and combinations of different drive-assist systems are feasible. Simulation results are presented.

A completely autonomous car with obstacle avoidance capability is presented in [17]. The application of potential fields to determine the risk yielded oscillatory behavior in overtaking situations. As a consequence, behavioral patterns were implemented for obstacle avoidance maneuvers. Longitudinal and lateral maneuvers are presented.

A very interesting approach both for robotics and intelligent vehicles applications is presented in [3]. In contrast to the other approaches presented here, obstacle avoidance is performed in configuration and in velocity space. Constant velocity is assumed for all obstacles.

3 Elastic Bands

3.1 Introduction to Elastic Bands

The original elastic band approach for collision avoidance was proposed by Quinlan and Khatib [15]. Similar physical properties are used for snakes in Computer Vision [10]. An initial, feasible path must be delivered by a path planner. This path is dynamically modified by treating the path as an elastic band that is able to change its shape. The

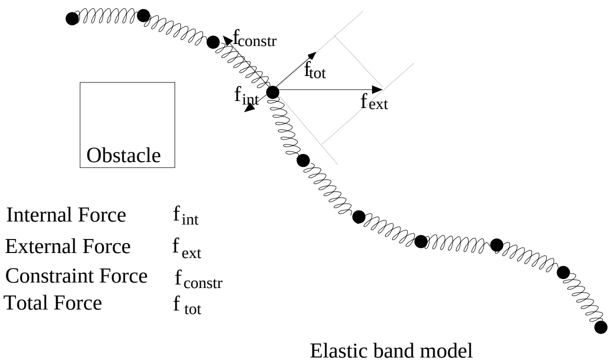

Figure 1: Representation of an elastic band as a series of particles with springs in between.

total energy of the elastic band is minimized yielding smooth paths. Forces acting on the elastic band are computed by taking the gradient of the potential energy at discrete path points. The repelling forces on the elastic band are produced by obstacles in the vicinity of the path. In total, three types of forces are acting on the elastic band. These forces and the representation of an elastic band is shown in Figure 1. Basically, the elastic band is modeled as a series of particles with a series of springs in between in the discrete case.

3.2 Forces Acting on the Elastic Band

For the **internal force** f_{int} modeling the spring force, using Hooke's law would be intuitive. To achieve the same avoidance behavior independent of the elastic band length, a normalized internal force is used.

The **external force** is due to obstacles that are modeled as potentials in the scene. Any potential shape that repels the elastic band from obstacles is conceivable. We decided to use a position dependent potential suggested by Quinlan [14] superimposed by a velocity-dependent potential proposed by Krogh [13]. The gradient of this potential, $\vec{f}_{ext}$, yields the external force. Details on the external force follow in Section 4.4.

The elastic band can potentially reduce its internal energy by moving particles along the elastic band. This is an undesired property since the band might thin out at some parts. To constrain the motion along the elastic band, a **constraint force** $\vec{f}_{constr}$ is introduced with a direction tangential to the elastic band.

3.3 The Elastic Band Algorithm

The elastic band is simulated with reduced dynamics since only the equilibrium state is of interest for obstacle avoidance. For every time step, the algorithm is repeated. The path is represented with particles $\vec{q}_i$ and these particles are subjected to the total force

$$\vec{f}_{tot} = \vec{f}_{int} + \vec{f}_{ext} + \vec{f}_{constr}. \tag{1}$$

With our pseudo-static simulation, the particles are moved along the total force to the new position

$$\vec{q}_{i,new} = \vec{q}_{i,old} + \alpha * \vec{f}_{tot}. \tag{2}$$

Higher order terms beyond particle acceleration are neglected here. This procedure is applied iteratively until the total force of all configuration points is sufficiently small, i.e. until the force equilibrium is reached.

In the original elastic band approach, the moving procedure is supplemented with a procedure of adding and removing particles in order to maintain a collision-free path at all times (see Section 4). So-called bubbles model the available free space around a configuration.

4 Adaptations for Vehicle Following

4.1 The Basic Idea

The elastic band approach is adapted to the vehicle-following scenario here. The path of the leader vehicle constitutes the initial path. Obstacles in the environment exert forces on the band and move it into a final configuration. This is the path the ego-vehicle tracks subsequently.

Driving situations that necessitate this dynamic modification of the leader vehicle path are

- passing a cyclist or pedestrian along the road while following a leader vehicle, or
- driving too close to parking cars due to the smaller size of the leader vehicle, or
- driving around a car or pedestrian that comes to a stop slightly inside the road intersection.

Many more scenarios can be identified. In addition, further extensions of the autonomous driving capability of such a vehicle definitely need this dynamic path planning component.

The following subsections cover the sensor data acquisition, algorithmic modifications to the elastic band approach, the chosen potential shapes, and the actual integration of the approach in the existing system.

4.2 Acquiring the Sensor Data

Our range sensor, a calibrated stereo camera system, delivers 3D measurement of significant points resulting in a 3D point cloud. The significant points of the left image are matched in the right image by standard correspondence analysis along the epipolar line similar to [4]. However, the algorithms described in the remainder of this paper are applicable to any sensor delivering range data.

The reference frame used here is depicted in Figure 3. The y-axis protrudes upwards. To extract objects from 3D measurements, we cluster close 3D points together, except the 3D points on or below the ground. We assume a flat road for that procedure. These clusters become objects once they become confirmed over several frames.

One object corresponds to one clustered 3D point cloud projected to the x-z-plane represented by its convex hull for collision avoidance purposes. Basically, the convex hull describes the contour of the obstacle.

The relative velocities of the objects w.r.t. the ego-vehicle are computed based on the center of the obstacles bounding boxes using an extended Kalman filter. One of the extracted objects is the leader vehicle supplying the initial path. The other detected objects constitute obstacles that have to be avoided.

4.3 Modifications to the Original Elastic Band Approach

The vehicle-following application of the elastic band differs from the original idea in the following ways:

- The initial path cannot be guaranteed to be collision free. Since the initial path is created by the path of the leader vehicle, changes in the scene might have occurred since the leader vehicle passed. It is possible that another traffic participant has approached that path in the meantime. In addition, the leader vehicle might be smaller in width than the autonomous vehicle and might have chosen a path very close to an obstacle.

- The initial position of the configuration particles is the leader vehicle path. We want the autonomous vehicle to follow exactly this path in the absence of obstacles. Hence the internal forces of the initial configuration receive an offset yielding zero in the absence of obstacles. This behavior was chosen to maintain the intuitive vehicle-following capability. In the original approach, the elastic band was assumed to have zero length and would always collapse to a straight line in the absence of obstacles.
- The leader vehicle path is not guaranteed to be collision free. Consequently, the equilibrium state of the elastic band might not be collision-free either. We need an additional algorithm after the equilibrium position has been found to assure a collision-free path. This is done by geometrically checking for overlaps along the final configuration of the elastic band.
- A regular car is an intrinsically non-holonomic vehicle. The original algorithm [15] applies only to holonomic robots. This limitation has not been explicitly taken into account. Hence the paths created by the elastic bands could be infeasible for non-holonomic cars. Since uncertainties in the 3D measurement of objects and uncertainties in the vehicle control requires additional slack around the planned path, this is not considered a serious problem. In addition, the non-holonomic constraint also applies to the leader vehicle and is reflected in the leader vehicle path. Work on elastic bands for non-holonomic vehicles has been presented in [12].
- In regular traffic situations, lane markings are also used for vehicle guidance. The lane markings are detected and are also modeled as virtual obstacles with repelling forces pointing away from the lane boundaries towards the lane center. A similar potential shape to the one in [7] is used.
- The external force of the elastic band must be shaped to comply with natural driving behavior. Drivers keep more distance from obstacles at high speed than at low speed (e.g. parking situations). Therefore, a velocity-dependent potential shape must be used. This is detailed in the following section.

4.4 The Potential Shape

The original approach for elastic bands is designed for mobile robots that rarely exceed 2 m/s. So a position-dependent potential is sufficient. We modified this approach in a way that the effective reach of Quinlan's potential increases with increasing velocity.

In addition, we superimpose a velocity-dependent potential, introduced by Krogh [13]. Since we already know an initial path, only obstacles close to that path are considered. A fading function for every obstacle is multiplied with the original Krogh potential to reduce the effect of obstacles exceeding a certain lateral distance to the planned path.

Note that the minimum lateral distance of obstacles to the planned path is only available for obstacle avoidance algorithms that plan the whole path. Algorithms only yielding current heading and accelerations do not deliver the information to compute that quantity.

The total external force per particle is the superposition of the Krogh and Quinlan force. When an obstacle overlaps with a particle of the elastic band, a maximum force is exerted towards a direction, where obstacle clearance is obtained on the shortest way.

4.5 Control with the Elastic Band

The result of the elastic band for the control algorithm is a modified path that is tracked subsequently. The controller selects a point of the path at a certain lookahead distance. The desired steering angle is computed to head towards that point [6]. Instead of the leader vehicle path, the elastic band path is used for control.

Since the elastic band algorithm operates statically on the current scene snapshot and is re-run at every time step, no connection between the elastic band results from one frame to another exists. A low-pass filter is applied to the lateral position delivered by the elastic band path.

5 Planning and Decision for Elastic Bands

In the standard vehicle-following approach, a planning and decision module selects the leader vehicle and sends the leader vehicle position to the controller. A leader vehicle is initially selected by projecting the planned corridor forward using the current steering angle and the first vehicle to intersect with this corridor is the leader vehicle. The driver has to confirm this leader vehicle selection manually.

The elastic band framework can be integrated easily using a path-based approach for vehicle following [6]. Only the leader vehicle path has to be exchanged with the elastic band path. The longitudinal control is implemented in such a way that we follow the leader vehicle at a safe distance. The elastic band algorithm only affects the lateral control.

The corridor to be searched for the leader vehicle becomes the corridor around the elastic band path. Hence, when small intersections with an obstacle occur, the elastic band algorithm bends the path in such a way that no intersection with the obstacle occurs. As a safety measure the bent of the elastic band path is monitored and when deviations beyond a certain threshold occur, the control is returned to the driver. Although the elastic band is still feasible in such a case, the behavior of the ego-vehicle would already be far from that of typical vehicle-following system. After such a situation occurred, a new leader vehicle must be selected.

6 Results

6.1 Real World Results Using Vision

We integrated our elastic band framework in the basic vehicle-following system. Computing the modified path runs in real-time without much optimization. With our current parameterization, the elastic band finds its equilibrium state within 20 iterations for most situations.

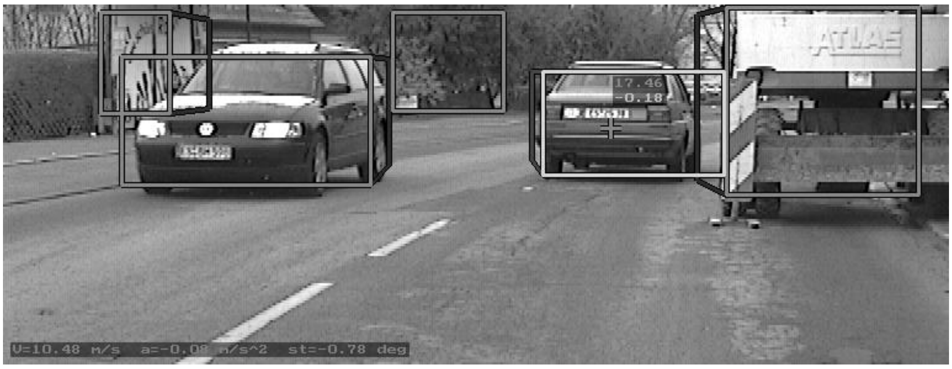

Figure 2: Traffic scene with a dredger on the right side of the street.

Figure 2 shows a typical traffic scene with counter traffic on the left and a parked obstacle (a dredger) on the right. The leading vehicle drove very close to the dredger (see initial path in Figure 3) and is smaller than our research vehicle. Hence following the initial path brings us dangerously close to the dredger. The elastic band approach yields the path marked with asterisks in Figure 3 which avoids the dredger and keeps a safety distance from the car on the left at the same time. Lane markings were not used here.

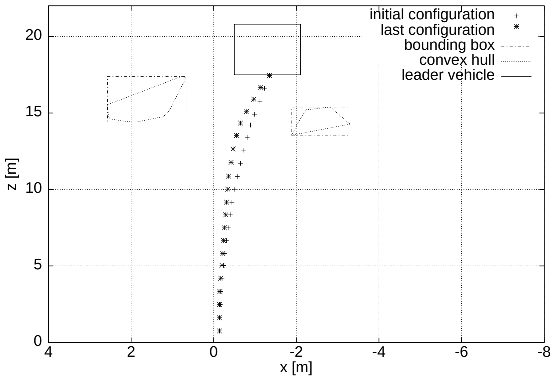

Figure 3: Bird view for the dredger scene. The leader vehicle is located at the end ($z = 17.5m$) of the path and is smaller than the ego-vehicle.

6.2 Collision Avoidance for Critical Maneuvers

Collision Avoidance Maneuvers are dangerous to conduct in the real-world. It is not safe to interfere with a car's path when it moves. So we decided to perform some of these maneuvers in the research vehicle driving autonomously but using simulated obstacles. This way, the experiments can be reproduced exactly. Figure 4 shows a scene, where a small leader vehicle drives in a straight way very close to an obstacle on the left. The ego-vehicle avoids this obstacle by performing a swerve maneuver. The right graph in Figure 4 shows the sequence of the swerve maneuver in three snapshots. The desired path as output from the elastic band algorithm is depicted in a dashed line. Note that the ego-vehicle does not follow exactly the elastic band path due to non-holonomic constraints and due to the simple controller design.

In all realistic scenarios the elastic band algorithm found an equilibrium state within 20 iterations. The average computation time for the algorithm with interfering obstacles is about $10ms$ on a 400 MHz Intel Pentium II PC. Even in infeasible situations with several obstacles, the maximum computation time stays below $50ms$.

7 Conclusions and Future Work

In this paper a dynamic collision avoidance component for the standard vehicle-following approach has been introduced. The elastic band framework is used to modify the initial path of the leader vehicle.

Modeling human driving behavior requires a lot of context knowledge that has to be represented as a rule base in some way. However, we consciously skipped that step and tried to model human driving behavior with a physical model in order to keep things intuitive and to analyze global properties of the planned path.

The results show, that for standard vehicle-following situations, no modification is necessary. In dynamic situations, the intuitive obstacle avoidance response is achieved. Computation time measurements show that real-time performance is achieved without much optimization effort.

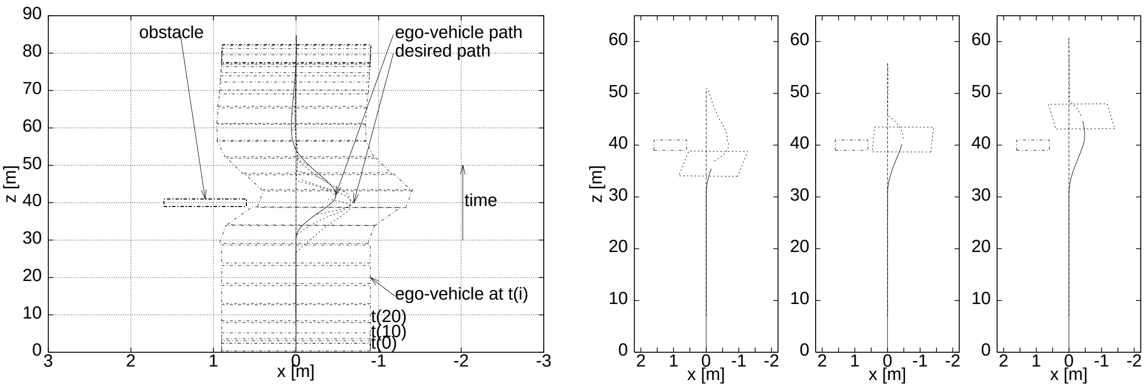

Figure 4: Bird view for a situation where a pedestrian slightly enters the driving corridor which necessitates a swerve maneuver. The ego-vehicle and the leader vehicle drive at $6m/s$ and they are about $15m$ apart. The right graph shows snapshots of the scene.

In the future, we will investigate the use of a discretized depth map in contrast to the obstacles as basis for the potential. This would yield a more reactive response closer related to the sensor data. The number of distance computations would increase significantly but at the same time the distance computation degenerates to a distance computation between point and line segment.

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