Follow the Past - a Path Tracking Algorithm for Autonomous Vehicles

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Abstract: A number of algorithms for path tracking are described in the robotics literature. Traditional algorithms, like Pure Pursuit and Follow the Carrot, use position information to compute steering commands that make a vehicle follow a predefined path approximately. These algorithms are well known to cut corners, since they do not explicitly take into account the actual curvature of the path. In this paper we present a novel algorithm that uses recorded steering commands to overcome this problem. The algorithm is constructed within the behavioral paradigm common in intelligent robotics, and is divided into three separate behaviors, each responsible for one aspect of the path tracking task. The algorithm is implemented both on a simulator for autonomous forest machines and a physical small-scale robot. The results are compared with the Pure Pursuit and the Follow the Carrot algorithms, and show a significant improvement in performance.

Keywords: Path tracking, Outdoor navigation, Behavioral robotics

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Ola Ringdahl, works as Research Engineer at department of Computing Science at Umeå University. He received his M.Sc. from the same department in 2003. His research interests are in path tracking, obstacle avoidance and system integration.

1 Introduction

The Follow the Past algorithm has been developed as part of the project Autonomous Navigation for Forest Machines (Hellström (2002)) at Umeå University, Sweden. The goal of this project is to develop a path-tracking forest vehicle. A human driver drives the path once, while a computer is continuously recording position, velocity, orientation, and steering angle. This information is then used to control the vehicle each time it autonomously travels along the path. If the vehicle gets off course, for example as a result of avoiding an obstacle or because of noise in the positioning sensors, the Follow the Past algorithm steers like the driver, plus an additional angle, based on the distance to the path. Traditional algorithms, like Follow the Carrot (Barton (2001)) and Pure Pursuit (Coulter (1992)), use position information only, and sometimes run into problems that can be avoided, by taking into account additional information from the human driver.

There are many variations on the basic Pure Pursuit algorithm. The Adaptive Pure Pursuit algorithm (Hebert *et al.* (1997)) addresses computational issues and stability at high speeds. The Feedforward Pure Pursuit algorithms (Hebert *et al.* (1997)) simulates the outcome of various control commands, and selects the most appropriate one. In (Coulter (1992)), the average curvature of the path is used instead of the recorded steering angle in a proportional path-following algorithm. Other researchers, e.g. (Ollero *et al.* (2001)), have approached the problem with a fuzzy-logic controller that uses the same additional information as Follow the Past, but has a more complex design. A brief survey of more path-tracking control algorithms can be found in (Mäkelä (2001)).

This report describes the derivation of the Follow the Past algorithm, presents simulated runs as well as tests with a physical robot, *Pioneer 2-AT8* (ActivMedia_Robotics (2004)), and compares these to traditional path-tracking algorithms. All simulations are run on a dedicated forest machine simulator, developed by Ringdahl. A full description of the simulator environment with mathematical derivations can be found in (Ringdahl (2003)). Initial tests and results can be found in our technical report (Hellström and Ringdahl (2004)).

2 Follow the Past algorithm

Since the forest vehicle uses articulated steering, the definitions of heading, orientation, and steering angle may not be obvious to the reader. In this paper we use the following definitions, also illustrated in Figure 1:

The steering angle ϕ is defined as the angle between the front and rear sections of the vehicle. The heading η is defined as the direction of the front part of the vehicle. The orientation θ is defined as the direction, in which the vehicle would travel, if the steering angle was zero and the baseline was maintained, as illustrated by the dashed vehicle in Figure 1. θ can be computed as the heading of the vehicle minus half the steering angle, i.e. $\theta = \eta - \phi/2$. The orientation θ and the heading η are expressed in a global system of coordinates.

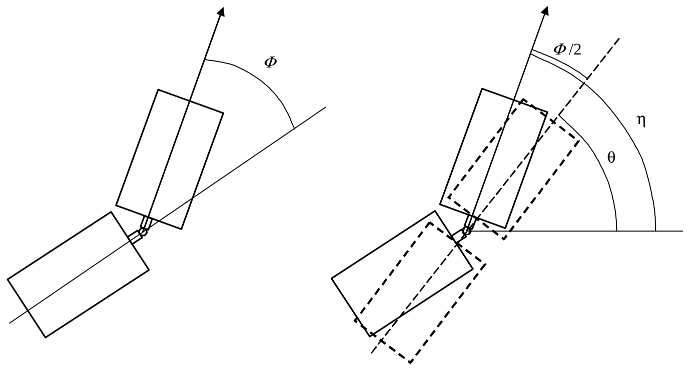

Figure 1: Definitions of steering angle ϕ, heading η, and orientation θ.

During the manual driving along the path, the orientation and steering angle are recorded together with the position at every moment. The recorded orientation θ' and the recorded steering angle ϕ' are used by the Follow the Past method, which is composed of three independent behaviors:

ϕ_β: Turn towards the recorded orientation θ'
ϕ_γ: Mimic the recorded steering angle ϕ'
ϕ_α: Move towards the path

Each behavior suggests a steering angle and is reactive, i.e. operates on the current input values; orientation, steering angle, and estimated shortest distance to the path. ϕ_α uses recorded closest positions (x', y') and actual position (x, y) as inputs. ϕ_β uses recorded orientation θ' and actual orientation θ as inputs. ϕ_γ uses the recorded steering angle ϕ' as input. The three behaviors are fused into one action, the commanded steering angle ϕ_t, as shown in Figure 2. The three independent behaviors ϕ_α, ϕ_β, and ϕ_γ operate

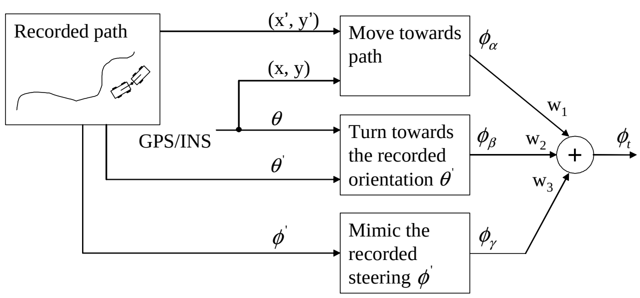

Figure 2: Path tracking with reactive control of steering angle ϕ_t.

in the following fashion:

ϕ_β: Turn towards the recorded orientation The angle θ' is defined as the recorded orientation at the closest point on the recorded path. This point is called the

path point. ϕ_β is computed as the difference between the current orientation θ and the recorded orientation θ':

$$\phi_\beta = \theta' - \theta. \tag{1}$$

ϕ_γ: Mimic the recorded steering angle This behavior simply returns the recorded steering angle ϕ' at the the path point:

$$\phi_\gamma = \phi'. \tag{2}$$

By using the recorded steering angle, the curvature of the path is automatically included in the final steering command. This is a great advantage compared to methods like Pure Pursuit (Coulter (1992)) and Follow the Carrot (Barton (2001)).

ϕ_α: Move towards the path This behavior is responsible for bringing the vehicle back to the path, if the vehicle deviates from the path for some reason. Such a deviation can be caused by noise in the position signal or by the obstacle-avoidance system, which is a separate behavior, not described in any detail in this report. ϕ_α can be implemented in many ways. We have implemented two different methods as described below.

Method One: directly proportional to the distance from the path
The simplest way is to calculate a value, directly proportional to the distance between the vehicle and the path point. This is done by multiplying the distance d by a constant k $[deg/m]$, i.e.:

$$\phi_\alpha = kd \tag{3}$$

with the constraint

$$|\phi_\alpha| \leq 90°.$$

d is the signed distance between the vehicle and the path point, and is negative or positive, depending on the side of the path at which the vehicle is. A typical value for k in the tested applications is 0.07. To ensure that ϕ_α does not become too large when the distance to the path is substantial, a constraint is required. The two behaviors ϕ_β and ϕ_γ see to it that the vehicle remains parallel to the path, and therefore the angle ϕ_α must be within $[-90°, 90°]$, i.e. $|\phi_\alpha| \leq 90°$.

Method Two: use a Look-Ahead Point
With Method One, the calculation of the control angle ϕ_α is linear. This may result in oscillations about the path, when the vehicle is close to it. Reducing the value for k results in a slow response, even for a large d, meaning that the vehicle requires more time to reach the path. Method Two overcomes this problem by using a Look-Ahead Point, and calculating

the angle between the vehicle and the Look-Ahead Point. See Figure 3. The algorithm for computing ϕ_α with Method Two is:

1. Determine the closest point on the recorded path (i.e. the path point).
2. Compute a Look-Ahead Point at a Look-Ahead Distance ℓ from the path point, in a direction δ, defined as the sum of the recorded orientation θ' and the recorded steering angle ϕ' at the path point, i.e.:$\delta = \phi' + \theta'$.
3. Calculate a Look-Ahead Angle ψ, defined as the polar angular coordinate for the vector between the vehicle's current coordinates and the Look- Ahead Point.
4. Compute ϕ_α as the difference between ψ and the angle δ., i.e.: $\phi_\alpha = \psi - \delta$.

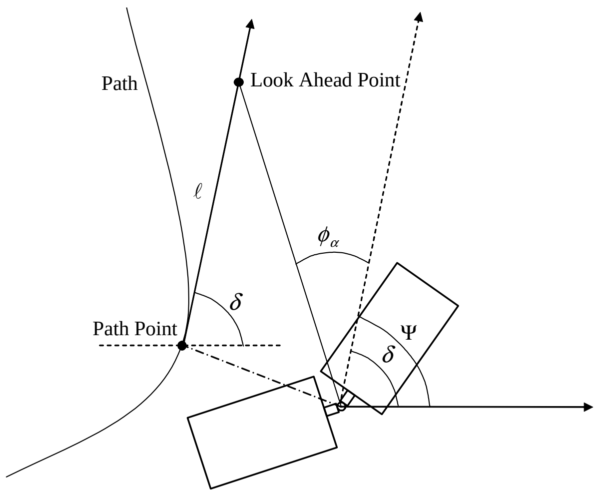

Figure 3: Calculation of ϕ_α in Method Two.

2.1 Command fusion

The three behaviors ϕ_α, ϕ_β, and ϕ_γ all return a suggested steering angle, aiming at fulfilling the goals of the respective behaviors. These three values are fused into one value ϕ_t by a weighted addition, as shown in Figure 2. In our tests, all weights have been set to 1. I.e.:

$$\phi_t = \phi_\beta + \phi_\gamma + \phi_\alpha. \tag{4}$$

For Method One above, this expression is:

$$\phi_t = \theta' - \theta + \phi' + kd. \tag{5}$$

For Method Two above, the expression for the fused ϕ_t is:

$$\begin{aligned}\phi_t &= \psi - \delta + \phi_\beta + \phi_\gamma \\ &= \psi - (\phi' + \theta') + (\theta' - \theta) + \phi' \\ &= \psi - \theta.\end{aligned} \tag{6}$$

3 Testing and Results

The developed algorithm has been tested both in a simulator for forest machines (Ringdahl (2003)) and on a Pioneer robot (ActivMedia_Robotics (2004)), and is compared to the already existing implementations of the Follow the Carrot (Barton (2001)) and Pure Pursuit (Coulter (1992)) methods. No significant difference between the two methods for calculating ϕ_α can be seen in the presented examples, therefore only the tests done with Method Two are shown here. In the simulator, a Look-Ahead Distance ℓ of 12 meters is used, and in the robot test cases $\ell = 1.2$ meter. These values are determined experimentally, and affect the vehicle's ability to quickly return to the path, for example when avoiding obstacles, as well as the sensitiveness to noise in the position sensors. Extensive tests with different values for k and ℓ at different noise levels in the simulator can be found in (Hellström and Ringdahl (2004)).

The reason for using a simulator in addition to a real robot is that the physical layout of the Pioneer robot differs significantly from the eventual target machine: a real forest machine, with articulated steering. The simulator simulates a large forest vehicle that takes time to turn and has more difficulties with sharp turns. This gives some indication as to how the algorithm will perform on a real forest machine. In the examples below, it is assumed that there is no noise in the simulated position sensors. This illustrates how the algorithm performs with ideal sensors. The Pioneer robot is equipped with a RTK-DGPS[a] for positioning and a magnetic compass combined with a gyro to measure the heading of the vehicle. The optimal accuracy of the GPS position is ±2 cm.

Figure 4(a) shows results for path tracking in the forest machine simulator. The vehicle (thick line) is capable of perfectly following a recorded path (thin line) by the Follow the Past algorithm, with practically no deviation from the path. As a reference, Figures 4(b) and 4(c) show how the vehicle behaves when using the Follow the Carrot and Pure Pursuit methods respectively, under the same conditions. This path has some sharp turns, which makes it difficult for both Follow the Carrot and Pure Pursuit, as they tend to "cut corners" instead of following a highly curved path. Under ideal conditions, this problem is avoided by the Follow the Past algorithm. As we can

[a]Real-Time Kinematics - Differential GPS

see in Figure 5, the Follow the Past algorithm still has superior performance over the other two algorithms when applied to the physical Pioneer robot. The behaviors of the algorithms are very similar to the simulator tests.

It is illuminating to study how the three behaviors ϕ_β, ϕ_γ, and ϕ_α contribute to the path-following in different situations. For the purpose of illustration, the robot was placed 1.5 meters away from the recorded path. Figure 6 shows the behaviors produced by Follow the Past, when tracking the path in Figure 7. The resulting steering angle is composed of all three behaviors as long as the vehicle is far away from the path, and has an incorrect heading. About nine seconds from the start, both ϕ_α and ϕ_β get reduced to almost zero, and the total behavior consists almost entirely of mimicking the steering angle, i.e. $\phi_t \approx \phi_\gamma$. For the first two seconds, the resulting set steering angle is greater than the maximum steering angle of the vehicle (20°), and therefore the actual steering angle differs from the set value in this situation.

4 Conclusions

We have implemented and evaluated a new path-tracking algorithm that uses the operator's steering commands and the recorded heading values as inputs, in addition to actual position and heading information. The algorithm has proven to be a much more appropriate choice than the traditional Pure Pursuit and Follow the Carrot algorithms for our application. The reason for this is primarily the inclusion of extra information into the algorithm. Taking into account the human driver's steering commands makes it possible to avoid the well known drawbacks of the traditional algorithms. The two described methods for computing ϕ_α, the behavior responsible for moving towards the path, have comparable performances. The algorithm is currently being implemented on a full-size forest machine.

5 Acknowledgements

The authors would like to acknowledge Thomas Johansson, who has designed and implemented the control and sensor software for the Pioneer robot used in the experiments. This work was funded by The Kempe Foundation and VINNOVA under Award No. 2003-00777.

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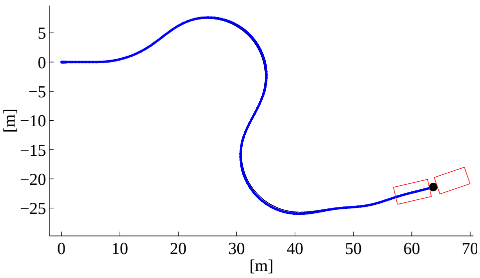
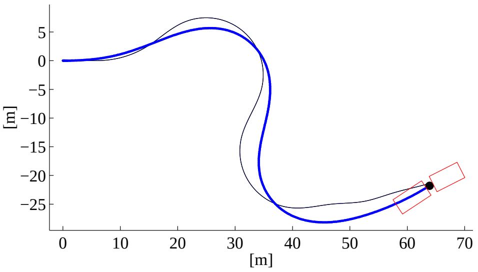
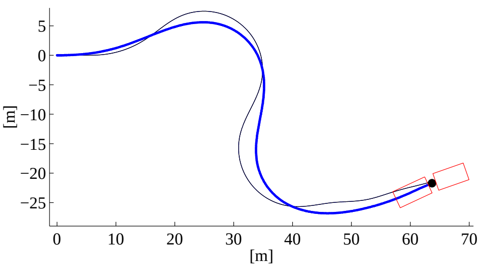


(a) Follow the Past

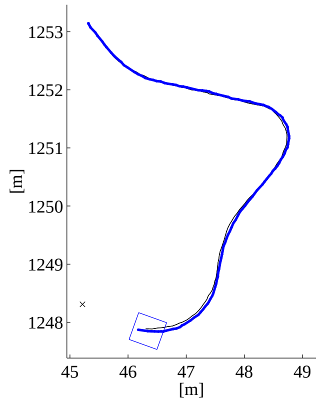


(b) Follow the Carrot

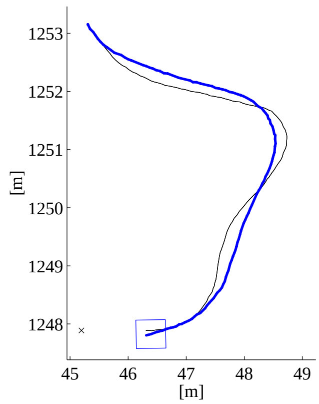


(c) Pure Pursuit

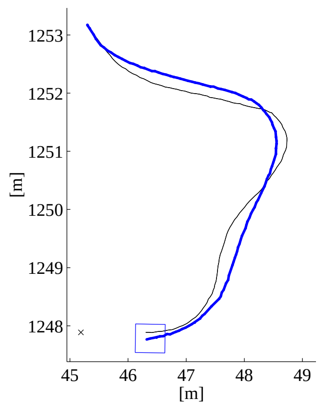
Figure 4: The *Follow the Past* algorithm does not cut the corners like the other algorithms do. The shown examples are from the forest machine simulator.



(a) Follow the Past



(b) Follow the Carrot



(c) Pure Pursuit

Figure 5: The *Follow the Past* algorithm still performs better than the other two algorithms when applied to a physical vehicle. The examples above are from tests with the Pioneer robot.

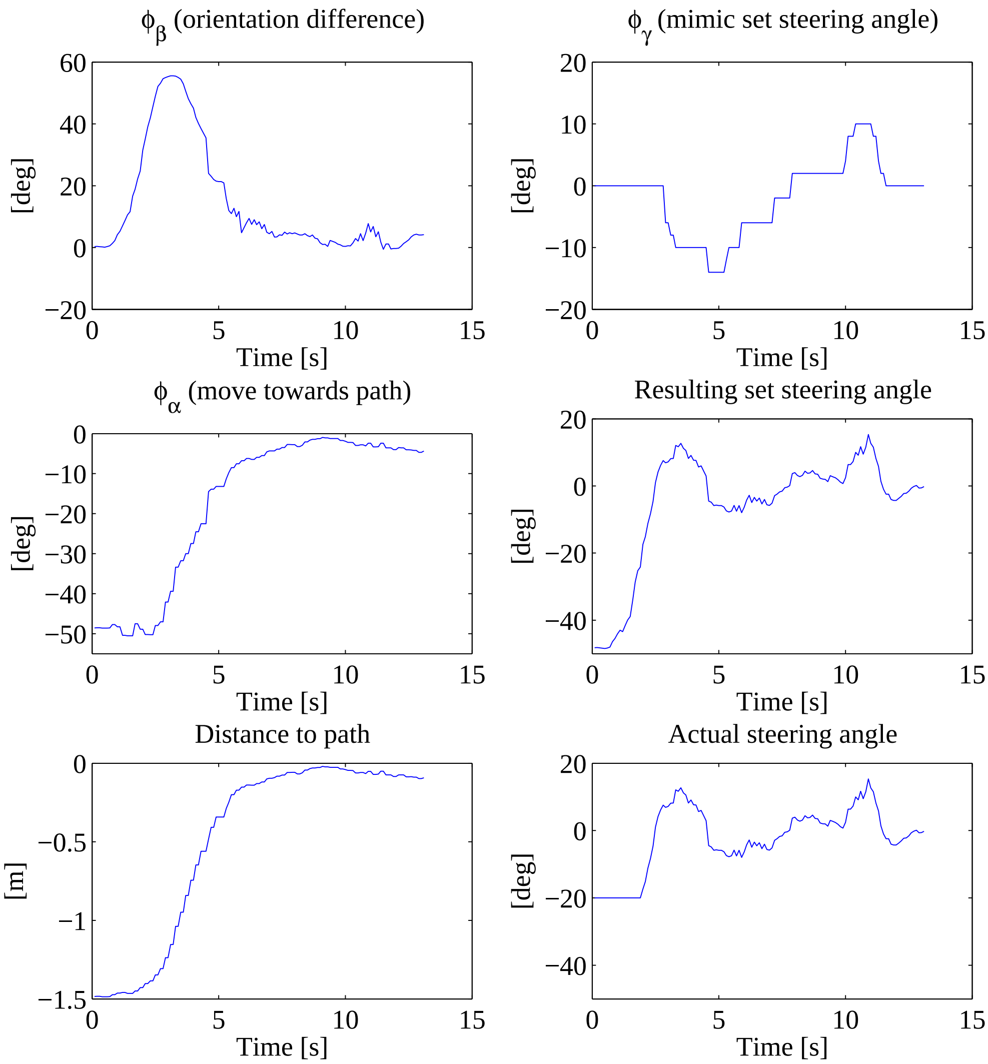


Figure 6: Illustration of the three different behaviours in Follow the Past, when following the path in Figure 7. The Pioneer robot was initially placed 1.5 meters away from the recorded path. The resulting set steering angle is the sum of ϕ_α, ϕ_β and ϕ_γ. When the distance to the path has been reduced close to zero, the set steering angle is essentially ϕ_γ, i.e. the robot tries to mimic the human driver's steering commands.

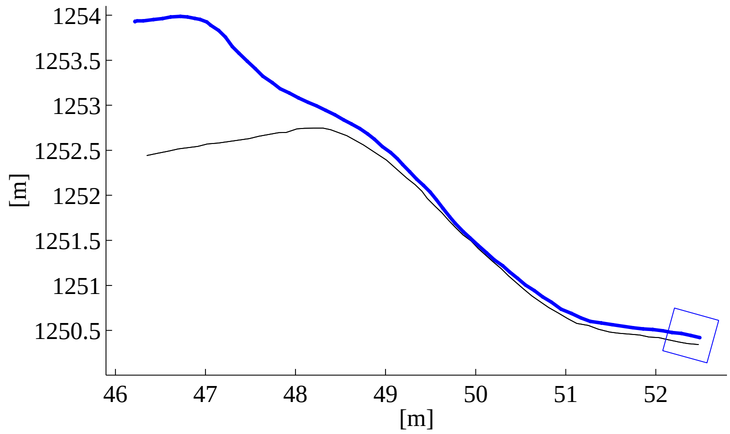


Figure 7: The robot starts 1.5 meters from the recorded path and tracks it with the Follow the Past algorithm. The three behaviours that define the set steering angle are shown in Figure 6.