The F1/10 Autonomous Racing Platform: Enabling Research in Autonomy at the University of Virginia

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Abstract

The long-term goal of building a 1/10th scale autonomous racecar by the F1/10 racing team at the University of Virginia is to provide an open-source platform for autonomous vehicle research. Such a platform should have safety and reliability built in from the start. Recent events involving the fatal crashes of several self-driving vehicles have caused the general public to question the viability of self-driving technology. In each of these instances, the self-driving cars were moving at high speeds when they crashed. One of the long-term goals of our research is to improve the driving and overtaking algorithms of autonomous cars when they are pushed to the limits of their control; that is, at the highest speeds possible. First, we must develop a model to afford the cars we are designing and building the ability to drive autonomously. This paper develops a naïve parallel-to-wall following model that can be easily extended by an innovative approach known as the "follow the gap" algorithm to afford truly autonomous behavior in large, open-spaces.

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1. Introduction

1.1 Background

While many cars already have semi-autonomous features like autopilot, automatic braking, and lane-centering assistance, fully autonomous cars have not flooded the scene as quickly as we thought they would when we first started discussing their practicality a decade ago. In 2004, the Defense Advanced Research Project Agency (DARPA) offered a $1 million prize to any team who could create an autonomous car capable of completing a 150-mile obstacle course in the Mojave Desert (Thompson, 2015). While no team could produce a successful run in the first instance of this challenge, five cars successfully completed the challenge just one year later in 2005, prompting car manufacturers around the world to lead their own research teams. This marked a shift from academically-led theoretical research to industry-led practical research in autonomous vehicles. This shift was important in the development of autonomous cars because it allowed end-users to see the merit of such an idea, while shifting the focus of research from performance to safety. Today, both industry and academia are interested in developing safety conscious vehicles to make the prospect of self-driving cars more viable.

1.1 Research Motivations

The advent of truly autonomous cars is near. Although truly self-driving cars will not hit our roads in a noticeable way until 2020, it is expected that nearly 95 percent of new cars sold by the year of 2040 will feature a fully autonomous mode of operation (Munster, 2017). While truly self-driving cars will offer numerous benefits to both consumers and producers, they are not without their criticisms, and 2018 has been a tough year for the industry. Prior to January of 2018, there was just a single known incident of a self-driving car accident resulting in the fatality of either a passenger, pedestrian, or driver. This infamous incident was the crash of a Tesla Model S car in Florida that resulted in the death of its driver while driving in autopilot mode. Recently, Uber decided to pull its self-driving cars from several cities throughout Canada and the United States when one of its cars struck and killed a pedestrian crossing the road in Arizona, and just a week later, an Apple engineer was killed when his Tesla car swerved and hit the median of the highway upon which he was traveling to get to work. After hearing about one story after the other in the news with alarming frequency, the general public started to question the safety measures taken by companies to ensure the reduced likelihood of future accidents involving autonomous agents on the roads.

While the sentiment of the public has been negative recently, the actions of researchers in academia and industry suggest that there is still a strong interest in pushing this type of technology to market. Part of this interest lies in the tangible benefits of such a technology, including safer roads, shorter commute times, and reduced emissions. According to Business Insider writer Danielle Muoio, driverless cars will increase our productivity relative to other nations and are expected to increase our gross domestic product (GDP) per capita. So, even politicians are interested in them. In all of the aforementioned fatal accidents involving self-driving cars, the driver was distracted, the car was traveling at high speeds, or both. There seems to be a necessity to develop and test the performance of the self-driving algorithms at high speeds; that is, at the limits of their control. One of the longer-term research goals of the F1/10 team is to develop an open-source platform for autonomous vehicle research that will enable safer, more reliable control at higher speeds. This is also, not coincidentally, the goal of the annual F1/10 Autonomous Racing Competition: a competition that pits $1/10^{th}$ scale racecars against one another once a year, awarding prizes to the teams with the best performing algorithm(s). The idea here is a simple one: competition drives innovation. In an effort to win the race, teams will invariably have to develop an algorithmic approach that considers the performance of their methods when tested at the limits of the car's control. Before advanced overtaking algorithms can be considered, these research cars must first be able to drive themselves in both a reliable and efficient manner. The purpose of this project is to develop a platform enabling exactly this.

1.2 The F1/10 Autonomous Racing Competition

The F1/10 Autonomous Racing Competition is an annual event that pits $1/10^{th}$ scale autonomous racecars against one another; the car with the best algorithm finishes first and wins the race. The competition began at the University of Pennsylvania in 2016 as a challenging design experience that affords ambitious students the ability to learn about how real-time perception, planning, and control algorithms are used for autonomous vehicle navigation. The competition was an immediate success as students from around the world started to form their own teams to compete. The growing interest and relevance of the competition enabled it to expand into an international racing competition in under two years from its conception. The 2018 iteration was recently held at the Great Hall of Palacio da Bolsa in Porto, Portugal, and featured teams from the Czech Republic, South Korea, and the United States.

2. Project Description

2.1 Statement of Purpose

The goal of this project is to achieve the short-term goals of the F1/10 autonomous racing team at the University of Virginia. In order to achieve the longer-term safety and performance goals of the F1/10 autonomous racing team, a much simpler platform enabling basic navigation functionality is essential. The short-term goals of the F1/10 autonomous racing team at U.Va. and the goals of this research endeavor are as follows: enable straight line following, wall following, and remote control for enabling and disabling autonomous features of the 1/10th scale racecar. The basic task of driving by minimizing the error of a predefined objective function is essential for driving autonomously. So, the first two points mentioned above will be elaborated upon in more detail in this report as they are essential for achieving the long-term goals of the F1/10 team. The last point about remote control, albeit a necessary and important feature for both testing and using self-driving vehicles, is not a point of particular interest in the short-term for the F1/10 team and thus will not be elaborated upon further in this report.

2.2 The F1/10 Autonomous Racing Platform

2.2.1 Hardware Components

2.2.1.1 Parts List

The F1/10 Autonomous Racecar is built from the following component parts, which will vary slightly between builds.

Main Components	**Supporting Electronic Components**	**Supporting Mechanical Components**
3mm ABS Plastic	4 AA batteries	Allen Key Set
6mm ABS Plastic	Barrel Jack Connectors	M1.6 Screw x 8mm
Energizer XP18000AB Universal Power Adapter	Ethernet cable	M3 Hex nuts
F1/10 Control Board	FTDI	M3 M-F Hex Standoff x 14mm
Hokuyo URG-04LX LiDAR	Micro USB Cable	M3 Screw x 8mm
NVIDIA Jetson TK1	Mini USB Cable	Traxxas 3769 Spring Preload Spacers
SparkFun 9DoF Razor IMU M0	M-M DC power coupler	
Teensy 3.2 Microcontroller	Power Over Ethernet (POE) cable	
Traxxas 1/10th Scale Racecar Chassis	SD Cards	
Ubiquiti PicoStation	Servo cables	
USB Hub	Traxxas 2976 AC to DC Converter	

Please visit www.f1tenth.org for an up-to-date list of component parts, a complete bill of material (BOM), and build instructions for assembling the latest version of the F1/10 Autonomous Racecar.

2.2.1.2 Important Component Descriptions

ABS Plastic

The 3mm and 6mm ABS Plastic sheets are to be laser cut to form the body of the F1/10 racecar. The racecar body acts as a wire hub for housing the connecting wires in a clean and efficient manner.

Energizer Universal Power Adapter

The Energizer power pack provides 12V power supply to the on-board NVIDIA Jetson computer and the Hokuyo URG-04LX LiDAR sensor. The power pack is also able to provide a 20V power supply to the Ubiquiti PicoStation to enable point-to-point connection between the NVIDIA Jetson and the user's host machine.

The F1/10 Control Board

The control board affords the racecar the ability to switch easily between manual and autonomous modes of operation. When in autonomous mode, the board takes pulse-width modulated (PWM) signals produced by the Teensy 3.2 microcontroller and sends them to the servo and ESC to control the speed and turning angles for the F1/10 autonomous racecar.

Hokuyo URG-04LX LiDAR

The LiDAR sensor is used to detect the surrounding surfaces of the F1/10 autonomous racecar and communicates information about the environment in real time to the on-board NVIDIA Jetson TK1 computer.

NVIDIA Jetson TK1

The Jetson is the on-board computer that processes the data collected by the various sensors, executes the desired algorithms, and sends information to the Teensy 3.2 microcontroller for controlling the steering servo motor and the electronic speed controller (ESC).

SparkFun 9DoF Razor IMU

The inertial measurement unit (IMU) is used to monitor and log positional information as well as Euler angles (orientation).

Teensy 3.2 Microcontroller

The Teensy is used to communicate steering angles and velocity values, generated from code running on the Jetson TK1, to the servo and ESC used for steering and driving respectively.

Traxxas 1/10th Scale Racecar Chassis

The Traxxas racecar chassis is a radio-controlled (RC) car chassis used by both hobbyists and professional RC car drivers. The Traxxas 1/10th scale racecar chassis is capable of speeds in excess of 35 miles per hour.

Ubiquiti PicoStation

The Ubiquiti PicoStation is used to extend wireless capabilities to the on-board NVIDIA Jetson TK1. Doing so affords wireless point-to-point connectivity between the Jetson and the user's local machine.

USB Hub

The USB Hub simply extends the total number of USB ports available for the NVIDIA Jetson TK1. It allows for more sensors and devices to be added or subtracted from the model without requiring large changes to the platform's design.

2.2.2 Software Components

2.2.2.1 Robot Operating System (ROS)

Robot Operating System (ROS) is an open source robotics platform that is used by the F1/10 team to enable autonomous behavior. There are several versions of ROS; the version of ROS used depends on the computing environment available. Since the NVIDIA Jetson TK1 runs a flavor of the Ubuntu 14.04 operating system, we have opted to use the Indigo distribution of ROS to ensure maximum compatibility. Robot Operating System is not an actual operating system; instead, ROS is a set of software libraries and tools that aid in the development of software for robotics applications. ROS is the middleware for robotics applications, providing a simple message-passing interface between nodes written in either the C++ or Python programming languages.

2.2.2.2 Terminal Multiplexors: tmux and Terminator

The F1/10 teams writes ROS nodes for receiving and sending data from sensors, processing raw data, and generating control signals for the electronic speed controller and the servo motor of the Traxxas chassis. In order to start of all these nodes, several terminals need to be open on the user's local machine and the user will need to use the SSH protocol to ensure secure remote login from their local machine to the on-board NVIDIA Jetson. In order to make the process more efficient, the user can use terminal multiplexor applications, such as tmux and Terminator listed above. Additionally, users can write ROS launch files, but these are more application specific and will not be discussed further here. Please visit ros.org for more information about writing and using ROS launch files for ROS nodes.

3. Autonomous Navigation

Before the F1/10 racecar can drive itself autonomously, we must first develop a model for driving. The typical feedback loop for autonomous agents involves sensing the world around it, planning its movement based on sensor inputs and an objective function, and then controlling its movement by communicating desired moves to the component hardware. We call this simple robotics feedback loop: perception, planning, and control. Figure 1 below depicts the process.

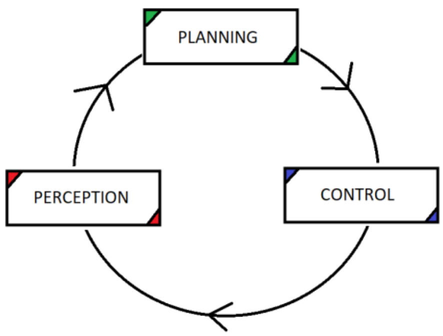

Figure 1: The Perception, Planning, and Control Feedback Loop for Autonomous Driving.

3.1 Perception, Planning, Control

Autonomous navigation involves repeatedly performing the perception, planning, and control feedback loop so that the racecar can reliably predict its future trajectory and speed. The system architecture used by the F1/10 team involves both hardware and software in the process, and this system architecture can be seen in detail in Figure 2 below.

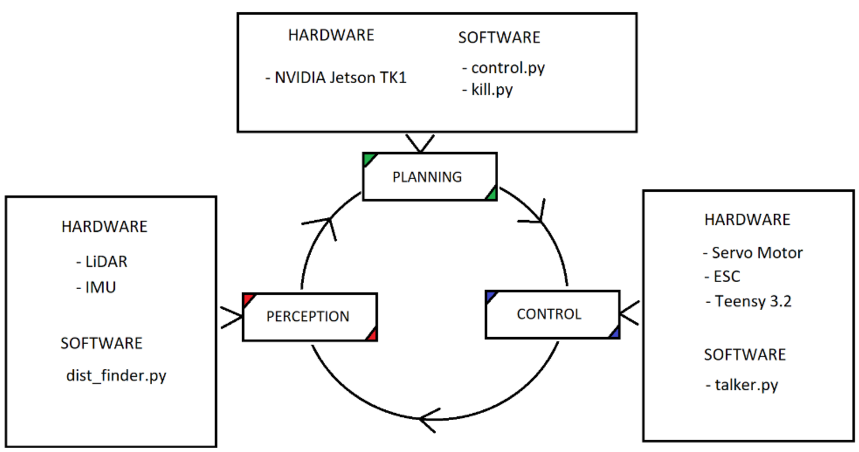

Figure 2: The Perception, Planning, and Control Feedback Loop with Hardware and Software

The software will be explained in further detail after we develop the control model for the F1/10 autonomous racecar. For now, let us briefly explain how the PID controller used by the F1/10 team achieves the short-term follow the line objective.

3.1.1 Control Theory: A Brief Introduction

To understand the PID controller, however, we must first briefly understand what control theory is all about. The objective of control theory is to develop mathematical models for the control of large-scale systems. This often boils down to developing a loss function (also called an error function) that describes the amount of error resulting from a system being in a state that deviates from the desired state. The further away the system's state and behavior is from the desired state and behavior, the larger the error term modeled by the loss function.

3.2 Proportional, Integral, Derivative (PID) Control

3.2.1 PID Control Description

PID control is a common controller used in industrial control applications and is also useful for manipulating the steering angle for the F1/10 autonomous racecar.

3.2.2 The PID Control Scheme

If we let the error term we are controlling be modeled as $e(t) = SP - PV(t)$ where SP is the set point – the desired value of our objective function – and PV(t) be the processed variable at time t, then the PID equation is as follows:

$$u(t) = K_p \cdot e(t) + K_d \cdot \frac{d\, e(t)}{dt} + K_i \cdot \int_0^t e(\tau) d\tau$$

Equation 1: General Form of the PID Control Equation

The values of K_p, K_d, and K_i are called the proportional, derivative, and integral gains respectively. They are used to tune the magnitude of the error, the change in error, and the cumulative error over time t. The proportional term adjusts the error proportional to the magnitude of the error, causing more aggressive correcting behavior for large error values and less aggressive correcting behavior when the error is very small. The derivative term is added to smooth the effects of the proportional term to prevent over- and under-correcting behavior. The integral term allows for the error to be adjusted based on how it accumulates over time.

3.3 The F1/10 Implementation

3.3.1 The F1/10 Navigation Objective

There are many models and objectives that can be implemented to afford the F1/10 autonomous racecar the ability to drive itself autonomously; however, in the short-term, we simply seek to develop a model that allows the car to drive itself parallel to a wall. Once the car is able to successfully and reliably drive parallel to a wall, extending this algorithm to allow for more robust autonomous behavior will be much easier. The model for following the wall is depicted below in Figure 3, and each component part will be described in further detail below it.

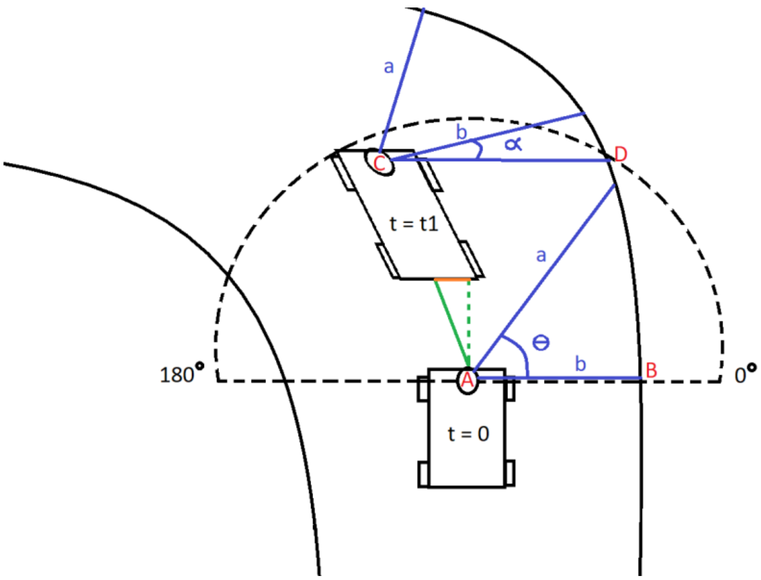

Figure 3: The F1/10 Autonomous Racecar Parallel-To-Wall Naïve Model

The desired distance to maintain from the wall is AB where,

$$\text{AB} = b \cdot \cos(\alpha)$$

Equation 2: The Desired Distance From the Wall

The projected actual distance from the wall is CD where,

$$\text{CD} = AB + AC \cdot \sin(\alpha)$$

Equation 3: The Projected Distance From the Wall

The angle α can be derived from the figure above using simple geometry as,

$$\alpha = \tan^{-1}\left(\frac{a\cos(\theta) - b}{a\sin(\theta)}\right);$$

(where θ is an angle between 30 and 70 degrees - we use 45 degrees)

Equation 4: The Turn Angle

3.3.2 The F1/10 Control Implementation

First, let us revisit Equation 1 from above and make a small modification. We will choose not to implement the integral term due to empirical observations. When the F1/10 autonomous racecar uses PID control with an integral term, the performance is worse than simply using PD control, so we will set the K_i term above to 0 to get the new equation:

$$u_1(t) = K_p \cdot e(t) + K_d \cdot \frac{d\,e(t)}{dt}$$

Equation 5: Modified PD Control Equation

The error term, e(t), is the difference between the desired trajectory AB and the actual trajectory CD from Equations 2 and 3 above:

$$e(t) = AB - CD$$

Equation 6: The Error Term

The error is thus negative when we are too far to the left and positive when we are too close to the wall. Conveniently, negative values correspond to making left turns and positive values correspond to making right turns for the servo motor of the Traxxas chassis. We can thus easily use this error term to encode turning angles for our racecar by scaling them properly to ensure that they are in the range [-100, 100].

4. Future Work

4.1 Limitations of the Current Approach

While the current approach works well for enclosed spaces – i.e. there exists a wall to follow – it will fail to work in large open spaces because the objective function of maintaining a predefined distance from the wall will not make sense in this context. A more robust autonomous navigation model should be flexible enough to afford the car true autonomy in open spaces.

4.2 Alternative Approach: the “Follow the Gap” Algorithm

An alternative approach called “Follow the Gap” solves the open-space problem described above using simple modifications to our current algorithm. The approach simply defines the objective function differently; instead of maintaining a predefined distance from the wall, the car simply iterates through the scans of its surroundings communicated by the LiDAR sensor and finds the largest “gap” in the scans to drive towards. The car will thus consistently attempt to find open space to drive into, completely eliminating the necessity for a wall. As an additional bonus, obstacle avoidance is built directly into the model. This approach was recently taken by a team from the Czech Technical University in Prague, Czech Republic. Their car won the 2018 iteration of the F1/10 Autonomous Racing Competition in Porto, Portugal achieving a time of nearly 6 seconds better than the approach taken by the U.Va. F1/10 racing team. There is clearly an advantage to the approach.

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