Control Systems in Self-Driving Cars

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Introduction

The technology behind self-driving cars has existed for centuries but has only recently seen a rapid increase in popularity among car manufacturers. In the past few years, major automotive companies have funded multiple research projects to develop advanced technology for autonomous systems. The focus of this research is centered around the concept of control systems. Fundamentally, a control system manages, commands, directs or regulates the behavior of other devices or systems using control loops. The system can be manipulated to behave a certain way by applying control theory to describe it with mathematical models. To obtain a specific outcome, inputs and constraints are imposed on variables to control the system. Control systems are a fundamental component of self-driving cars.

History of Control Systems

The first feedback control device was developed over two thousand years ago in ancient Greece. In only 325 BCE, a water clock was invented to measure time based on the flow of water out of a vessel. The flow of water was regulated by controlling the water level in the vessel which was revolutionary technology. Another invention using a control system was invented in Greece around 10 AD by the mathematician and engineer Heron of Alexandria. His creation pumped water into containers which weighed down ropes and pulleys to open a set of temple doors. In Europe during the seventeenth century, a set of dancing figurines, known as the clockwork automata, were created. These figurines closely resembled human movement by utilizing an open-control system to repeat the same task over and over. An example of a closed-loop feedback control mechanism is a device created by James Watt in 1788. His centrifugal flyball governor controls the speed of steam engines by regulating the fuel usage. The system can maintain a constant speed by making changes to the input variable of the driveshaft based on the difference between the measured and desired values. Nicolas Minorsky developed a mechanism which responds to the inputs of a system and applies accurate corrections to a control function appropriately. Known as the proportional integral derivative control, this control loop feedback mechanism continuously modulates the control of a system. James Clerk Maxwell, who also contributed greatly to the world's understanding of electromagnetism, provided the first theoretical basis for the mathematical analysis of a feedback control system in 1868. One of his discoveries was that specific characteristic equations must be analyzed to form a full understanding of the stability of a linear dynamic system. A mathematical test, known as the Routh-Hurwitz stability criterion, was devised that defines the necessary conditions for the stability of a linear time invariant control system. Edward Routh founded stability theory in 1874 which addressed the stability of solutions of differential equations under small changes in initial conditions. The role that Adolf Hurwitz played in the test for stability of a control system was proposing a way to arrange the coefficients of a polynomial into a square matrix. A control system is stable if the eigenvalues of its matrix have a negative real part. Eigenvalues are non-zero vectors that linear transformations can be applied to. The first major step taken towards optimizing control systems was when the digital computer became commercially available in the 1950s. Computers employ optimal control theory, allowing them to process massive quantities of inputs of data and produce results in a more efficient manner.

Modern Control Systems

A common modern application of control systems is in the automation of self-driving vehicles. Autonomous vehicles contain an extensive amount of control systems, each with its own respective varying degree of complexity. One current method for implementing control systems into autonomous vehicles is through linear systems control. This type of control system calculates a feedback matrix by assigning poles in the desired positions of the open-loop system. Poles are the frequencies for which a transfer function, the function relating the response of the system, become zero. The poles correspond to eigenvalues which allows the responses of the system to be controlledand are placed in pre-determined locations in the s-plane using Laplace transforms. To minimize the effects on performance in the event of unknown parameters and system variability, parametrized control invariant monitoring is used to provide guaranteed performance regardless of the parameter values. The measurement vector can be represented by a linear model with theoretical unknown parameters that has columns of a known signal matrix corresponding potential signals. In practical applications of model predictive control, safety constraints can be enforced with minimized control intervention. For example, a control design can be applied to semi-autonomous vehicles to keep the vehicle in the lane and avoid obstacles by planning an appropriate path. The majority of applications for model predictive control are linear with the feedback mechanism compensating for prediction errors due to structural mismatch between the model and the process. Other practical applications include rear-end collision avoidance systems, adaptive cruise control, and sensing blind spots. The cruise control system of a car uses proportional integral derivative control to control the power output of the engine of the vehicle. Safety interventions are activated automatically because of sensing technologies. Radar, ultra-sonics, and camera imaging systems provide inputs for the control systems to respond to. For example, the Kalman filter can be used to predict the next set of actions that the car in front of an autonomous vehicle is going to take. This prediction is based from linear quadratic estimation that uses data received by the vehicle. Self-driving cars are possible because of sensors, connectivity, which is the access to road data, and software and control algorithms.

History of Automated Vehicles

The first automated vehicle was invented in 1925 by Francis Houdina. The features of this radio-controlled car included being able to start its own engine and shift gears. In 1957, the American corporation-run RCA labs successfully demonstrated a car directed by a series of experimental detector circuits built into the pavement along the edge of the road. Similar to the concept developed by the RCA labs, the transport and road research lab in the United Kingdom tested a driverless car with cruise control devices in 1970 that interacted with signals produced from magnetic cables embedded in the road. In 1987, car manufacturers became involved in the development of automated vehicles with the EC Eureka Prometheus Project. This research program was headed by car manufacturers from 6 European companies. The ultimate goal of this project was to make the road traffic system more efficient by developing new information control and management systems. In 1995, the Navlab self-driving minivan traveled from coast to coast on the trip known as "No Hands Across America." Even though speed and braking still needed to be controlled remotely, this trek across the country made by a self-driving vehicle marked a milestone in automated vehicle history for the longest distance traveled by an almost fully-automated vehicle. The first DARPA Grand Challenge followed a couple of years after which also marked an important milestone in the progression of automated vehicles. This challenge presented an opportunity for competition in the hopes that it would also increase the amount of discoveries made regarding automated vehicle technology. Although the first year of competition ended with none of the competitors successfully completing the course, it sparked interest for years to come after to develop automated vehicles that would complete the challenge successfully. In 2009, the longest running automated vehicle project to have ever existed began. Known as the Waymo project, the company Google launched their own automated vehicle project led by Sebastian Thrun who was the former director of the Stanford Artificial Intelligence Lab and co-inventor of Google street view. The largest step for the automated vehicle industry was taken when Google revealed a prototype in 2014 of a driverless car without any steering wheel, gas pedal or brake pedal. This was significant because it meant the vehicle was completely autonomous with no way for the passenger to control it.

Major Corporations in the Industry

This competition has spurred an increase in funding among these companies towards programs for automated vehicles. The most widely recognized company with respect to self-driving cars is Waymo. After breaking apart from its parent company Google, Waymo became its own independent self-driving technology company. They have been extremely successful, having made a multitude of contributions to the enhancements of the technology behind autonomous vehicles. In order to fund these enhancements, $1.1 billion was invested over a 6-year period into the Project Chauffeur. With regards to the actual development of autonomous vehicles themselves, General Motors is currently the leading company in autonomous vehicle creation. In December of 2017, they announced that they will deploy driverless taxis in large cities by 2019. This made them the first developers of autonomous cars to provide a timeline to their efforts. They have invested $500 million in Lyft, a car transportation company, as well as having bought Cruise Automation for $581 million. Their testing grounds for self-driving vehicles are located in Michigan, San Francisco, California, and Scottsdale, Arizona. Another leader in the automated vehicle industry is Ford. They also teamed up with Lyft, invested $1 billion in Argo Artificial Intelligence and $150 million in 2016 into Velodyne, a lidar manufacturer. Lidar is light detection and ranging as opposed to radar which is radio detection and ranging. The laser used in lidar equates to a higher frequency which makes it more efficient in the use of sensors than the waves used in radar. Ford's testing grounds like General Motors are also in Michigan, California, and Arizona. A third significant competitor in the race for developing self-driving cars is the Renault-Nissan Alliance. Their biggest contribution to autonomous technology is ProPILOT Assist which is a self-driving feature that allows cars to drive autonomously on highways. Enhancing the overall driving experience, the hands-on-wheel technology reduces the hassle of stop-and-go highway driving in both heavy and flowing traffic situations. The ProPILOT Assist system was revealed at the Nissan Technical Center North America in Michigan and underwent over 50,000 miles of development on roads across the United States. Nissan announced that they have plans to launch more models in Europe, Japan, China, and the United States by the year 2020.

Conclusion

While the technology behind autonomous vehicles has undergone astounding growth and progress in recent years, there are still many prominent issues needed to overcome. The largest obstacle in the continuance of developing autonomous vehicle technology is related to government regulations. Many companies are faced with required extensive software validation and regulatory approval that varies depending on location. There is still also a large lack of understanding of the limitations with regard to self-driving autopilot features which has been demonstrated by fatal crashes by Tesla and Uber. These crashes show that the technology for self-driving cars is still not fully developed which is an issue that needs to be fixed going forward in the future.

MatlabModel

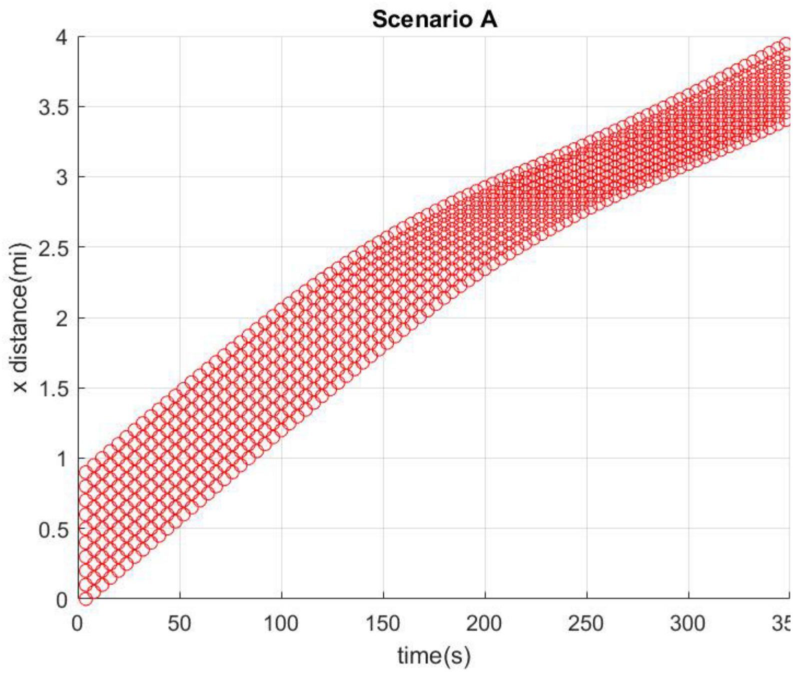
The Matlab code is an adjustable model that simulates the behavior of any number of vehicles. Two factors that impacted the performance of the vehicle were its responses to changes in the speed limit and its relative distance to other cars. The variables that were manipulated in forming the following scenarios were the initial definitions pertaining to time, speed limits, minimum safe following distance, the number of cars in the situation, and a proportionality factor.

```
clear
clc

tend = %End time [hr]
dt = %Time Increment [hr]
t = %Time Vector [hr]
N = %Number of Iterations
K = %Rate of increase or decrease in speed
Vt = %Speed Limit Vector
Xt = %Speed Limit Location Vector
Dmin = %Minimum Safe Following Distance
J = %Number of Cars
D(J) = %Creates Distance Vector and sets final distance to be large

figure
hold
grid
for j = 1:J
    X(j,1) = (1/J)*(j-1); %Defines the location of car initially
    V(j,1) = 0; %Adjust velocity to be the current speed based on location
end
TimePlot(1) = 0;
for n = 1:(N-1)
    for j = 1:(J-1)
        D(j) = X(j+1,n)-X(j,n);
    end
    for j = 1:J
        SpInd = 2;
        while ((X(j,n) > Xt(SpInd)) && (SpInd <length(Vt)))
            SpInd = SpInd + 1;
        end

        if D(j) > Dmin
            Vlim = Vt(SpInd-1);
            k = K;
        else
            Vlim = V(j+1,n);
            k = 1/D(j); %Proportionality factor
        end
        Vprime = -k*(V(j,n) - Vlim);
        V(j,n+1) = V(j,n) + Vprime * dt;
        X(j,n+1) = X(j,n) + V(j,n) * dt;
    end
    TimePlot = t(n+1)*ones(1,J);

plot(3600*TimePlot,X(:,n),'ro')
xlabel('time(s)')
ylabel('x distance(mi)')
title('Model')
pause(.01)
end
```

Scenarios

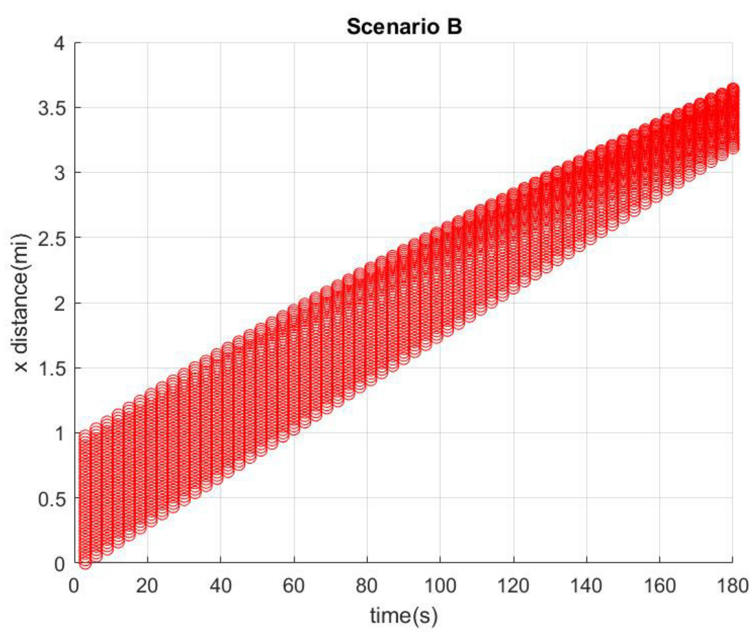
Three separate scenarios were simulated with the cruise control model. Having different scenarios demonstrates the flexibility of the code as well as the various results given in response to different situations. The first scenario is a portrayal of carsdriving along a road through a school zone. In the second scenario, a single lane of traffic is simulated on the highway during heavy traffic.Lastly, the third scenario shows cars that are being forced to stop at a railroad crossing.

First Scenario



Due to it being a school zone, there is a decrease in the speed limit from 45 mph to 35 mph back up to 45 mph. This can be seen in the decline in the slope of the plot around 3 miles. There are 10 total cars in this scenario and the minimum safe following distance is 0.05 miles.

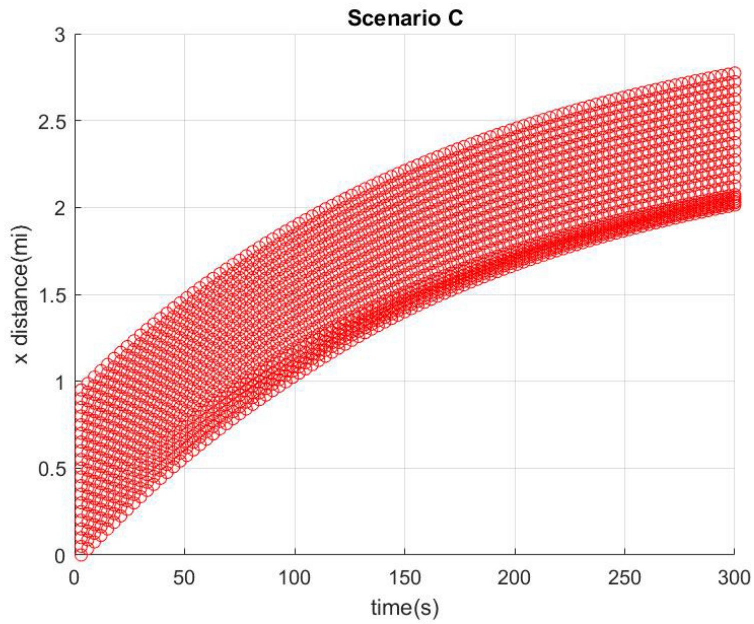
Second Scenario



There are 40 cars total in this scenario. The speed limit is 65 mph but decreases to 35 mph in response to the amount of traffic. An increase in the cars getting closer together presents itself around 1.5 miles into the simulation. However, they never collide and maintain the minimum safe following distance, which is 0.0375 miles in this scenario.

Third Scenario

There are 20 cars in this case. A gradual decrease in velocity can be seen, a result of the cars reducing their speed from 45 mph to a complete stop of 0 mph. The bottom rows of cars appear to be closer together, most likely due to a shorter response time for braking, but they still maintain minimum following distance.



Further Work

In the future, a more complex model would be created to simulate a more realistic traffic flow. This would consist of multiple lanes of traffic instead of the cars being in a single line. The model would take into accountvehicles changing lanes and other driving-related factors. A control system would also be developed that accurately utilizes the traffic flow model.

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