

# End-to-End Learning for Self-Driving Cars

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## I. ABSTRACT

II-A We trained a convolutional neural network (CNN) to map raw pixels from a single front-facing camera directly to steering commands. This end-to-end approach proved surprisingly powerful. With minimum training data from humans the system learns to drive in traffic on local roads with or without lane markings and on highways. It also operates in areas with unclear visual guidance such as in parking lots and on unpaved roads. The system automatically learns internal representations of the necessary processing steps such as detecting useful road features with only the human steering angles as the training signal. We never explicitly trained it to detect, for example, the outline of roads. Compared to explicit decomposition of the problem, such as lane marking detection, path planning, and control, our end-to-end system optimizes all processing steps simultaneously. We argue that this will eventually lead to better performance and smaller systems. Better performance will result because the internal components self-optimize to maximize overall system performance, instead of optimizing human-selected intermediate criteria, e. g., lane detection. Such criteria understandably are selected for ease of human interpretation which doesn't automatically guarantee maximum system performance. Smaller networks are possible because the system learns to solve the problem with the minimal number of processing steps. We used an NVIDIA DevBox and Torch 7 for training and an NVIDIA DRIVE Tegra PX2 self-driving car computer also running Torch 7 for determining where to drive. The system operates at 30 frames per second (FPS).



Fig. 1. Lane Detection and Vehicle Recognition

## II. INTRODUCTION

have revolutionized pattern recognition [2]. Prior to the widespread adoption of CNNs, most pattern recognition tasks were performed using an initial stage of hand-crafted feature extraction followed by a classifier. The breakthrough of CNNs is that features are learned automatically from training

examples. The CNN approach is especially powerful in image recognition tasks because the convolution operation captures the 2D nature of images. Also, by using the convolution kernels to scan an entire image, relatively few parameters need to be learned compared to the total number of operations. While CNNs with learned features have been in commercial use for over twenty years, their adoption has exploded in the last few years because of two recent developments. First, large, labeled data sets such as the Large Scale Visual Recognition Challenge (ILSVRC) [4] have become available for training and validation. Second, CNN learning algorithms have been implemented on the massively parallel graphics processing units (GPUs) which tremendously accelerate learning and inference. In this paper, we describe a CNN that goes beyond pattern recognition. It learns the entire processing pipeline needed to steer an automobile. The groundwork for this project was done over 10 years ago in a Defense Advanced Research Projects Agency (DARPA) seedling project known as DARPA Autonomous Vehicle (DAVE) [5] in which a sub-scale radio control (RC) car drove through a junk-filled alleyway. DAVE was trained on hours of human driving in similar, but not identical environments. The training data included video from two cameras coupled with left and right steering commands from a human operator. In many ways, DAVE-2 was inspired by the pioneering work of Pomerleau [1] who in 1989 built the Autonomous Land Vehicle in a Neural Network (ALVINN) system. It demonstrated that an end-to-end trained neural network can indeed steer a car on public roads. Our work differs in that 25 years of advances let us apply far more data and computational power to the task. In addition, our experience with CNNs lets us make use of this powerful technology. (ALVINN used a fully-connected network which is tiny by today's standard.) While DAVE demonstrated the potential of end-to-end learning, and indeed was used to justify starting the DARPA Learning Applied to Ground Robots (LAGR) program [7], DAVE's performance was not sufficiently reliable to provide a full alternative to more modular approaches to off-road driving. DAVE's mean distance between crashes was about 20 meters in complex environments. Nine months ago, a new effort was started at NVIDIA that sought to build on DAVE and create a robust system for driving on public roads. The primary motivation for this work is to avoid the need to recognize specific human-designated features, such as lane markings, guard rails, or other cars, and to avoid having to create a collection of if, then, else rules, based on observation of these features. This paper describes preliminary results of this new effort.

### A. Data Selection

The first step to training a neural network is selecting the frames to use. Our collected data is labeled with road type,

weather condition, and the drivers activity (staying in a lane, switching lanes, turning, and so forth). To train a CNN to do lane following we only select data where the driver was staying in a lane and discard the rest. We then sample that video at 10 FPS. A higher sampling rate would result in including images that are highly similar and thus not provide much useful information. Types of Neural Networks:

- Feed Forward Neural Network
  - 1) Single Layered Perceptron
  - 2) Multi Layered Perceptron
- Convolutional Neural Network
- Recurrent Neural Network
- Generative Adversarial Network

Steering angle is given by

$$SA = \arctan L/R + \delta - \alpha \quad (1)$$

## REFERENCES

- [1] Saharon Shelah. Note on a min-max problem of Leo Moser. *Journal of Combinatorial Theory*, 6:298–300, 1969.
- [2] Saharon Shelah. Stable theories. *Israel Journal of Mathematics*, 7:187–202, 1969.