

# Workload Analysis of Autonomous Driving System: Apollo, Baidu Inc.

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**Abstract**—Autonomous driving is a field that gathers many interest from the academics world and from industry leaders. The software of an autonomous driving systems (ADS) incorporates the state-of-the-art from many disciplines, such as computer vision, robotics, geo-localization. Although the high level architecture of an autonomous driving system and the main algorithms used are known, the complete analysis of a real ADS is still difficult, especially for what concerns the modules interdependencies, interactions, either software and hardware, and pre- and post-processing. In this paper, we want to extract those point of views and quantify them according different architectural aspects: response times, memory movements, computational complexity and CPU-GPU relationship. The analysis is based on the open-source Apollo ADS developed by Baidu and is focused on the most important modules: perception, prediction and planning.

## I. INTRODUCTION

Autonomous driving system has several design constraints [1] to be met in order to produce a safe and reliable output.

Response time [1] is crucial for the predictability and accuracy of the system, especially when multiple sensors and components are present, each of them with a processing routine associated. The maximum response time, which has been adopted as standard in the field of autonomous driving, is 100 ms and should ensure a proper and safe reaction to any possible situation. Several processing routines use time deltas to perform corrections and projections of input and if those time-deltas are exceeding context-related thresholds then the input is discarded, losing some potential useful information, thus limiting the response time will affect also the accuracy of the system.

Apollo is a modular data-driven ADS, containing several modules, each of them pursues an high level feature of autonomous driving, such as perception, prediction, planning, control, localization. Modules can be treated as black boxes and described in terms of input/output relationships. This characterization enables the analysis of modules independently, provided that the inputs fed are feasible. Modules are further expressed in terms of set of components, which represent lower level tasks. Each component follows the same paradigm of modules, which means interactions within a module are based on input/output relationships through a publisher and subscriber architecture.

Cyber is the Apollo's runtime framework that implements the communication among components. The publisher and

subscriber communication adopted by Cyber is based on channels and messages. Messages are serialized objects, using the Google's Protocol Buffer, which then are broadcast on channel(s). Each component can be a reader or writer of multiple channels at the same time.

Apollo supports multiple sensors, different prediction evaluators and several scenario-based planners. This rich environment carries out the need of having the right hardware equipment to support each task. CPU should be able to sustain many multi-threaded algorithms and provides enough cores to execute several processes concurrently. GPU is required for the execution of convolutional neural networks (CNN), vector and matrix operations, which are especially encountered in the perception module.

A schematic overview of the Apollo software architecture is presented in Figure 1. Although the communication is data-driven, is reasonable to describe the architecture starting from sensors. Apollo supports two Full-HD cameras with two different focal lengths, 6mm and 12mm respectively, which are polled at 20 fps. Two types of lidars are used in Apollo: 128L and 16L. The 128L lidar is set to be the master sensor in the architecture. GPS and IMU data are provided to the localization module in order to estimate the car's position and pose. The perception detects obstacles present in the environment perceived from cameras and lidars and then the prediction module predicts obstacle trajectories using detections, localization estimations and trajectories chosen by the planner. Finally, the planning module selects the best trajectory, coherent to the route requested and obstacle trajectories, containing the path and speed profile to adopt. Many modules rely on HDMap to get an enriched understanding of the surrounding environment, being able to query road signs, junctions, lanes and many more.

In the next sections, we will describe the perception, prediction and planning modules. The description will be composed by an high level overview of the module and the analysis of each component within the module. The analysis is focused on response times, computational complexity, data dependencies, CPU-GPU relationship and memory movements. In the last section, we will detail the simulation environment, settings and datasets used in this work.

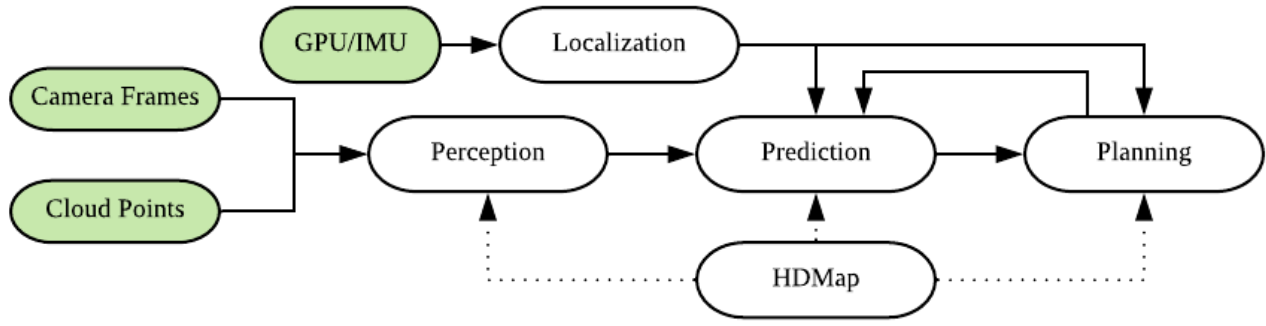


Fig. 1. Apollo Software Architecture

## II. PERCEPTION

The perception module perceives the environment, through the data coming from cameras and lidars, by detecting obstacles. In the Figure 2 is presented the internal representation of the perception modules, highlighting the module's components and flow. Due to the different nature of the inputs, camera frames and cloud points require different detection algorithm, pre- and post-processing. The Fusion Camera Detection is a unique component shared from both 6mm and 12mm camera frames.

Perception diagram. General description: what it does, sensors descriptions, output and general overview.

For each component: camera, lidar segmentation, lidar recognition, fusion component and traffic lights

### A. Camera Component

1) *What it does and how:* Explain which are the input of module, output and tasks. Explain what each task does.

2) *Complexity:* Explain the complexity of the tasks and their dependencies

3) *Response time:* Response time analysis and on which device each task runs. Table or graph about response times.

### B. Lidar Segmentation Component

1) *What it does and how:* Explain which are the input of module, output and tasks. Explain what each task does.

2) *Complexity:* Explain the complexity of the tasks and their dependencies

3) *Response time:* Response time analysis and on which device each task runs. Table or graph about response times.

### C. Lidar Recognition Component

1) *What it does and how:* Explain which are the input of module, output and tasks. Explain what each task does.

2) *Complexity:* Explain the complexity of the tasks and their dependencies

3) *Response time:* Response time analysis and on which device each task runs. Table or graph about response times.

### D. Fusion Component

1) *What it does and how:* Explain which are the input of module, output and tasks. Explain what each task does.

2) *Complexity:* Explain the complexity of the tasks and their dependencies

3) *Response time:* Response time analysis and on which device each task runs. Table or graph about response times.

### E. Traffic Light Component

1) *What it does and how:* Explain which are the input of module, output and tasks. Explain what each task does.

2) *Complexity:* Explain the complexity of the tasks and their dependencies

3) *Response time:* Response time analysis and on which device each task runs. Table or graph about response times.

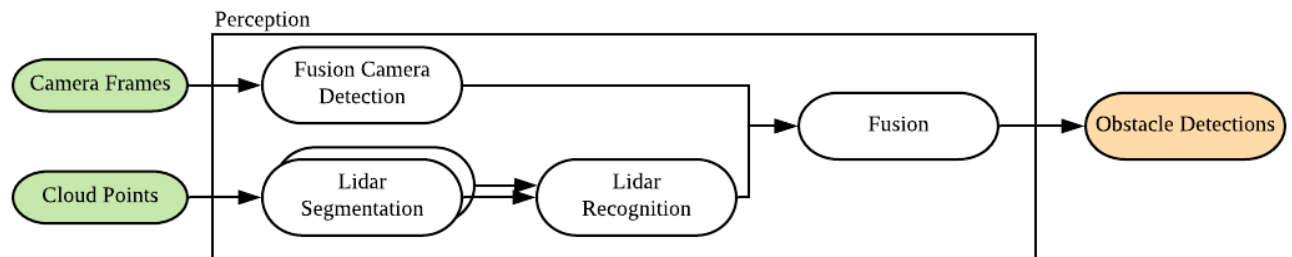


Fig. 2. Perception Software Architecture

### III. PREDICTION

### IV. PLANNING

### V. MEMORY THROUGHPUT SIMULATION

Analyze the impact of accelerating, through a PCI device, the inference of CNN in terms of memory movements from the GPU/CPU to PCI Device.

### VI. SIMULATION DETAILS

Datasets, gpu, cpu, software used and so on

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Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, ac, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

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$\LaTeX$  can’t read your mind. If you assign the same label to a subsection and a table, you might find that Table I has been cross referenced as Table IV-B3.

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TABLE I  
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Table Head	Table Column Head		
	Table column subhead	Subhead	Subhead
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<sup>a</sup>Sample of a Table footnote.

Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity “Magnetization”, or “Magnetization, M”, not just “M”. If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write “Magnetization (A/m)” or “Magnetization {A[m(1)]}”, not just “A/m”. Do not label axes with a ratio of quantities and units. For example, write “Temperature (K)”, not “Temperature/K”.

#### ACKNOWLEDGMENT

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For papers published in translation journals, please give the English citation first, followed by the original foreign-language citation [6].

## REFERENCES

- [1] Shih-Chieh Lin, Yunqi Zhang, Chang-Hong Hsu, Matt Skach, Md E. Haque, Lingjia Tang, and Jason Mars, "The Architectural Implications of Autonomous Driving: Constraints and Acceleration." In Proceedings of the Twenty-Third International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS '18). ACM, New York, NY, USA, 751-766. DOI: <https://doi.org/10.1145/3173162.3173191>
- [2] J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.
- [3] I. S. Jacobs and C. P. Bean, "Fine particles, thin films and exchange anisotropy," in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.
- [4] K. Elissa, "Title of paper if known," unpublished.
- [5] R. Nicole, "Title of paper with only first word capitalized," J. Name Stand. Abbrev., in press.
- [6] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interface," IEEE Transl. J. Magn. Japan, vol. 2, pp. 740–741, August 1987 [Digests 9th Annual Conf. Magnetism Japan, p. 301, 1982].
- [7] M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.

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