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

1st Alessandro Toschi
Shanghai Jiao Tong University
Shanghai, China
aleto_95@sjtu.edu.cn

2nd Jingwen Leng
Shanghai Jiao Tong University
Shanghai, China
leng-jw@sjtu.edu.cn

3rd Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address

***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, 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.

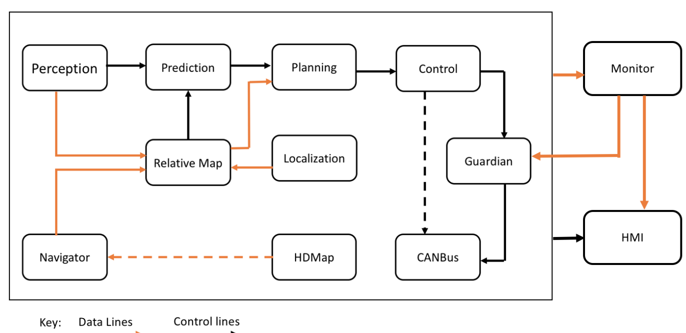

Fig. 1. Apollo Software Architecture

Autonomous driving requirements.
Introduction to Apollo: what is it, how is it implemented, data communication.
Modules that are going to be analyzed.
Image of apollo software architecture.

II. Perception

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.

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

The IEEEtran class file is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

VII. Prepare Your Paper Before Styling

Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections VII-A–VII-E below for more information on proofreading, spelling and grammar.

Keep your text and graphic files separate until after the text has been formatted and styled. Do not number text heads—LaTeX will do that for you.

A. Abbreviations and Acronyms

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.

B. Units

- Use either SI (MKS) or CGS as primary units. (SI units are encouraged.) English units may be used as secondary units (in parentheses). An exception would be the use of English units as identifiers in trade, such as "3.5-inch disk drive".
- Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity that you use in an equation.
- Do not mix complete spellings and abbreviations of units: "Wb/m^2" or "webers per square meter", not "webers/m^2". Spell out units when they appear in text: ". . . a few henries", not ". . . a few H".
- Use a zero before decimal points: "0.25", not ".25". Use "cm^3", not "cc".)

C. Equations

Number equations consecutively. To make your equations more compact, you may use the solidus (/), the exp function, or appropriate exponents. Italicize Roman symbols for quantities and variables, but not Greek symbols. Use a long dash rather than a hyphen for a minus sign. Punctuate equations with commas or periods when they are part of a sentence, as in:

$$a+b=\gamma \tag{1}$$

Be sure that the symbols in your equation have been defined before or immediately following the equation. Use "(1)", not "Eq. (1)" or "equation (1)", except at the beginning of a sentence: "Equation (1) is . . ."

D. LaTeX-Specific Advice

Please use "soft" (e.g., `\eqref{Eq}`) cross references instead of "hard" references (e.g., `(1)`). That will make it possible to combine sections, add equations, or change the order of figures or citations without having to go through the file line by line.

Please don't use the `{eqnarray}` equation environment. Use `{align}` or `{IEEEeqnarray}` instead. The `{eqnarray}` environment leaves unsightly spaces around relation symbols.

Please note that the `{subequations}` environment in LaTeX will increment the main equation counter even when there are no equation numbers displayed. If you forget that, you might write an article in which the equation numbers skip from (17) to (20), causing the copy editors to wonder if you've discovered a new method of counting.

BibTeX does not work by magic. It doesn't get the bibliographic data from thin air but from .bib files. If you use BibTeX to produce a bibliography you must send the .bib files.

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

LaTeX does not have precognitive abilities. If you put a `\label` command before the command that updates the counter it's supposed to be using, the label will pick up the last counter to be cross referenced instead. In particular, a `\label` command should not go before the caption of a figure or a table.

Do not use `\nonumber` inside the `{array}` environment. It will not stop equation numbers inside `{array}` (there won't be any anyway) and it might stop a wanted equation number in the surrounding equation.

E. Some Common Mistakes

- The word "data" is plural, not singular.
- The subscript for the permeability of vacuum μ_0, and other common scientific constants, is zero with subscript formatting, not a lowercase letter "o".
- In American English, commas, semicolons, periods, question and exclamation marks are located within quotation marks only when a complete thought or name is cited, such as a title or full quotation. When quotation marks are used, instead of a bold or italic typeface, to highlight a word or phrase, punctuation should appear outside of the quotation marks. A parenthetical phrase or statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.)
- A graph within a graph is an "inset", not an "insert". The word alternatively is preferred to the word "alternately" (unless you really mean something that alternates).
- Do not use the word "essentially" to mean "approximately" or "effectively".
- In your paper title, if the words "that uses" can accurately replace the word "using", capitalize the "u"; if not, keep using lower-cased.
- Be aware of the different meanings of the homophones "affect" and "effect", "complement" and "compliment", "discreet" and "discrete", "principal" and "principle".
- Do not confuse "imply" and "infer".
- The prefix "non" is not a word; it should be joined to the word it modifies, usually without a hyphen.
- There is no period after the "et" in the Latin abbreviation "et al.".
- The abbreviation "i.e." means "that is", and the abbreviation "e.g." means "for example".

An excellent style manual for science writers is [7].

F. Authors and Affiliations

The class file is designed for, but not limited to, six authors. A minimum of one author is required for all conference articles. Author names should be listed starting from left to right and then moving down to the next line. This is the author sequence that will be used in future citations and by indexing services. Names should not be listed in columns nor group by affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organization).

G. Identify the Headings

Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads.

Component heads identify the different components of your paper and are not topically subordinate to each other. Examples include Acknowledgments and References and, for these, the correct style to use is "Heading 5". Use "figure caption" for your Figure captions, and "table head" for your table title. Run-in heads, such as "Abstract", will require you to apply a style (in this case, italic) in addition to the style provided by the drop down menu to differentiate the head from the text.

Text heads organize the topics on a relational, hierarchical basis. For example, the paper title is the primary text head because all subsequent material relates and elaborates on this one topic. If there are two or more sub-topics, the next level head (uppercase Roman numerals) should be used and, conversely, if there are not at least two sub-topics, then no subheads should be introduced.

H. *Figures and Tables*

a) Positioning Figures and Tables: Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation "Fig. **??**", even at the beginning of a sentence.

TABLE I
TABLE TYPE STYLES

Table Head	**Table Column Head**		
	Table column subhead	***Subhead***	***Subhead***
copy	More table copy[a]		

[a]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

The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression "one of us (R. B. G.) thanks . . .". Instead, try "R. B. G. thanks. . .". Put sponsor acknowledgments in the unnumbered footnote on the first page.

REFERENCES

Please number citations consecutively within brackets [1]. The sentence punctuation follows the bracket [2]. Refer simply to the reference number, as in [3]—do not use "Ref. [3]" or "reference [3]" except at the beginning of a sentence: "Reference [3] was the first . . ."

Number footnotes separately in superscripts. Place the actual footnote at the bottom of the column in which it was cited. Do not put footnotes in the abstract or reference list. Use letters for table footnotes.

Unless there are six authors or more give all authors' names; do not use "et al.". Papers that have not been published, even if they have been submitted for publication, should be cited as "unpublished" [4]. Papers that have been accepted for publication should be cited as "in press" [5]. Capitalize only the first word in a paper title, except for proper nouns and element symbols.

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. Magnetics Japan, p. 301, 1982].

[7] M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.