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DL-AMP and DBTO: An Automatic Merge Planning and Trajectory Optimization and its Application in Autonomous Driving

Yuncheng Jiang, Qi Lin

Abstract— **This paper presents an automatic merging algorithm for autonomous driving vehicle, which decouples the specific motion planning problem into a Dual-Layer Automatic Merge Planning (DL-AMP) and a Descent-Based Trajectory Optimization (DBTO). This work leads to great improvements in finding the best merging opportunity, lateral and longitudinal merging control, trajectory postprocessing and driving comfort. Our algorithm's efficiency, adaptiveness and robustness have been tested and validated both in simulations and on-road tests.**

I. Introduction

Since the 1980s, autonomous driving has made a great process extending the ability of autonomous vehicle from Adaptive Cruise Control (ACC) and Lane Keeping Assistance (LKA) to more complex functions such as automatic lane changing, off-road navigation, stopping at traffic light, etc. [1][2]. In merging scenarios, human can predict other vehicles intentions and react intelligently to make the best merge choice. To deal with such scenario, prediction and planning should be well coupled considering driving efficiency, safety, and comfort. Therefore, a robust and intelligent algorithm that can interact with human-operated traffic on freeways is still under research and development. There are mainly two approaches in dealing with automatic merge problem:

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One category is prediction and planning coupled method which convert the prediction and planning problem into a convex optimization form, and prediction information is transferred into inequality constraints [3]. Mixed Logical Dynamics (DML) [4][5] is also applied in solving this optimization problem. [6] uses quintic polynomials in merge planning, while polynomial parameters are chosen as optimization targets. This approach usually lacks computational efficiency, and its robustness is not well guaranteed. The other category is prediction and planning decoupled method which first find the best merging opportunity, and then plan a merge maneuver. [7] uses Prediction and Cost Function Based (PCB) method to find the best merge opportunity, while this planner has to run continuously throughout the whole merge process, and its acceleration and velocity outputs are discontinuous. [8] uses a rule-based planner to decide when to merge based on its fixed definition of environment safety, but it may fail when faced with complex traffic scenarios.

In terms of merge planning, there are also two major approaches: path/speed decoupled method and path/speed coupled method. In decoupled method, polynomial curvature spiral is generated, and spatial trajectory is solved by using Lagragian method [xx][xx][xx]. Cubic polynomial is also used to generate spatial trajectory [xx][xx]. In the two methods, piece -wise velocity profile is then generated satisfying some road and trajectory constraints. In merge problem, path/speed decoupled methods do not work well since merging maneuver require that the vehicle reaches some position at some specific time stamp (position/time strictly coupled). In coupled method, quintic polynomials are generated longitudinally and laterally, and they are combined to generate spatial and temporal trajectories [xx][xx]. Such method, however, does not consider comfort and merge opportunity when deal with merge problem. Therefore, it may lead to uncomfortable lateral acceleration in lane changing, and even lead to danger if unreasonable merge opportunity is selected.

In trajectory postprocessing, gradient descent method is used in [xx] to optimize trajectory curvature, but it fails to do collision checking after smoothing. A Dual-Loop Iterative Anchoring Path Smoothing (DL-IAPS) is used to smooth trajectory generated by hybrid A* algorithm, by converting the smoothing problem into a convex optimization problem. The algorithm has an average running time about 0.18s- 0.21s [xx]. However, in merging problem, where vehicles usually move at high speed, optimization based algorithm may degrade system instantaneity.

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In this paper, we propose a novel path/speed coupled method for automatic merge planning. More specifically, we decoupled the method into two hierarchical steps, including, Dual-Layer Automatic Merge Planning (DL-AMP) and a Descent-Based Trajectory Optimization (DBTO). Our method addresses above mentioned issues with the following advantages:

1) **The Best Merging Opportunity**: In our DL-AMP, the first layer is a prediction and cost function based algorithm which can find the best merging opportunity. The difference between our method and that in [xxx] are: 1) our method is only used in find the best merging opportunity, when the autonomous vehicle begins to merge, the second layer algorithm will be trigger. Therefore, the output continuity is guaranteed by the second layer algorithm. Meanwhile, since the task is much easier for the first layer algorithm, it has less cost function parameters to tune. In our method, candidate ego vehicle acceleration and time are sampled in some ranges. Based on the sampled acceleration and time, constant acceleration prediction model is used to predict the relative distance and velocity between ego vehicle and other traffics. Cost function that emphasis driving efficiency and comfort is designed, and the maneuver that satisfies safety hard constraints with the minimum cost is chosen.

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2) **Sampling Reasonability**: although quintic polynomial sampling method has been used in [], it does not well deal with merge scenario motion planning. In our DL-AMP, the second layer algorithm is based on path/speed quintic polynomial sampling method. The longitudinal planning is divided into distance control and velocity control to adapt to difference merge scenarios. In lateral planning, we divide the scenarios into four categories, and different desired distance is selected under different scenarios. To improve sampling efficiency, the sampling dimension desired distance in lateral planning and desired velocity in longitudinal planning are constrained in reasonable ranges which are calculated in prior. Vehicle dynamic constraints are considered to calculate the constraints for the sampling range so that the sampling is warm started from some suboptimal point, and it can quickly find the global optima which is usually near the suboptimal point.

3) **Driving Comfort and Control Feasibility**: To improve driving comfort and control feasibility. We do trajectory smoothing after optimal trajectory is generated. A gradient based method that considers trajectory smoothness and curvature is used to reduce trajectory discontinuity and turning radius which results in reduced lateral acceleration and wheel turning angles in control. Since we use DL-AMP to find the best merge opportunity, free space is ensured at the very beginning, and collision checking is not necessary after smoothing. Unlike [xx], we also modify our gradient based method to deal with exploding and vanishing gradient problems.

This paper is organized as follows: the problem statement is presented in Section II, DL-AMP and DBTO are illustrated in Section III and IV respectively. The simulation and on-road tests results are shown in Section V.

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II. Procedure for Paper Submission

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Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

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, sc, 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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- 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”.
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- Use a zero before decimal points: “0.25”, not “.25”. Use “cm3”, not “cc”. (*bullet list*)

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C. Equations

The equations are an exception to the prescribed specifications of this template. You will need to determine whether or not your equation should be typed using either the Times New Roman or the Symbol font (please no other font). To create multileveled equations, it may be necessary to treat the equation as a graphic and insert it into the text after your paper is styled. Number equations consecutively. Equation numbers, within parentheses, are to position flush right, as in (1), using a right tab stop. 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

$$\alpha + \beta = \chi. \tag{1}$$

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Note that the equation is centered using a center tab stop. 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. 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, semi-/colons, 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).
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- 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".
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- There is no period after the "et" in the Latin abbreviation "et al.".
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An excellent style manual for science writers is [7].

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Highlight author and affiliation lines of affiliation 1 and copy this selection.

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C. Figures and Tables

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TABLE I. TABLE TYPE STYLES

Table Head	**Table Column Head**		
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a. Sample of a Table footnote. (Table footnote)

We suggest that you use a text box to insert a graphic (which is ideally a 300 dpi TIFF or EPS file, with all fonts embedded) because, in an MSW document, this method is somewhat more stable than directly inserting a picture.

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Figure 1. Example of a figure caption. *(figure caption)*

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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."

V. CONCLUSION

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

APPENDIX

Appendixes should appear before the acknowledgment.

ACKNOWLEDGMENT

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REFERENCES

[1] G. O. Young, "Synthetic structure of industrial plastics (Book style with paper title and editor)," in *Plastics*, 2nd ed. vol. 3, J. Peters, Ed. New York: McGraw-Hill, 1964, pp. 15–64.
[2] W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.
[3] H. Poor, *An Introduction to Signal Detection and Estimation*. New York: Springer-Verlag, 1985, ch. 4.
[4] B. Smith, "An approach to graphs of linear forms (Unpublished work style)," unpublished.
[5] E. H. Miller, "A note on reflector arrays (Periodical style—Accepted for publication)," *IEEE Trans. Antennas Propagat.*, to be published.
[6] J. Wang, "Fundamentals of erbium-doped fiber amplifiers arrays (Periodical style—Submitted for publication)," *IEEE J. Quantum Electron.*, submitted for publication.
[7] C. J. Kaufman, Rocky Mountain Research Lab., Boulder, CO, private communication, May 1995.
[8] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interfaces(Translation Journals style)," *IEEE Transl. J. Magn.Jpn.*, vol. 2, Aug. 1987, pp. 740–741 [*Dig. 9th Annu. Conf. Magnetics* Japan, 1982, p. 301].
[9] M. Young, *The Techincal Writers Handbook.* Mill Valley, CA: University Science, 1989.
[10] J. U. Duncombe, "Infrared navigation—Part I: An assessment of feasibility (Periodical style)," *IEEE Trans. Electron Devices*, vol. ED-11, pp. 34–39, Jan. 1959.
[11] S. Chen, B. Mulgrew, and P. M. Grant, "A clustering technique for digital communications channel equalization using radial basis function networks," *IEEE Trans. Neural Networks*, vol. 4, pp. 570–578, July 1993.
[12] R. W. Lucky, "Automatic equalization for digital communication," *Bell Syst. Tech. J.*, vol. 44, no. 4, pp. 547–588, Apr. 1965.
[13] S. P. Bingulac, "On the compatibility of adaptive controllers (Published Conference Proceedings style)," in *Proc. 4th Annu. Allerton Conf. Circuits and Systems Theory*, New York, 1994, pp. 8–16.
[14] G. R. Faulhaber, "Design of service systems with priority reservation," in *Conf. Rec. 1995 IEEE Int. Conf. Communications,* pp. 3–8.
[15] W. D. Doyle, "Magnetization reversal in films with biaxial anisotropy," in *1987 Proc. INTERMAG Conf.*, pp. 2.2-1–2.2-6.
[16] G. W. Juette and L. E. Zeffanella, "Radio noise currents n short sections on bundle conductors (Presented Conference Paper style)," presented at the IEEE Summer power Meeting, Dallas, TX, June 22–27, 1990, Paper 90 SM 690-0 PWRS.
[17] J. G. Kreifeldt, "An analysis of surface-detected EMG as an amplitude-modulated noise," presented at the 1989 Int. Conf. Medicine and Biological Engineering, Chicago, IL.
[18] J. Williams, "Narrow-band analyzer (Thesis or Dissertation style)," Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, 1993.
[19] N. Kawasaki, "Parametric study of thermal and chemical nonequilibrium nozzle flow," M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan, 1993.
[20] J. P. Wilkinson, "Nonlinear resonant circuit devices (Patent style)," U.S. Patent 3 624 12, July 16, 1990.

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