Agile maneuvering with intelligent articulated vehicles:
a look from a control perspective

by
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Abstract: Articulated vehicles are the popular means of freight and public transportation. Current trends and development forecasts indicate an increase in their use in the near future, mainly for economic and environmental reasons. Modular High Capacity Vehicles or articulated urban buses are examples of modern transportation solutions that require agile maneuvering in cluttered spaces. Since maneuvering with articulated vehicles, as an inherently nonlinear process, is non-intuitive and burdening for drivers, it seems reasonable to equip such vehicles with systems which provide (semi) autonomous maneuvering capabilities. The aim of the lecture is to provide a unified methodology for designing motion control systems that could be used in the intelligent articulated vehicles to efficiently perform various types of agile maneuvers using a driver-assistance system or in an autonomous mode. In this context, we discuss the key properties of the so-called N-trailer kinematics, and next we address the correspondence between practical motion problems, which are defined for articulated vehicles, and their formulation in the language of control engineering. Finally, a modular and highly scalable cascade-like control system is presented that allows solving various motion control tasks in a unified way for vehicles of different kinematic structures and any number of segments. Solutions to selected control problems are illustrated by numerical and experimental results.

Lecture description

The first objective of the lecture is to introduce the audience to practical control problems arising in the context of intelligent guidance and agile maneuvering with automated vehicles of the tractor-trailers type, and to discuss unique properties of articulated vehicles' models. The lecture is intended to illustrate, by examples, and justify the need of potential applications of autonomous or semi-autonomous articulated vehicles in the industrial, public, and private transportation. Current trends in the development of highly automated tractor-trailers vehicles will be discussed. The second objective is to show how the various practical motion tasks, defined for articulated vehicles, can be expressed in the control-theoretic language and effectively addressed by the modular control system design. An emphasis will be put on a correspondence between practical requirements imposed on the task and its formal description in a language of control engineering. This part of a lecture shall also reveal the beauty, complexity, and uniqueness of tractor-trailers kinematics from the perspective of dynamical systems analysis, where the features like high nonlinearity, instability, nonminimum-phasiness, nonholonomy, and underactuation all together meet in a single dynamical system of so important practical meaning. The third objective concerns presentation of recent solutions to the motion control problems mentioned above in the context of a cascade-like control system design, emphasizing its modularity, scalability, and practical effectiveness for different kinematic structures of articulated vehicles. Finally, one is also going to draw and discuss selected open research and implementation problems which have got either theoretical or application meaning in the context of maneuvering with tractor-trailers vehicles.

The lecture will address the following detailed issues:

A. Introductory and motivating remarks (a general level)

- Current trends in usage of articulated vehicles in modern transportation (High Capacity Vehicles and road-trains, articulated buses and buses with attached trailers).

- Illustration of a practical meaning of the agile maneuvering with articulated vehicles by discussing selected examples of tasks arising in freight transportation, urban buses, passenger cars with trailers, transportation for logistic chains in factories, and agricultural machinery.
- Explanation of main difficulties related to the maneuvering problems and their influence on the drivers' comfort, environment conditions and energy consumption, as well as safety and quality of vehicles' motion.
- Discussion of potential benefits from autonomous (or semi-autonomous) maneuvering with intelligent articulated vehicles emphasizing a tremendous help for human operators in these burdening and stressful tasks, less energy/fuel consumption and lower environment pollution, economic benefits due to less human costs, higher safety and efficiency of maneuvers.

B. Kinematics of articulated vehicles and definitions of control tasks (more formal level but with clear connections to practical applications)

- Description of two hitching types used in tractor-trailer vehicles and their influence on kinematics of articulated vehicles. Classification of N-trailer structures from the control perspective distinguishing the Standard N-Trailers (SNT), Generalized N-Trailers (GNT), and non-Standard N-Trailers (nSNT). Kinematic decompositions of exemplary articulated vehicles with respect to the hitching types used in their construction.
- Cascade-like compact description of N-trailer kinematics leading to a dynamical driftless system which is universal for all mechanical structures comprising a tractor and arbitrary number of N passive trailers with non-steerable wheels.
- Discussion of selected properties of N-trailer kinematics which are crucial from a control perspective and resulting fundamental control limitations they imply; we will address in particular: inherent high nonlinearity of agile maneuvering processes, instability of articulation dynamics and jackknife effect, nonminimum-phasiness in some motion conditions, nonholonomy, underactuation, kinematic singularities, and differential flatness or its lack.
- Description of practical maneuvers characteristic for tractor-trailer vehicles in terms of formal control tasks stated for the N-Trailer kinematics, i.e., mathematical description of selected practical maneuvers leading to such problems like the trajectory-tracking task (e.g., synchronization of a combine-harvester with a trailer position), the path-following task (e.g., precise spraying the plants on a field), the set-point control task (e.g., docking with a trailer in a logistic center or precise positioning a pantograph of an electric articulated bus to the power source station), the lining-up task (e.g., when preparing a multi-body kinematic chain to more advanced parking maneuvers), and the averaged-path-following task with off-track minimization for long articulated vehicles (e.g., the so-called High Capacity Vehicles and the road-trains).

C. Modular cascade-like control scheme for N-Trailers and its applications (more formal level but with clear connections to practical applications)

- Description of a modular and highly scalable cascade-like control strategy for the N-Trailer vehicles, its properties, benefits and limitations.
- Presentation of selected results of autonomous agile maneuvering with a 3-Trailer vehicle using the cascade-like controller for various control tasks. The results of numerical simulations as well as laboratory experiments will be presented in the form of animations and movies.
- Short discussion on alternative control solutions existing in the literature for the N-Trailer vehicles and their qualitative comparison to the cascade-like control concept.
- Explanation how to use the proposed control system in a form of the active or passive

Advanced Driver Assistance Systems (ADAS) if the semi-automated (assisted) maneuvering with a tractor-trailers vehicle is considered.

- Short presentation of open research and application problems from the control perspective in the context of maneuvering with articulated vehicles in real-life scenarios (unsolved control problems, the need of reliable state measurements, addressing the presence of state and control constraints).

D. Final remarks (a general level)

- General summary of the lecture.
- Exploration of current endeavors/projects in autonomization of articulated vehicles, and practical examples of intelligent articulated vehicles.

The lecture will be prepared in a way to be relatively easily accessible to a wide audience interested in the fields of feedback control, robotics, autonomous vehicles, and intelligent transportation systems. Intended audience will encompass the doctoral students and newcomers in the field, to experienced researchers and developers who would like to contribute in the area of articulated vehicles control. This effect will be obtained by appropriately balancing the level of a mathematical/theoretical content with engineering and application side of the presentation. The audience from the industry should also benefit from the lecture.

The main threads of the talk shall be accessible to most of the scientific-engineering audience typically attending the meetings like IAV Symposium. Hence, any special prerequisite knowledge will not be necessary to understand the main message provided during the lecture. However, to fully appreciate some more formal details and a beauty of control-theoretic aspects of the lecture the basic knowledge and/or research experience will be helpful in the areas of kinematics of mobile robots and tractor-trailer vehicles, properties of basic control tasks formulated for dynamical systems (especially for nonholonomic wheeled vehicles), Lyapunov-like stability concepts, stability of zero-dynamics, and a general paradigm of a cascade control system.

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