Oszlopban és csoportban haladó járművek együttes irányítása

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Introduction and motivation
Introduction

The idea behind organizing and controlling vehicles in a platoon during typical traffic situations in which several vehicles are traveling along the same road for a long distance is to increase safety and economy with the help of automation.
Advantages of organizing vehicles in a platoon:

- Smaller spacing, steady velocities ⇒ Two or three times greater traffic capacity, thus junctions can be avoided.
- Drivers are greatly relieved, therefore human error related accidents can be avoided.
- Comfort level can be increased by smoother and smaller number of accelerations.
- Smaller ram for the following vehicles ⇒ Reduced fuel consumption and $CO_2$ emission.
- The direct and external costs of transportation can be reduced.
Under normal running conditions the control of the follower vehicles can be divided into a velocity control problem (longitudinal control) and a lane keeping problem (lateral control).

The controller input depends on the applied control strategy, but the leader or the preceding vehicle’s acceleration, velocity and position (distance) information is usually necessary. The output of the controller is the prescribed acceleration for the controlled vehicle.
Stability problem

Controlling a platoon two types of stabilization problem has to be solved. First the spacing error between vehicles has to be defined:

\[ e_i = x_i - x_{i-1} + L_{des} \]

- Individual vehicle stability: The ability to track any bounded acceleration and velocity profile of the predecessor with a bounded spacing and velocity error:

\[ \ddot{x}_{i-1} \to 0 \Rightarrow e_i \to 0 \]

- String stability: Ensures that the spacing errors do not amplify upstream from vehicle to vehicle in the platoon:

\[ H(s) = \frac{e_i}{e_{i-1}}, \quad \|H(s)\|_\infty \leq 1, \quad h(t) > 0, \quad \forall t > 0. \]
One possible control strategy

The control of a platoon can be realized along diverse strategies. Two main methods:

- Constant spacing strategy: the spacing among vehicles is irrespective of the velocity of the platoon.
- Constant headway time strategy: the tracking time is constant ⇒ the spacing is a function of the velocity.

The controller examined below uses the leader and the preceding vehicles position, velocity and acceleration information for keeping a constant spacing among vehicles:

\[
    u = k_a \ddot{x}_{i-1} - k_{d\epsilon} \dot{\epsilon}_i - k_c \epsilon_i + k_l \ddot{x}_l - k_v (v_i - v_l) - k_p (x_i - x_l + \sum_{j=1}^{i} L_j)
\]

Onboard sensors are not sufficient for this strategy, communication between vehicles is necessary!
Disturbances and delays in the design
Simulation example

Simulation example with a platoon containing diverse heavy duty vehicles under the following assumptions:

- Signal transfer and actuator delays: Communication sampling time, brake system delay, gear shifting time.
- The elevation and inclination angle of the path is significant.
- The leader vehicle follows a target velocity adjusted by the onboard cruise control.
- Dynamically diverse vehicles in the platoon with different mass, size and performance figures.
Simulation results:

- Saturation occurred within the following vehicles having worse mass/performance figures.
- The saturating vehicles are not able to match the acceleration prescribed by their controller, therefore they cannot keep the desired spacing.
- Because of the splitting off the following vehicle prescribes bigger acceleration than necessary due to the growing distance from the leader vehicle.
Methods for collision avoidance

It has been shown, that the controller is not able to carry out the phenomenon of saturation caused by the diverse vehicle formation of the platoon and the delays and environmental disturbances. Possible methods to avoid collision:

- Ordering vehicles by mass/performance.
- Modifying the velocity of the leader vehicle.
- Breaking up the platoon.
Avoiding collision by modifying the velocity of the leader vehicle

Inter-vehicular communication methods play a fundamental roll in the problem of a platoon control. For gathering information GPS receiver, WiFi module and CAN communication channel is used. In the design of a platoon control it is required to consider the delays of the communication network and possible losses of data. In the following strategy the communication with the leader vehicle is two-way.

- To avoid the saturation and the consequent split off of the following vehicles the velocity of the leader is moderated.
- The throttle angle serves as the indicator for saturation.
- The newly adjusted velocity of the leader vehicle is determined by the saturating vehicle with a proper weighting of its actual acceleration and velocity state.
- The leader vehicle follows the modified velocity target for a predefined time interval, and in case the saturation cease among the following vehicles, it restores the original velocity target set by the cruise control.
Avoiding collision by modifying the velocity of the leader vehicle
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Simulation results:

- The strategy enables to avoid collision without the need of breaking up the platoon.
- The platoon velocity decreases from the adjusted 80 km/h to under 60 km/h on the elevation.
- The driver of the leader vehicle may feel insecure because of the external velocity correction.
Avoiding collision by breaking up the platoon

The following control strategy is based on the so-called mini-platoon structure. The platoon dissolves into several platoons following each other, where the last vehicle of the preceding platoon serves as the reference vehicle for the following platoon.

- The magnitude of the spacing error serves for saturation detection
- The saturating vehicle scales off from the original platoon creating a new platoon.

Simulation results:

- Two-way communication not required $\Rightarrow$ the realization is simple.
- Cannot ensure the cohesion of the original platoon.
Vehicle environment in the design of the platoon velocity
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Considering the two-way communication ability of a platoon system and that all of the vehicles in the string there is a possibility to choose an optimal velocity for the platoon:

- The road conditions are assumed to be available for the vehicles (road slope, velocity regulations).
- The main idea behind the design is that each vehicle in the platoon is able to calculate its optimal velocity independently from the other vehicles. The optimal velocity corresponds with the actual slope angle of the road.
- The platoon velocity is determined by the leader vehicle. Thus the leader’s velocity should be chosen as to guarantee the best compromise between the individual optimal velocities of the platoon members.
Initial and reference velocities

The road ahead of the vehicle is divided into several sections.

- Reference velocities are defined at the endpoints of each section, $v_{ref0}, v_{ref1}, ..., v_{refn}$.
- The rates of the slope of the road and those of the speed limits are assumed to be known at each section.
- An important question is how the momentary velocity $\dot{\xi}_0$ should be selected at the initial point by which the reference velocities can be reached.
- It is important to emphasize that the longitudinal force $F_{lj}$ affects only the actual section, and it does not affect the subsequent sections.
The velocities at the section points

E.g., the velocity of the second section point:

$$\dot{\xi}_2 = \dot{\xi}_1 + 2\ddot{s} = \dot{\xi}_0 + \frac{2s}{m} (F_{l1} - F_{d1} - F_{d2}) = v_{ref,2}^2,$$

is defined as the second reference velocity, where $s$ is the section length. The disturbance force is divided in two parts: the force resistance from road slope $F_{di,r}$, while $F_{di,o}$ contains all the other unknown resistances:

$$\dot{\xi}_0 + \frac{2s}{m} F_{l1} - \frac{2s}{m} F_{d1,o} = v_{ref,2}^2 + \frac{2s}{m} (F_{d1,r} + F_{d2,r})$$

In case of $n$ number of segments $n$ equations are formalized between the first and the end points. The velocity of the $n^{th}$ section point is the following:

$$\dot{\xi}_0 + \frac{2s}{m} F_{l1} - \frac{2s}{m} F_{d1,o} = v_{ref,n}^2 + \frac{2s}{m} \sum_{i=1}^{n} F_{di,r}$$
Selection of the weighting factors

The road sections to be taken into consideration are qualified by different weights, which have an important role in control design. In the next step a weight $Q$ is applied to the momentary (initial) velocity and weights $\gamma_1, \gamma_2, ..., \gamma_n$ are applied to the further reference velocities, where

$$\gamma_1 + \gamma_2 + ... + \gamma_n + Q = 1.$$ 

While the weights $\gamma_i$ represent the rate of changes in road conditions, weight $Q$ determines the tracking requirement of the momentary reference velocity $v_{ref,0}$.

- $Q = 1$ and $\gamma_i = 0, i \in [1, n]$: simple cruise control without any predicted road conditions.
- $Q = \gamma_i, i \in [1, n]$: the predicted road conditions are considered with the same importance.

The number of the selected section points is important.

- In case of flat roads it is enough to use relatively few section points.
- In case of undulating roads it is necessary to use a relatively large number of section points and shorter sections.
Weighting factors

- By summarizing the equations of the vehicle at the section points the following formula is yielded. In this equation $F_{l1}$ is the longitudinal force and $F_{d1,o}$ is the unknown disturbance.

\[ \dot{\xi}_0^2 + \frac{2s}{m} (1 - Q) F_{l1} - \frac{2s}{m} (1 - Q) F_{d1,o} = \vartheta \]

The value $\vartheta$ depends on the predicted road slopes, the reference velocities and the weights.

- The formula is the following:

\[ \vartheta = Qv_{ref,0}^2 + \sum_{i=1}^{n} \gamma_i v_{ref,i}^2 + \frac{2s}{m} \sum_{j=i}^{n} \gamma_j \sum_{i=1}^{n} F_{di,r}. \]

where $F_{di,r} = mg \sin \alpha_i$.

Thus, the values $\vartheta$ can be calculated in advance during the journey.

- The momentary velocity should be

\[ \dot{\xi}_0 = \lambda \]

with the parameter $\lambda$, which contains the road information:

\[ \lambda = \sqrt{\vartheta + 2s(1 - Q)(\ddot{\xi}_0 + g\sin \alpha)} \]

where $m\ddot{\xi}_0 = F_{l1} - F_{d1,o} - mg \sin \alpha$. 
The cruise control problem can be divided into two optimization problems in the following forms:

**Optimization I:** The longitudinal control force must be minimized:

\[ |F_{l1}^2| \rightarrow Min! \]

where \( F_{l1} \) depends only on the prediction weights.

**Optimization II:** The difference between the momentary velocity and the reference velocity must be minimized:

\[ |v_{ref0} - \dot{\xi}_0| \rightarrow Min! \]

The second criterion is optimal if the road information is ignored.
Simulation example for velocity planning

Considering the slope information the proposed control can save up to 25 percent of control energy.

Considering the speed limit information up to 20 percent of energy can be saved.
Optimization method in the platoon

Each vehicle in the platoon is able to calculate its velocity independently from the other vehicles.

- The optimal prediction weights are set \( \{Q_j; \gamma_{i,j}\} \), \( i \in [1; n] \) where \( n \) is the number of division points.
- The momentary velocities of all the vehicles are calculated \( \lambda_j \), \( j \in [1; m] \) where \( m \) is the number of the vehicles in the platoon.

In the platoon, the velocity of the leader vehicle determines the same velocity of all the vehicles. The aim is to calculate the reference velocity of the leader vehicle \( \bar{\lambda}_1 \).

The goal is to determine the velocity at which the velocities of all the vehicles \( \dot{\xi}_{0,j} \) are as close to their reference velocity \( \lambda_j \) as possible:

\[
\sum_{j=1}^{n} |\lambda_j - \dot{\xi}_{0,j}|^2 \to 0.
\]
Dynamic relationship between velocities:

\[ \dot{\xi}_{0,j} = G_j \dot{\xi}_{0,j-1} \rightarrow \dot{\xi}_{0,j} = \prod_{k=1}^{j-1} G_k \bar{\lambda}_1 \]

The optimization task:

\[ \sum_{j=1}^{n} |\lambda_j - \dot{\xi}_{0,j}|^2 \rightarrow 0. \]

Here the only unknown variable is \( \bar{\lambda}_1 \) is the reference velocity of the leader. The solution of the optimization task:

\[ \bar{\lambda}_1 = \frac{\sum_{j=1}^{n} (\lambda_j \prod_{k}^{j-1} G_k)}{\sum_{j=1}^{n} (\prod_{k=1}^{j-1} G_k)^2} \]
The calculation of the longitudinal force is performed in three steps:

- The optimization of velocities of the vehicles is based on two criteria: \(|F_{l1}^2| \rightarrow Min!\) and \(|v_{ref0} - \dot{\xi}_0| \rightarrow Min!\). A simplex algorithm is used.

- The optimization of the velocity of the leader vehicle:
  \[\sum_{j=1}^{n} |\lambda_j - \dot{\xi}_{0,j}|^2 \rightarrow 0\]. A simple matrix manipulation is used.

- The required longitudinal force is based on the robust control method. The robust control is designed in an off-line way.
Real data motorway simulation

The terrain characteristics and geographical information are those of the M1 Hungarian highway between Tatabánya and Budapest in a 56 km length section. The regulated maximal velocity is 130 km/h, but the road section contains other speed limits.

The proposed method required smaller energy than the conventional method, and the energy saving is approximately 15%. The difference in the duration of the journey is only 2 minutes.
Conclusions
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- The presentation has proposed platoon control design methods dealing with the dangerous effects of saturation.
- It has been shown, that with the use of two-way communication it is possible to moderate the platoon velocity such way that the platoon’s integrity remains intact.
- An adaptive cruise control system was presented which is able to consider the inclinations of the road, keep compulsory speed limits and is able to adapt to the traffic environment.
- By integrating the vehicle actuators and road conditions the designed control reduces fuel consumption and the energy required by the actuators.
Köszönetnyilvánítás

A kutatás a Nemzeti Fejlesztési Ügynökség és az OTKA (OTKA CNK 78168) támogatásával jött létre. A munka szakmai tartalma kapcsolódik a ”Minőségorientált, összehangolt oktatási és K+F+I stratégia, valamint működési modell kidolgozása a Műegyetemen” c. projekt szakmai célkitűzéseinek megvalósításához. A projekt megvalósítását az ÚMFT TÁMOP-4.2.1/B-09/1/KMR-2010-0002 programja támogatja.
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Köszönöm a figyelmet!