IMPROVED INFORMATION FLOW TOPOLOGY FOR VEHICLE CONVOY CONTROL

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DEDICATION

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ABSTRACT

A vehicle convoy is a string of inter-connected vehicles moving together for mutual support, minimizing traffic congestion, facilitating people safety, ensuring string stability and maximizing ride comfort. There exists a trade-off among the convoy's performance indices, which is inherent in any existing vehicle convoy. The use of unrealistic information flow topology (IFT) in vehicle convoy control, generally affects the overall performance of the convoy, due to the undesired changes in dynamic parameters (relative position, speed, acceleration and jerk) experienced by the following vehicle. This thesis proposes an improved information flow topology for vehicle convoy control. The improved topology is of the two-vehicle look-ahead and rear-vehicle control that aimed to cut-off the trade-off with a more robust control structure, which can handle constraints, wider range of control regions and provide acceptable performance simultaneously. The proposed improved topology has been designed in three sections. The first section explores the single vehicle's dynamic equations describing the derived internal and external disturbances modeled together as a unit. In the second section, the vehicle model is then integrated into the control strategy of the improved topology in order to improve the performance of the convoy to two look-ahead and rear. The changes in parameters of the improved convoy topology are compared through simulation with the most widely used conventional convoy topologies of one-vehicle look-ahead and that of the most human-driver like (the two-vehicle look-ahead) convoy topology. The results showed that the proposed convoy control topology has an improved performance with an increase in the inter-vehicular spacing by 19.45% and 18.20% reduction in acceleration by 20.28% and 15.17% reduction in jerk by 25.09% and 6.25% as against the one-look-ahead and two-look-ahead respectively. Finally, a model predictive control (MPC) system was designed and combined with the improved convoy topology to strictly control the following vehicle. The MPC serves the purpose of handling constraints, providing smoother and satisfactory responses and providing ride comfort with no trade-off in terms of performance or stability. The performance of the proposed MPC based improved convoy topology was then investigated via simulation and the results were compared with the previously improved convoy topology without MPC. The improved convoy topology with MPC provides safer inter-vehicular spacing by 13.86% refined the steady speed to maneuvering speed, provided reduction in acceleration by 32.11% and a huge achievement was recorded in reduction in jerk by 55.12% as against that without MPC. This shows that the MPC based improved convoy control topology gave enough spacing for any uncertain application of brake by the two look-ahead or further acceleration from the rear-vehicle. Similarly, manoeuvering speed was seen to ensure safety ahead and rear, ride comfort was achieved due to the low acceleration and jerk of the following vehicle. The controlling vehicle responded to changes, hence good handling was achieved.

ABSTRAK

Konvoi kenderaan adalah rantaian kenderaan yang bergerak bersama melalui sokongan mutual antara kendereaan bagi mengurangkan kesesakan lalu lintas, menjaga keselamatan orang awam, memastikan kestabilan rantaian dan memaksimumkan keselesaan perjalanan. Dalam rantaian konvoi terdapat 'trade-off' pada indeks prestasinya, yang diwarisi dari konvoi kenderaan semasa. Penggunaan topologi aliran maklumat (IFT) yang tidak realistik dalam kawalan konvoi kenderaan, secara amnya mempengaruhi keseluruhan prestasi konvoi dan menyebabkan pergerakan tersebut mengalami perubahan yang tidak diingini dalam parameter dinamik (kedudukan relatif, halaju, cepatan dan sentakan). Tesis ini mencadangkan penambahbaikan aliran informasi terhadap topologi aliran untuk kawalan konvoi kenderaan. Topologi yang ditambahbaik adalah topologi melihat dua-kenderaan di hadapan dan satu kenderaan di belakang, yang bertujuan untuk menafikan 'trade-off' dengan struktur kawalan yang lebih teguh dan dengan serentak mengendali kekangan, memperuntukkan kawasan kawalan yang lebih besar serta memberikan prestasi yang boleh diterima. Topologi yang diperbaiki ini telah direka dalam tiga bahagian. Bahagian pertama meneroka persamaan dinamik bagi sebuah kenderaan yang menunjukkan gangguan dalaman dan luaran yang diterbitkan sebagai satu unit. Pada bahagian kedua, model kenderaan ini kemudiannya diintegrasikan ke dalam cadangan strategi kawalan topologi yang diperbaiki untuk meningkatkan prestasi konvoi itu supaya dapat melihat dua buah kenderaan di hadapan dan sebuah kenderaan di belakang. Perubahan dalam parameter topologi konvoi yang diperbaiki ini telah dibandingkan melalui simulasi dengan konvoi topologi konvensional melihat sebuah kenderaan di hadapan dan konvoi topologi yang paling mirip dengan pemanduan manusia (dua buah kenderaan di hadapan). Keputusan menunjukkan bahawa topologi kawalan konvoi yang dicadangkan mempunyai prestasi yang lebih baik dengan jarak antara kenderaan dengan nilai peratusan sebanyak 19.45% dan 18.20%, pengurangan dalam cepatan sebanyak 20.28% dan 15.17%, pengurangan terhadap sentakan sebanyak 25.09% dan 6.25% untuk topologi melihat masing-masing sebuah kenderaan di hadapan dan dua buah kenderaan di hadapan. Akhirnya, satu model sistem kawalan ramalan (MPC) telah direka dan digabungkan dengan topologi konvoi yang dicadangkan untuk mengawal kenderaan tersebut secara rapi. MPC berfungsi untuk mengendalikan kekangan, memberikan respon yang lebih lancar dan memuaskan, serta memberikan keselesaan perjalanaan tanpa melakukan pertukaran dari segi prestasi dan kestabilan. Prestasi topologi konvoi yang berasaskan MPC yang dicadangkan ini kemudiannya disiasat melalui simulasi dan keputusan tersebut dibandingkan dengan topologi konvoi yang diperbaiki tanpa MPC. Topologi konvoi yang diperbaiki dengan MPC telah memperbaiki jarak antara kenderaan dengan nilai peratusan sebanyak 13.86%, pengurangan kadar cepatan yang stabil kepada cepatan bergerak, menghasilkan pengurangan dalam cepatan sebanyak 32.11% dan pencapaian terbesar telah dicatat dalam pengurangan sentakan sebanyak 55.12% setelah dibandingkan dengan tanpa MPC. Ini menunjukkan bahawa konvoi topologi yang dicadangkan yang berasaskan MPC ini telah menberi ruang yang cukup untuk mana-mana aplikasi brek yang tidak pasti daripada melihat dua kenderaan di hadapan atau mempercepatkan daripada kenderaan-ke belakang. Begitu juga, halaju bergerak yang telah dilihat untuk memastikan keselamatan arah hadapan dan belakang, pemanduan yang selesa telah dicapai berikutan oleh kadar cepatan yang rendah dan sentakan oleh kenderaan berikutan. Pengawalan kenderaan telah bertindak balas kepada perubahan dan ini membolehkan pengendalian yang baik dicapai.

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BD	-	Bi-Directional following
CACC	-	Cooperative Adaptive Cruise Control
CS	-	Constant Spacing
CTH	-	Constant Time Headway
DC	-	Distributed Controller
DSRC	-	Dedicated Short Range Communications
ESO	-	Extended State Observer
GCDC	-	Grand Cooperative Driving Challenge
GF	-	Geometry Formation
H_∞	-	H-infinity
IFT	-	Information Flow Topology
ITS	-	Intelligent Transport Systems
LR	-	Limited Range following
LTI	-	Linear Time Invariant
MPC	-	Model Predictive Control
ND	-	Node Dynamics
PATH	-	Partners for Advanced Transit and Highways
PD	-	Proportional Derivative
PF	-	Predecessor Following
PFL	-	Predecessor Following Leader
PID	-	Proportional Integral Derivative
SARTRE	-	Safe Road Trains for the Environment
SMC	-	Sliding Mode Control
TCS	-	Traction Control System
TL	-	Two-Look-ahead following
TPL	-	Two Predecessor Leader following
TPLF	-	Two Predecessor following Leader
UD	-	Uni-Directional following
V2V	-	Vehicle-to-Vehicle
VANET	-	Vehicular Adhoc Networks

LIST OF SYMBOLS

P	-	Vehicle engine power
τ_e	-	Engine torque
v	-	Speed
$\vec{F}$	-	Force acting on the object at time t in a specific direction
m	-	Mass of the object (vehicle)
$\vec{v}$	-	Object speed
$\vec{F}_{xi}$	-	$i-\text{th}$ force acting on the object in the same direction of x.
$\vec{a}_x$	-	Acceleration in the forward direction x
T_{xi}	-	$i-\text{th}$ torque about the x axis
I_x	-	Moment of inertia about the x axis
T_e	-	Engine torque at a given speed
T_c	-	Torque at the clutch
T_{rot}	-	Engine rotational torque
T_o	-	Output torque
N_t	-	Gear ratio
T_{rot_trans}	-	Rotational torque of the transmission
T_a	-	Torque on the axles
F_x	-	Tractive force
r	-	Vehicle's wheel radius
T_w	-	Torque on the wheels and axle shafts
N_f	-	Final drive ratio
T_{rot_drive}	-	Torque on the driveshaft
F_d	-	Aerodynamic drag force

F_{fd}	-	Viscous friction drag force
F_{rr}	-	Rolling resistance force
C_d	-	Non-dimensional drag coefficient
A	-	Frontal area of the vehicle
ρ_a	-	Density of the ambient air
b_t	-	Vehicle's width
h_t	-	Vehicle's height
C_{df}	-	Non-dimensional friction drag coefficient
l	-	Characteristic length
Re	-	Reynolds number
υ	-	Kinematic viscosity
μ	-	Dynamic viscosity of the fluid
ρ_f	-	Density of the fluid
C_{rr}	-	Rolling resistance coefficient
g	-	Acceleration of free fall due to gravity
θ	-	Slope angle with the ground
τ	-	Time delay constant
$\dot{a}$	-	Vehicle jerk
a	-	Vehicle acceleration
u	-	Command signal of acceleration
a_{act}	-	Actual acceleration
a_{pro}	-	Vehicle propulsive force
a_{dra}	-	External drag forces
$\dot{x}_i$	-	Velocities of the *i*-th vehicle
K_{p1}	-	Spring constant to predecessor vehicle
x_{i-1}	-	Instantaneous positions of the (*i-1*)-th vehicle
x_i	-	Instantaneous positions of the *i*-th vehicle
K_{v1}	-	Damper constant to predecessor vehicle

$\dot{x}_{i-1}$	-	Velocities of the (*i-1*)-th vehicle
K_{p2}	-	Spring constant to leading vehicle
x_{i-2}	-	Instantaneous positions of the (*i-2*)-th vehicle
K_{v2}	-	Damper constant to leading vehicle
$\dot{x}_{i-2}$	-	Velocities of the (*i-2*)-th vehicle
K_{p3}	-	Spring constant to rear vehicle
x_{i+1}	-	Instantaneous positions of the (*i+1*)-th vehicle
K_{v3}	-	Damper constant to rear vehicle
$\dot{x}_{i-1}$	-	Velocities of the (*i-1*)-th vehicle
$f(.,.)$	-	Nonlinear vector function that describes the dynamics
u_i	-	Control signal
$\ddot{x}_i$	-	Acceleration of the i-th vehicle
h	-	Head way
v_i	-	Velocity of the *i*-th vehicle
$G_m(s)$	-	Transfer function of the system
F_i	-	Applied force to vehicle
F_m	-	Final moving force of vehicle
ε	-	Inter-vehicular spacing
L	-	Vehicle including desire spacing
A	-	System state matrix
B	-	System input matrix
C	-	System output matrix
$x_i^{'}(k+1)$	-	Discrete-time model
N_p	-	Prediction horizon
I	-	Unit matrix
J_s	-	Cost function
$\overline{Q}$	-	Block diagonal output weighting matrix

$\overline{R}$	-	Block diagonal input weighting matrix
N_c	-	Control horizon
$S_{1(i)}$	-	Initial position of the control vehicle
$\Delta S_{1(i)}$	-	Change in position of the control vehicle
$S_{1(i-1)}$	-	Initial position of the predecessor vehicle
$\Delta S_{1(i-1)}$	-	Change in position of the predecessor vehicle
$S_{1(i-2)}$	-	Initial position of the leading vehicle
$\Delta S_{1(i-2)}$	-	Change in position of the leading vehicle
$S_{1(i+1)}$	-	Initial position of the rear vehicle
$\Delta S_{1(i+1)}$	-	Change in position of the rear vehicle
$hx_{1(i)}$	-	Speed-dependent spacing with respect to the headway

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Demand for highway travel keeps on growing as population rises, more importantly in urban areas. Construction of new highway capacity to accommodate this growth in traffic density has not kept pace. The capacity for goods transportation alone is projected to almost double by 2020 as compared to 2012. The traffic problem is mainly expected to be a problem of the metropolis, but this problem is also common in small urban areas and rural areas [1].

The deployment of autonomous vehicles on the highway has the potential of playing important role in intelligent traffic system by minimizing the problems of traffic congestion, facilitating people safety; cutting down energy wastage, maximizing ride comfort and reducing fuel consumption [2]. Several vehicle convoy models and controllers were proposed in the literature. In essence, vehicle control strategies need vehicles in the same convoy to move at a stable agreement in speed while maintaining the desired inter-vehicular spacing with respect to the neighboring vehicles within the convoy. Furthermore, it is to ensure stable string which is the ability of the controlled vehicle to move along the convoy without amplifying the oscillation of the leading vehicle upstream and to also provide minimum jerk in the control vehicle.

To achieve string stability, desired inter-vehicular spacing and ride comfort, the vehicle convoy has to comply with either of the control policies variable spacing or constant spacing. It is of importance to know that ride comfort is the third order differential of the displacement of the vehicle, which is called as jerk of the vehicle. In the variable spacing policy, the inter-vehicle spacing is large (a function of velocity), which is applicable for low traffic density conditions. This technique facilitates string stability through the use of onboard information. This implies that vehicles do not rely largely on the information from other vehicles. While constant spacing policy depends mostly on inter-vehicle communication and this policy facilitates string stability with little spacing and it is generally applicable in high traffic density conditions [2]. To achieve desired spacing, the time headway would play a significant role [3] in inter-vehicular spacing and to avoid collision with the vehicles of the convoy. The constant time headway (CTH) describes the desired inter-vehicular spacing as proportional to the control vehicle's speed, the constant of proportionality from the CTH policy is referred to as the time headway (h) [4, 5]. To achieve passenger's comfort, the control vehicle's jerk has to be minimized to not more than one-third of the vehicle's acceleration (not more than $5\ ms^{-3}$) [6, 7]. The smaller the vehicle's jerk the more comfortable the passenger's in the vehicle [8].

String stability is mostly achieved in situations where errors (spacing and information flow) are not amplified within the convoy as vehicles move. For perfect cancellation of such errors, the errors must have the same sign as to avoid collision within the convoy [9, 10, 11]. The concept of vehicle convoy refers to a string of vehicles that aim to keep a specified, but not necessarily constant inter-vehicle distance with respect to either of the two policies discussed above.

This work introduces an improved information flow topology (IFT) for vehicle convoy control, where the controlling vehicle is expected to be controlled at consensual speed and to maintain desired space with the independent vehicles and to greatly reduce jerk. The proposed convoy control topology ensures information flow from the leader, predecessor and the rear vehicle to the controlled vehicle, where the control vehicle utilizes the information received to adjust in speed and position in the convoy. A dynamic model for the proposed IFT convoy control is implemented to facilitate realistic, slinky-effect free, high passenger's comfort and safe spacing. The proposed IFT convoy control of the two-vehicle look-ahead and rear-vehicle is then compared with the conventional two-vehicle look-ahead convoy to ascertain its dynamic parameters (relative position, speed, acceleration and jerk) performance. The high-performance convoy among the two is then compared with the proposed improved IFT controlled by model predictive control (MPC) to ascertain the robustness of the improved topology and performance over the same IFT with no MPC controller.

1.2 Problem Statement

To control a vehicle in a mix of independent vehicles in a convoy is quite challenging, due to the inherent string unstable behavior associated with such convoy and a huge amount of jerk. Moreover, it is tasking for the controlling vehicle to simultaneously track the path taken by the preceding vehicle with safe speeding and without compromising the inter-vehicular spacing among the vehicles. Therefore, most of the vehicle convoy systems implemented in literature suffer from the problem of string instability and ride comfort due to the common adoption of the conventional IFT. It has been established that the existing IFT used does not fully define a safe convoy scenario and hence the string stability cannot be guaranteed. This is due to the error propagation within the dynamic parameters of the convoy (slinky-effect), the presence of disturbances (friction and wind) and the fact that vehicle's comfort reduces with increase in jerk above the said $5\,\mathrm{ms}^{-3}$. All these coupled together makes vehicle convoy systems a challenging control problem.

There is a need for an enhancement and more realistic IFT for convoy operation. This is achieved through design and implementation of an improved topology of an improved two-vehicle look-ahead and rear-vehicle convoy equipped with a robust controller.

1.3 Research Objectives

The present research work proposed to find possible solutions to the stated problems through the following objectives:

(a) To develop an improved IFT of two-vehicle look-ahead and rear-vehicle convoy, which will give wider operating range than the conventional IFT for an effective communication and more realistic vehicle convoy.
(b) To design and implement a PD-like control strategy of the improved topology for the vehicle convoy in (a) and to investigate its performance (string stability and ride comfort) against the conventional one and two-vehicle look-ahead convoy control system via simulations.
(c) To design and implement a model predictive control (MPC) for the improved IFT of (a) for an effective and robust control of the two-vehicle look-ahead and rear-vehicle convoy to investigate its performance (string stability and ride comfort) against that of (b) via simulation.

1.4 Scope of the Research

The scope of this research work is outlined as follows:

(a) The research covers the motion of two-vehicle look-ahead and rear-vehicle.
(b) 1-DOF vehicle motion is considered. That is the longitudinal vehicle convoy, without a lane change.
(c) Simulation is conducted using MATLAB Simulink environment.
(d) Homogeneous vehicle convoy is considered. That is the vehicle convoy, in which all the vehicles have the same dynamics.
(e) Effects of friction and aerodynamic drag are used as external disturbances to the convoy.
(f) Comparison is on simulation results of the developed and the conventional convoy topologies in respect to string stability and rides comfort.

1.5 Thesis Contribution

The expected contributions of the research work are as listed:

(a) The improved information flow topology

An implementation and investigation of the improved information flow topology of the two-vehicle look-ahead and rear-vehicle convoy control will provide new results and knowledge in the area of vehicle convoy system.

(b) Overall convoy of the improved topology

Design and implementation of the overall improved PD-like convoy control is expected to provide a higher performance (string stability and ride comfort) convoy operation.

(c) Overall MPC based convoy control of the improved topology

A robust MPC based control is designed for the improved topology. This will efficiently predict and enable positioning, track reference input speeds, reject external disturbances, ensure string stability with a possible minimum jerk, handle constraints and maximize the operational range of the convoy system.

1.6 Hypothesis of the Research

In this research work, some hypothesis was made to guide towards the findings as follows:

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