Pontifícia Universidade Católica
do Rio de Janeiro

Abel Arrieta Castro

Development of a robust and fault tolerant integrated control system to improve the stability of road vehicles in critical driving scenarios

Tese de Doutorado

Thesis presented to the Programa de Pós–graduação em Engenharia Mecânica of PUC-Rio in partial fulfillment of the requirements for the degree of Doutor em Ciências - Engenharia Mecânica.

Advisor : Prof. Hans Ingo Weber
Co-advisor: Prof. Georg Rill

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Abstract

Arrieta Castro, Abel; Ingo Weber, Hans (Advisor); Rill, Georg (Co-Advisor). **Development of a robust and fault tolerant integrated control system to improve the stability of road vehicles in critical driving scenarios**. Rio de Janeiro, 2017. 106p. Tese de Doutorado – Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Nowadays new technologies are pushing the road vehicle limits further. Promising applications, e.g. self-driving cars, requires control systems that are able to ensure the vehicle's stability during autonomous driving or under dangerous scenarios. In most of modern cars, the control systems actuates independently, i.e. there is no coordination or data sharing between them. This approach can produce conflicts between these standalone controllers, thereby no improvements on the vehicle's stability are achieved or even a worse scenario can be produced. In order to overcome these problems, an integrated approach is designed in this work. This integration, defined as Integrated control system (IC), use a rule to coordinate the Electronic stability program (ESP) and the Four-wheel steering system (4WS). The ESP performs a selective braking depending of the current state of the vehicle. This condition is estimated by the difference between the desired yaw rate, obtained using a linear vehicle model, and the actual yaw rate. In addition, the braking pressures at each wheel are computed by the Anti-lock braking system (ABS). In this work, an on-off switching logic and a first-order hydraulic model are employed to model the ABS system. To model the 4WS, a simple feed-forward control strategy that consider the front steering as input is used. Finally, in order to test the advantages of the IC system against the non-integrated one, simulations considering a nonlinear vehicle model under critical driving scenarios were performed. The vehicle model was derived employing the multibody approach and the Jourdain's principle, and then it is validated using a set of experimental data obtained by sensors mounted on a scaled car.

Keywords

Multibody vehicle model; ABS; ESP; 4WS; Integrated control system; Critical driving scenarios.

Resumo

Arrieta Castro, Abel; Ingo Weber, Hans; Rill, Georg. **Desenvolvimento de um sistema de controle integrado robusto e tolerante a falhas para melhorar a estabilidade de veículos em cenários críticos de condução**. Rio de Janeiro, 2017. 106p. Tese de Doutorado – Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Rio de Janeiro.

Atualmente, as novas tecnologias estão estendendo os limites físicos dos veículos automotivos em busca de mais segurança e comforto. Novas aplicações, como por exemplo veículos autônomos, exigem sistemas de controle capazes de garantir a estabilidade do veículo durante a condução autônoma ou em cenários perigosos. Na maioria dos carros modernos, os sistemas de controle atuam de forma independente, ou seja, não há coordenação ou compartilhamento de dados entre eles, pois poderiam produzir conflitos entre esses controladores. Desse modo, nenhuma melhoria na estabilidade do veículo é alcançada ou inclusive, piores cenários podem ser produzidos. Para superar esses problemas, uma abordagem integrada é projetada neste trabalho. Esta integração, definida como sistema de controle integrado (IC), usa uma regra para coordenar o programa eletrônico de estabilidade (ESP em inglês) e o sistema de direção de quatro rodas (4WS em inglês). O ESP realiza uma frenagem seletiva dependendo do estado atual do veículo. Esta condição é estimada pela diferença entre a taxa de guinada desejada, obtida usando um modelo linear do veículo, e a taxa de guinada real. Adicionalmente, as pressões de frenagem em cada roda são calculadas pelo sistema de travagem antibloqueio (ABS em inglês). Neste trabalho, uma lógica de comutação on-off e um modelo hidráulico de primeira ordem são empregadas para modelar o sistema ABS. Para projetar o 4WS, usou-se uma estratégia por alimentação direta que considera o ângulo de esterçamento das roas frontais. Finalmente, para testar as vantagens do sistema IC proposto nesta tese contra o enfoque não integrado, realizaram-se simulações considerando um modelo não-linear do veículo em cenários críticos de condução. O modelo do veículo foi derivado empregando a abordagem multicorpos e o princípio de Jourdain, e depois é validado usando um conjunto de dados experimentais obtidos por sensores montados em um carro a escala.

Palavras-chave

Modelo multicorpo do veículo; ABS; ESP; 4WS; Controle integrado; Cenários críticos de condução.

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List of abbreviations

ABS	Anti-lock braking system
ESP	Electronic stability program
4WS	Four-wheel steering system
ASR	Anti-slip regulation
AFS	Active front steering system
IC	Integrated control system
ECU	Electronic control unit
DOF	Degrees of freedom
COG	Center of gravity
MBS	Multibody systems
SHM	Simple handling model
TMeasy	Tire model easy to use
WHO	World Health Organization
EC	European Commission
EU	European Union
ISO	International Organization for Standardization

List of symbols

Mathematical objects within this thesis are denoted as follows:

$$
\begin{aligned}
\mathrm{m} &- \text{scalar},\\
\boldsymbol{m} &- \text{vector},\\
\boldsymbol{M} &- \text{matrix}.
\end{aligned}
$$

When present, symbols in sub- and superscripts of a variable r are employed in the form $r^3_{1,2}$. The numbers denote the position of the following optional assignments:

1 – a position, e.g. W for wheel center

2 – the coordinate system in which the variable is measured, e.g. V for vehicle-fixed axis system

3 – an exponent or an additional assignment, e.g. r^{min} for the minimum value of r

Coordinate systems

$\{O_V, x_V, y_V, z_V\}$	origin and Cartesian coordinate axes of vehicle-fixed axis system
$\{O_C, x_C, y_C, z_C\}$	origin and Cartesian coordinate axes of chassis-fixed axis system
$\{O_{Wi}, x_{Wi}, y_{Wi}, z_{Wi}\}$	origin and Cartesian coordinate axes of i-th wheel-fixed axis system
$\{O_{Ki}, x_{Ki}, y_{Ki}, z_{Ki}\}$	origin and Cartesian coordinate axes of i-th knuckle-fixed axis system
$\{O, x, y, z\}$	origin and Cartesian coordinate axes of global coordinate system (inertial frame)

Variables, parameters and constants[1]

m	vehicle mass
Θ	vehicle moment of inertia around z_V axis
δ_i	steering angle at the inner wheel
δ_o	steering angle at the outer wheel
δ	mean steering angle
l_f	distance from vehicle's COG to front axle
l_r	distance from vehicle's COG to rear axle
l	vehicle's wheel base
w	vehicle's track width
β	vehicle's sideslip angle
$\dot{\psi}$	vehicle's yaw rate
α	vehicle roll angle
γ	vehicle yaw angle
$\boldsymbol{v}$	vehicle's velocity at COG
z_i	vertical displacement of i-th wheel relative to the chassis
ρ	upper control arm rotation angle
e_ρ	upper control arm axis of rotation
ϕ	lower control arm rotation angle
e_ϕ	lower control arm axis of rotation
δ	steering angle around the kingpin axis
e_δ	kingpin rotation axis
u_F	front rack displacement
u_R	rear rack displacement

[1] SI units are used throughout this manuscript. Unless specifically noted otherwise, the unit radians was used for all angles.

R	radius of curvature
$\mathcal{I}$	instantaneous center of rotation
i	wheel index, $i = \{fl, fr, rl, rr\}$
j	axle index, $i = \{f, r\}$
$\boldsymbol{F}$	vector of tire forces at contact point
s_x	longitudinal tire slip
s_y	lateral tire slip
r_D	dynamic tire radius
r_S	static tire radius
Ω_i	absolute angular velocity of i-th wheel
ω_i	rotational speed of i-th wheel
e_{yR}	wheel rotation axis
K_f	cornering stiffness at front axle
K_r	cornering stiffness at rear axle

Wisdom must be intuitive reason combined with scientific knowledge.

Aristotle, *Nicomacheian Ethics, VI.7.*