Stability Control via In-Wheel Motors of a Solar-Electric Vehicle

by Anna Lidfors Lindqvist

Thesis submitted in fulfilment of the requirements for
the degree of

Doctor of Philosophy

under the supervision of Dr. Paul D. Walker
and Dr. Ricardo P. Aguilera

University of Technology Sydney
Faculty of Engineering and Information Technology

December 2021

Certificate of Original Authorship

I, Anna Lidfors Lindqvist declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical and Mechatronics Engineering at the Faculty of Engineering And Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Production Note:

Signed: Signature removed prior to publication.

Date: 30-12-2021

Stability Control via In-Wheel Motors of a Solar-Electric Vehicle

by

Anna Lidfors Lindqvist

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Abstract

Emission reduction and increased safety are crucial for future mobility development. Vehicle dynamic control systems have an important role in vehicle safety and the reduction of weight in vehicle design has been proven to improve efficiency and reduce energy consumption. Very lightweight vehicles, however, impose a challenge when it comes to the vehicles handling stability, as their inertial parameters are impacted by additional load from e.g. passengers. As such, this thesis presents the study of vehicle dynamics of a lightweight customised solar-electric vehicle which is sensitive to the variation in loading conditions.

This thesis investigates the principle and engineering application of dynamic yaw moment control through simulation and real-time testing of the Australian Technology of Networks (ATN) solar car. The ATN solar car competed in the Bridgestone World Solar Challenge (BWSC), 2019; an Australian international biannual competition, where teams drive 3,000 km from Darwin to Adelaide in custom designed solar-electric vehicles. The cruiser class vehicles were introduced to recognise the necessity of sustainable transportation by encouraging practical vehicle designs with two or more seats. Drivers are exposed to long driving stints in vehicles with generally poorer handling and steering performance, owing to the need for lightweight, high performing designs. In such the novelty of this research should be considered in terms of the control theory and its application to a unique vehicle configuration. The design features, particularly being rear-wheel drive and very light weight, impact controllability and dynamic behaviour of the case study solar car in this research. This type of research is very important for extreme cases of vehicle design that is present in the Bridgestone World Solar Challenge vehicles. In addition, investigating vehicles susceptible to extreme handling, the handling safety can be improved within solar racing sports, but also within the development of future lightweight road vehicles.

To undertake this investigation a simulation-based approach was achieved via co-simulation of the vehicle model and control. Using Siemens Amesim a nonlinear 15-DOF model was realised, incorporating the load transfer effects and nonlinear tyre characteristics. The control algorithms were developed in MATLAB/Simulink

This thesis presents four control method that can be applied to the rear in-wheel motors; Dynamic Curvature Control (DCC), Proportional–Integral Control (PI), Sliding Mode Control (SMC) and Model Predictive Control (MPC).

Using this simulation-based approach the dynamics of the vehicle is studied. Large variations load-to-curb weight ratios are linked to significant changes in parameters critical to control design for vehicle stability control system. Unique and highly customised vehicles, such as the lightweight solar car, are more susceptible to the impact of such variations when developing control methods. As such the influence of variation in loading condition and the effect of ignoring changes in inertial parameters is studied. The study demonstrated that by ignoring the change in the inertial parameters in simulation environments can produce an incorrect translation of the control performance.

Finally, to verify the applicability and performance of the simulations, open loop real-time testing was performed. This is done by implementing the control to the vehicles Control Area Network (CAN), via a dSPACE MicroAutoBox II. The evaluation was performed by comparing a slow speed baseline vehicle to tests with higher velocity, addition of passenger, low tyre pressure and cases of uneven tyre pressures. It was found that despite significant sensor and estimation errors due to compromises caused by COVID-19, the SMC and MPC both have vigorous performance capabilities and are safe for future closed-loop testing.

Acknowledgements

Firstly I would like to thank my supervisor Paul D. Walker whose expertise was invaluable in order for me to complete my research, it has been a pleasure to work alongside you and thanks for giving me the free hands to explore my research topic and the extracurricular task of managing students and the solar car team. I would like to thank and acknowledge my co-supervisor Ricardo Aguilera Echeverria who's invaluable knowledge and help with the control design and integration was essential for the success of this research.

I also want to give warm thanks to my colleague and friend Shiei Zhou for your expertise knowledge and patience when working together with software integration issues, control design, vehicle integration, testing and for always lending a helping hand when needed. I would like to extend a thanks to my colleague Mohamed Awadallah for sharing his knowledge and working with us on the installation and realisation of the real-time control set-up on the dSPACE MicroAutoBox II and the integration to the solar car.

I would like to acknowledge each of the ATN solar car team, team members and associates, thanks for being part part of the journey and acknowledgement of the contributors to some images and graphics in this thesis. I would also like to thank the technical team Richard Jamie, Bang Nguyen and Michael Lee for supporting the work and testing of the solar car.

In addition, I would like to thank my dear friend and previous colleague, Hasti Hayati, for always being an inspiration and motivating me to achieve my goals. Also many thanks to my partner, and of course the scrubblets, my close friends Somaia Ahmadi, Martin Do and Ben Hayles, for reminding me there is life outside of the PhD work.

Finally, I could not have completed my dissertation without the support of my family and friends back home, who despite being far away when times are tough, have encouraged me to be persistent and work hard. Special thanks to my mum, Lena Lidfors, who's expert academic knowledge saved me on numerous occasions throughout my journey, my dad, Thomas Lindqvist, who's technical expertise helped me with trouble shooting even if he was on the other side of the world, and my sister, Linnea Lidfors Lindqvist for keeping me grounded; but most of all for their unlimited support to always strive for the very best.

Contents

List of Figures

List of Tables

Acronyms & Abbreviations

2DOF Two Degrees of Freedom

3DOF Three Degrees of Freedom

ADAS Advanced Drivers Assistance Systems

ATN Australian Technology of Networks

BWSC Bridgestone World Solar Challenge

CAN Controller Area Network

DCC Dynamic Curvature Control

DSC Dynamic Stability Program

DYC Direct Yaw Moment Control

ECU Electronic Control Unit

ESC Electronic Stability Control

ESP Electronic Stability Program

EV Electric Vehicle

GPS Global Pointing System

IMU Inertial Measurement Unit

MBD Model-Based Design

MDoF Multiple Degrees of Freedom

MF	Magic Formula
MAB	MicroAutoBox
MPC	Model Predictive Control
PI	Proportional Integral
PiL	Processor-in-the-Loop
RPC	Rapid Control Prototyping
SAS	Steering Angle Sensor
SMC	Sliding Mode Control
TV	Torque Vectoring
VCU	Vehicle Control Unit
VDC	Vehicle Dynamics Control
VSC	Vehicle Stability Control
UTS	University of Technology Sydney

Nomenclature

	General Notations
X	Robot Pose vector in 2D space. Consists of the position components x, y and the orientation component ϕ.
Y	Position.
ϕ	Roll angle
θ	Pitch angle
ψ	Yaw angle
δ	Steering wheel angle
r	Yaw rate
F_x	Longitudinal tractive/breaking force of the tires
F_y	Lateral cornering force of the tires
F_z	Vertical/normal force of the tires
m	Total mass of the vehicle.
I_x	Moment of inertia around the x-axis
I_y	Moment of inertia around the y-axis
I_z	Moment of inertia around the z-axis
C_f	Tyre cornering stiffness of the front wheels
C_r	Tyre cornering stiffness of the rear wheels
r_w	tire radius
l	Wheelbase; the distance between centre of the front and rear wheels.
l_f	Length from the centre of the front wheel to COG.
l_r	Length from the centre of the rear wheel to COG.

t_r	Track; the distance between the centre line of two wheels on the same axle.
m_{fl}	Mass measured at the front left wheel.
m_{fr}	Mass measured at the front right wheel.
m_{rl}	Mass measured at the rear left wheel.
m_{rr}	Mass measured at the rear right wheel.
m_l	Left hand side mass, about the center line of the track.
m_{Right}	Right hand side mass, when added with $m_l = m$
m_f	Front mass in relations to the center of l
m_r	Rear mass, makes up m with m_f
h_z	Vertical height raised at the rear axis during COG measurement.
m_{fh_z}	front mass when raised at height (h_z)
l_{adj}	The adjacent length below the vehicle during raised height (h_z)
$m_{\Delta f}$	Front axle mass change

Publications

2021 **Lidfors Lindqvist A.**, Walker P.D. (2021) *Handling Dynamics of an Ultra-Lightweight Vehicle During Load Variation.* In: Oberst S., Halkon B., Ji J., Brown T. (eds) Vibration Engineering for a Sustainable Future. Springer, Cham. DOI:10.1007/978-3-030-47618-2_7

2020 **Lidfors Lindqvist A.**, Zhou S., Walker P.D. (2020) *Direct yaw moment control of an ultra-lightweight solar-electric passenger vehicle with variation in loading conditions*, Vehicle System Dynamics, DOI: 10.1080/00423114.2020.1853784

2020 **Lidfors Lindqvist A.**, Walker P.D. (2020) *Handling Dynamics of a Lightweight Solar-Electric Vehicle with Direct Yaw Moment Control.* In: Klomp M., Bruzelius F., Nielsen J., Hillemyr A. (eds) Advances in Dynamics of Vehicles on Roads and Tracks. IAVSD 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. DOI: 10.1007/978-3-030-38077-9_136