

# 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

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# 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.

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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.

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# Acronyms & Abbreviations

<b>2DOF</b>	Two Degrees of Freedom
<b>3DOF</b>	Three Degrees of Freedom
<b>ADAS</b>	Advanced Drivers Assistance Systems
<b>ATN</b>	Australian Technology of Networks
<b>BWSC</b>	Bridgestone World Solar Challenge
<b>CAN</b>	Controller Area Network
<b>DCC</b>	Dynamic Curvature Control
<b>DSC</b>	Dynamic Stability Program
<b>DYC</b>	Direct Yaw Moment Control
<b>ECU</b>	Electronic Control Unit
<b>ESC</b>	Electronic Stability Control
<b>ESP</b>	Electronic Stability Program
<b>EV</b>	Electric Vehicle
<b>GPS</b>	Global Pointing System
<b>IMU</b>	Inertial Measurement Unit
<b>MBD</b>	Model-Based Design
<b>MDoF</b>	Multiple Degrees of Freedom

<b>MF</b>	Magic Formula
<b>MAB</b>	MicroAutoBox
<b>MPC</b>	Model Predictive Control
<b>PI</b>	Proportional Integral
<b>PiL</b>	Processor-in-the-Loop
<b>RPC</b>	Rapid Control Prototyping
<b>SAS</b>	Steering Angle Sensor
<b>SMC</b>	Sliding Mode Control
<b>TV</b>	Torque Vectoring
<b>VCU</b>	Vehicle Control Unit
<b>VDC</b>	Vehicle Dynamics Control
<b>VSC</b>	Vehicle Stability Control
<b>UTS</b>	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 $\phi$ .
$Y$	Position.
$\phi$	Roll angle
$\theta$	Pitch angle
$\psi$	Yaw angle
$\delta$	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.

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$t_r$	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

