OPTIMAL COMPOSITE NONLINEAR FEEDBACK CONTROL WITH MULTI OBJECTIVE ALGORITHMS FOR ACTIVE FRONT STEERING SYSTEM

LIYANA BT RAMLI

A thesis submitted in fulfilment of the requirements for the award of the degree of Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

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Specially dedicated to my beloved family
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Liyana Ramli
The main purpose of controlling vehicle handling is to ensure that the vehicle follows the desired path. Vehicle yaw rate must be controlled in order to achieve a good vehicle handling. In this thesis, optimal Composite Nonlinear Feedback (CNF) controller with multi objective algorithms is proposed for the Active Front Steering (AFS) system in improving the vehicle yaw rate response. The model used to validate the performance of the controller is a 7 degree-of-freedom (DOF) nonlinear vehicle model. This vehicle model is also simplified to a 2 DOF bicycle model for the purpose of controller design. In designing the optimal CNF control, the parameter selection of optimal linear and non-linear gain parameters becomes very important to obtain a good system response. Optimization algorithms are utilized to minimize the complexity in selecting the best parameters. Hence, Multi Objective Particle Swarm Optimization (MOPSO) and Multi Objective Genetic Algorithm (MOGA) are proposed to produce the optimal CNF. Moreover, manual tuning method was utilized and has been compared with the proposed algorithms. As a result, the performance of the yaw rate response is improved with a 98 percent reduction in error. Hence, the vehicle handling can be improved and the vehicle will be able to travel safely on the desired path.
ABSTRAK

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<td>Active Front Steering</td>
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<td>DOF</td>
<td>Degree of Freedom</td>
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<td>MOPSO</td>
<td>Multi-objective Particle Swarm Optimization</td>
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<td>MOGA</td>
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<td>TS</td>
<td>Settling Time</td>
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<td>SSE</td>
<td>Steady State Error</td>
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<td>SISO</td>
<td>Single Input Single Output</td>
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<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<td>LQR</td>
<td>Linear Quadratic Regulator</td>
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<td>IAE</td>
<td>Integral Absolute of Error</td>
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<td>ITAE</td>
<td>Integral of Time Multiplied Absolute Error</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>PSO</td>
<td>Particle Swarm Optimization</td>
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<td>MOOP</td>
<td>Multiple Objective Optimization Problem</td>
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<td>EA</td>
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<td>ASC</td>
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<td>A4WS</td>
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<td>ABS</td>
<td>Anti Lock Braking System</td>
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<td>LWS</td>
<td>Linear Weight Summation</td>
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LIST OF SYMBOLS

\( r \) - Target reference
\( g \) - Gravitational acceleration
\( m \) - Vehicle mass
\( C \) - Mass center
\( R \) - Tire radius
\( F \) - Linear Feedback Gain
\( h \) - Vertical distance from CG of sprung mass to roll axis
\( T \) - Track of vehicle
\( g \) - Gravity constant
\( D \) - Maximum number of iteration set by the user
\( N \) - Number of chromosome
\( cr \) - Crossover rate value
\( mr \) - Mutation rate value
\( \rho \) - Nonlinear function
\( \varphi \) - Roll angle
\( \theta \) - Pitch angle
\( \psi \) - Yaw angle
\( \dot{\psi} \) - Yaw rate
\( v \) - Velocity vector of vehicle
\( \omega \) - Angular velocity
\( \dot{\omega} \) - Angular acceleration
\( \beta \) - Body side slip angle
\( \alpha \) - Side slip angle
\( \delta \) - Steer angle
\( \kappa \) and \( \gamma \) - Nonlinear gain parameters
\( \mu \) - Road adhesion coefficient
\(\rho\) - Nonlinear function of CNF
\(\varepsilon\) - Different between min and max fitness value in the iteration
\(\omega_t\) - Inertia weight
\(F_x\) - Longitudinal tire force
\(F_y\) - Orthogonal tire force
\(F_z\) - Normal tire force
\(M_z\) - Yaw moment
\(\delta_f\) - Front steer angle
\(\delta_r\) - Rear steer angle
\(C_y\) - Tire cornering stiffness
\(C_{yr}\) - Rear tire cornering stiffness
\(C_{yf}\) - Front tire cornering stiffness
\(F_{yf}\) - Front lateral force
\(F_{yr}\) - Rear lateral force
\(\delta_{fd}\) - Steer input commanded by driver
\(\delta_c\) - Corrected steer angle
\(\psi_d\) - Desired yaw rate
\(\beta_d\) - Desired side slip angle
\(I_w\) - Wheel moment of inertia
\(n_s\) - Steering wheel ratio
\(\alpha_i\) - Side slip at \(i^{th}\) wheel
\(\lambda_i\) - Tire longitudinal slip ratio at \(i^{th}\) wheel
\(F_{xi}\) - Longitudinal tire force at \(i^{th}\) wheel
\(F_{yi}\) - Lateral force at \(i^{th}\) wheel
\(F_{zi}\) - Normal force at \(i^{th}\) wheel

**Fitness\(_{ij}\)** - Fitness of the \(i^{th}\) particle/chromosome in dimension \(j\)

**\(v_{ij}^{t+1}\)** - Velocity vector of particle \(i\) in dimension \(j\) at time \(t\)
**\(x_{ij}^t\)** - Position vector of particle \(i\) in dimension \(j\) at time \(t\)
**\(P_{best,i}^t\)** - Personal best position of particle \(i\) in dimension \(j\) found from initialization through time \(t\)
**\(G_{best}\)** - Global best position of particle \(i\) in dimension \(j\)
through time $t$

$c_1$ & $c_2$ - Positive acceleration constants

$w_{SSE}$ - weight value for the steady state error

$w_{OS}$ - weight value for the overshoot

$w_{Ts}$ - weight value for the settling time

$P_i$ - Fitness probability of $i^{th}$ chromosome

$C_i$ - Cumulative probability of $i^{th}$ chromosome

$R_i$ - Random number of $i^{th}$ chromosome

$Chromosome_i$ - $i^{th}$ chromosome in a population

$t_{max}$ - maximum iteration number

$t$ - current iteration number

$\omega_{max}$ - Maximum values of inertia weight

$\omega_{min}$ - Minimum values of inertia weight
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CHAPTER 1

INTRODUCTION

1.1 Research Background

Recently, many researchers have implemented active safety systems with a variety of controllers to improve the handling and stability performances of a vehicle. Active safety systems, specifically in lateral control are capable to improve the vehicle’s stability and enhance comfort. Besides, it also manages to avoid any unexpected changes occurring in a vehicle’s dynamics response to the driver’s steer input. One of the examples of an active safety system is active front steering system (AFS). Figure 1.1 illustrates the basic diagram of an active vehicle dynamics control system. By applying an active control system, it decreases the driver’s workload so that the driver can use her/his skills during normal driving conditions to control a vehicle in an emergency situation.

In controlling a vehicle handling system, the driver serves as a major controller to control the vehicle’s dynamic behaviour through three control inputs provided in the vehicle which are the throttle, brake pedals and steering wheel. Throttle and brake pedals are known to control the longitudinal motion for forward speed and acceleration, respectively. The steering wheel is used by the driver to control the lateral motion or the direction of the vehicle. Hence, lateral motion is a major interest to be studied and analysed in this project. The driver’s steering input will be the main component to be examined in detail. Basically, there are two main tasks for the driver in order to control the steering wheel, which are the path following task and stabilisation due to any disturbance (Ackermann, 1990). The task
of path following needs the driver to apply steering angles consistently, following the desired path. Meanwhile for stabilisation, the driver must compensate for any deviation from the desired path by providing extra or less steering angle to neutralize the effect of deviation. This can happen under untypical situations, for example, any objects such as an animal, a human or other vehicles which suddenly appear ahead and lead to dangerous driving situations. Moreover, external disturbances such as crosswind could become additional distractions in driving. Thus, vehicle handling behaviour becomes highly unpredictable and could lead to unsafe conditions.

![Disturbance](image)

**Figure 1.1** Active vehicle dynamics control diagram

In AFS system, the important vehicle parameters that can improve handling stability performance is the yaw rate. Vehicles without a proper yaw rate control could lose precision in driving, especially in severe cornering manoeuvres. More importantly, the yaw rate needs to follow the desired yaw rate preference to ensure that the system is able to produce satisfactory results in terms of transient and steady state performance characteristics. Hence, a specific controller is needed for AFS system to meet these characteristics such as fast response and small overshoot. The implementation of AFS with composite nonlinear feedback (CNF) to control vehicle
handling and stability systems is significant due to its advantage in improving the transient performance. This is because CNF is designed such that the closed loop system has desired performances such as fast response and small overshoot (Chen and Weiyao, 2007). CNF has also been implemented in the AFS system as reported in Hassan (2013) and the results showed that CNF was able to improve the yaw rate of vehicles in maintaining stability performance.

However, in the CNF controller, there are a few parameters in CNF control law that must be optimized in order to obtain the optimal performance response. These parameters consist of linear feedback gain and nonlinear gain parameters of the CNF control law. In order to find all these parameters, an optimization algorithm is necessary to be applied, rather than using the trial and error method. By utilizing an optimization algorithm, it could reduce the computational complexity of the optimization process. A result of poor output response is due to improper technique used to optimize the controller. A lot of work was done using the trial and error method which is not practical to be applied and requires extra time to determine the optimal values of those parameters. Besides, the results obtained are also not guaranteed, as the parameters are not precisely determined. This problem could be solved by using an optimization algorithm that manages to capture all possible optimal points by using its special capability of the designed algorithm. Furthermore, an optimization algorithm with the multi-objective approach will ensure that the system achieves all the desired requirements, especially in meeting more than one objective function.

1.2 Problem Statement

A fast response and small overshoot are desirable in the target tracking control problems (Chen and Weiyao, 2007). In general, fast response results in a large overshoot (Chen and Weiyao, 2007). For a high performance system, it should settle fast without any overshoot.
The CNF controller has advantages in producing a fast response and eliminating overshoot of the system (Chen et al., 2003). However, in CNF control law, the linear feedback gain and nonlinear gain parameters are the important parameters that could affect the performance of output response. An artificial intelligence method can be applied to select the optimal values for all these parameters. Hence, the trial and error process can be eliminated and optimal parameters can be designed and selected based on the desired design criteria. Regarding the design criteria, an optimal CNF is designed based on the transient and steady state performance of the output response. Specifically, those parameters in CNF control law will be optimized based on the overshoot, settling time and steady state error to find the minimal error between the actual and desired response to produce a good system performance. By the implementation of a multi-objective approach, all the objective functions can be computed together in one optimization algorithm. The application of this investigation is implemented on the AFS system.

1.3 Research Objectives

The objectives of the study are defined as follows:

1. To obtain the optimal values of linear and nonlinear gain parameters in CNF control by using multi-objective optimization algorithms called multi-objective particle swarm optimization (MOPSO) and multi-objective genetic algorithm (MOGA).
2. To investigate the effectiveness of MOPSO and MOGA in CNF for the application of the AFS system.

1.4 Research Contributions

The significant contributions of this research are
1. Optimal algorithms for tuning CNF parameters to achieve a better AFS system.

2. An active steering system with the optimal CNF controller to ease drivers’ effort in handling and stabilizing vehicles.

1.5 Research Scopes

This thesis focuses on the optimization method in order to enhance the performance of CNF controller by using a multi-objective optimization approach. The scopes of the overall project are listed as:

i. A 7-DOF nonlinear two track vehicle model is implemented for the evaluation of optimal controller performance and constructed using Matlab/Simulink software.

ii. A mathematical model of a linearized 2-DOF single track model is derived and used for the controller design.

iii. The CNF controller is implemented to the AFS system only to improve vehicles’ steering response, with steerability as a control objective.

iv. The model is a time invariant system. The uncertainties occurring in the system is due to external disturbance.

1.6 Research Methodology

This section presents information on the research methods applied throughout the project. The main topics involved in the research methods are the implementations of vehicle modelling system, active front steering system, controller, and optimization algorithm. Figure 1.2 shows the flowchart of the overall process.
The research started with the physics fundamental law that comprises the vehicle body system and tyre dynamics in order to build a whole body with a certain number of DOF. Body dynamics with certain DOF must be constructed based on some assumptions in accordance with the given control strategy. The vehicle model...
utilized to evaluate control performance is a two track nonlinear vehicle model. Besides that, this model is simplified into a bicycle model (single track model) for the purpose of controller design. In order to design the tyre dynamics, the Magic Formula (Pacejka, 2002) has been used for the nonlinear tyre characteristic. Other than that, the vehicle’s condition in certain situations such as understeer and oversteer are studied and analysed to investigate the main reasons that may lead to accidents. This is important as the application conducted in the project is related to the active safety system. A lot of manoeuvre tests can be used, such as J-turn, lane change, fishhook and many more. It depends on the aim of the control strategy. In this project, the J-turn has been chosen because it represents an avoidance manoeuvre. The evaluation of transient and steady state properties can also be performed.

AFS is an active steering system that is specifically designed to control a vehicle’s handling system. Hence, the main component in this system is the steering wheel that is used to control the lateral motion of a vehicle. The important parameters needed to control lateral motion are the yaw rate and side slip angle. A CNF controller is utilized for the AFS system in order to control the handling performance by producing a corrective steer angle to the steering wheel’s angle set by the driver. Hence, the yaw rate and side slip angle of the vehicle can be controlled and the vehicle can have a good handling performance.

In CNF, there are certain parameters that has to be estimated in order to yield an optimal output response for the system. These parameters can be tuned easily by using an intelligence algorithm. In designing the optimization algorithm, the strategies involved must be constructed first in the form of a flowchart. Based on the flowchart, all main steps can be clearly assigned, especially when doing algorithm programming in the software. Furthermore, for the optimization problem, the tuning parameters must satisfy all limitations provided in CNF control law. This is essential in order to specify the search space area that has the most possibility in finding the optimal point.
1.7 Structure of Thesis

Chapter 2 presents literature studies on ASC, vehicle dynamics model and CNF controller. The studies reviewed comprise of the design background and existing tuning methods. Besides that, the effectiveness of using the swarm intelligent approach is also discussed. Chapter 3 explains the vehicle model that will be used for the AFS system. The 2-DOF single track vehicle model and the 7-DOF nonlinear two track vehicle model are constructed. In Chapter 4, a thorough design of CNF control law is presented which consists of linear and nonlinear feedback law methods. Besides that, the reference model used in this project and the control objective for the design of the AFS controller are presented. Chapter 5 presents the proposed multi-objective optimization approach for the CNF controller. The multi-objective optimization problem is applied in these two algorithms called the Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). Chapter 6 presents the results and discussions based on the optimal CNF performance achieved through the optimization approaches of MOPSO and MOGA. Lastly, the overall conclusions are stated and some recommendations for future implementation are discussed in Chapter 7.
REFERENCES


