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

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Specially dedicated to *my beloved family*

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# ABSTRACT

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

Tujuan utama dalam kawalan pengendalian sesebuah kenderaan adalah untuk memastikan kenderaan dapat mengikuti jalan yang diberikan dengan baik. Kadar rewang kenderaan mesti dikawal dalam usaha mencapai satu kawalan kenderaan yang baik. Dalam tesis ini, teknik-teknik Pengawal Maklum Balas Komposit Tidak Linear (CNF) yang optimum dicadangkan untuk aplikasi Sistem Stereng Hadapan Aktif (AFS) bagi memperbaiki kadar rewang kenderaan. Model kenderaan yang tidak linear dengan 7 darjah kebebasan (DOF) telah digunakan untuk pengesahan mutu prestasi pengawal CNF. Model ini juga dimudahkan menjadi model basikal dengan 2 DOF untuk diguna pakai dalam mereka bentuk pengawal CNF. Bagi reka bentuk pengawal CNF yang optimum, pemilihan parameter-parameter gandaan linear dan tidak linear yang optimum adalah penting untuk menghasilkan tindak balas sistem yang baik. Algoritma-algoritma pengoptimuman telah digunakan untuk mengurangkan kerumitan dalam pemilihan parameter-parameter yang terbaik. Maka, Objektif Berganda Pengoptimuman Kawanan Zarah (MOPSO) dan Objektif Berganda Pengoptimuman Algoritma Genetik (MOGA) dicadangkan untuk menghasilkan CNF yang optimum. Bagi tujuan perbandingan dan pengesahan terhadap kedua-dua kaedah optimum ini, kaedah penalaan manual telah dilaksanakan. Hasilnya, keseluruhan prestasi untuk kadar rewang kenderaan telah bertambah baik dengan kadar 98 peratus penyusutan kesilapan. Dengan ini, pengawalan pengendalian kereta dapat ditingkatkan dan kereta dapat bergerak dengan selamat tanpa terpesong keluar daripada jalan yang dikehendaki.

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| | | |
|---|---|---|
| CNF | - | Composite Nonlinear Feedback |
| AFS | - | Active Front Steering |
| DOF | - | Degree of Freedom |
| MOPSO | - | Multi-objective Particle Swarm Optimization |
| MOGA | - | Multi-objective Genetic Algorithm |
| TS | - | Settling Time |
| OS | - | Overshoot |
| SSE | - | Steady State Error |
| SISO | - | Single Input Single Output |
| MIMO | - | Multiple Input Multiple Output |
| LQR | - | Linear Quadratic Regulator |
| IAE | - | Integral Absolute of Error |
| ITAE | - | Integral of Time Multiplied Absolute Error |
| DC | - | Direct Current |
| PSO | - | Particle Swarm Optimization |
| MOOP | - | Multiple Objective Optimization Problem |
| GA | - | Genetic Algorithm |
| EA | - | Evolutionary Algorithm |
| ASC | - | Active Steering Control |
| A4WS | - | Active Four Wheel Steering |
| ARS | - | Active Rear Steering |
| ABS | - | Anti Lock Braking System |
| TCS | - | Traction Control System |
| LWS | - | Linear Weight Summation |

# 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 |
| ϒ and γ | - | Nonlinear gain parameters |
| $\mu$ | - | Road adhesion coefficient |

| | | |
|---|---|---|
| $\rho$ | - | Nonlinear function of CNF |
| $\varepsilon$ | - | Different between min and max fitness value in the iteration |
| $\omega_I$ | - | 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 |
| $\dot{\psi}_d$ | - | 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 |
| $\omega_{I_{max}}$ | - | Maximum values of inertia weight |
| $\omega_{I_{min}}$ | - | 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.

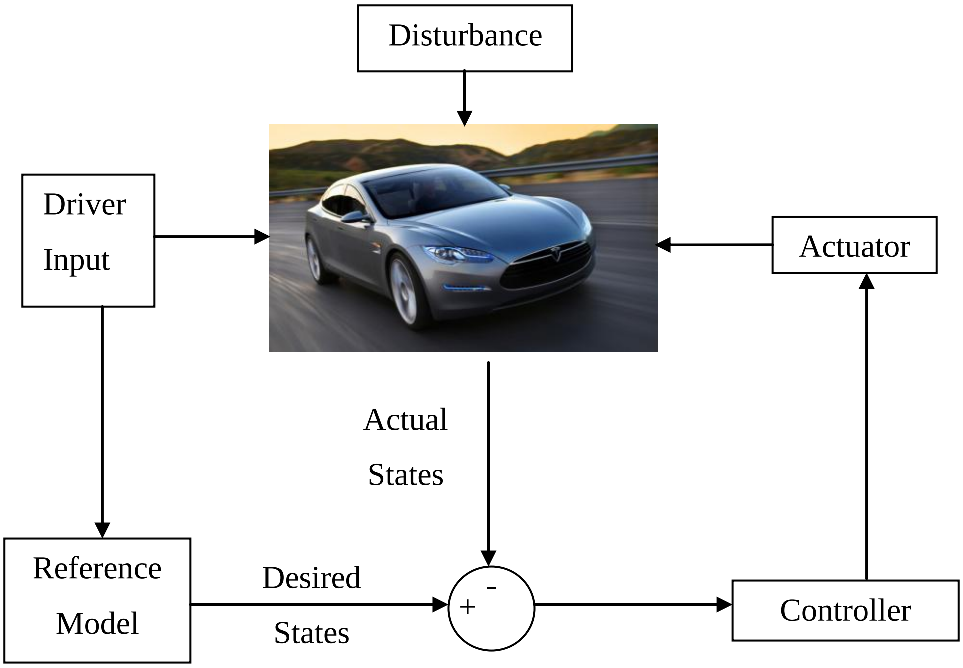


**Figure 1.1** Active vehicle dynamics control diagram

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.

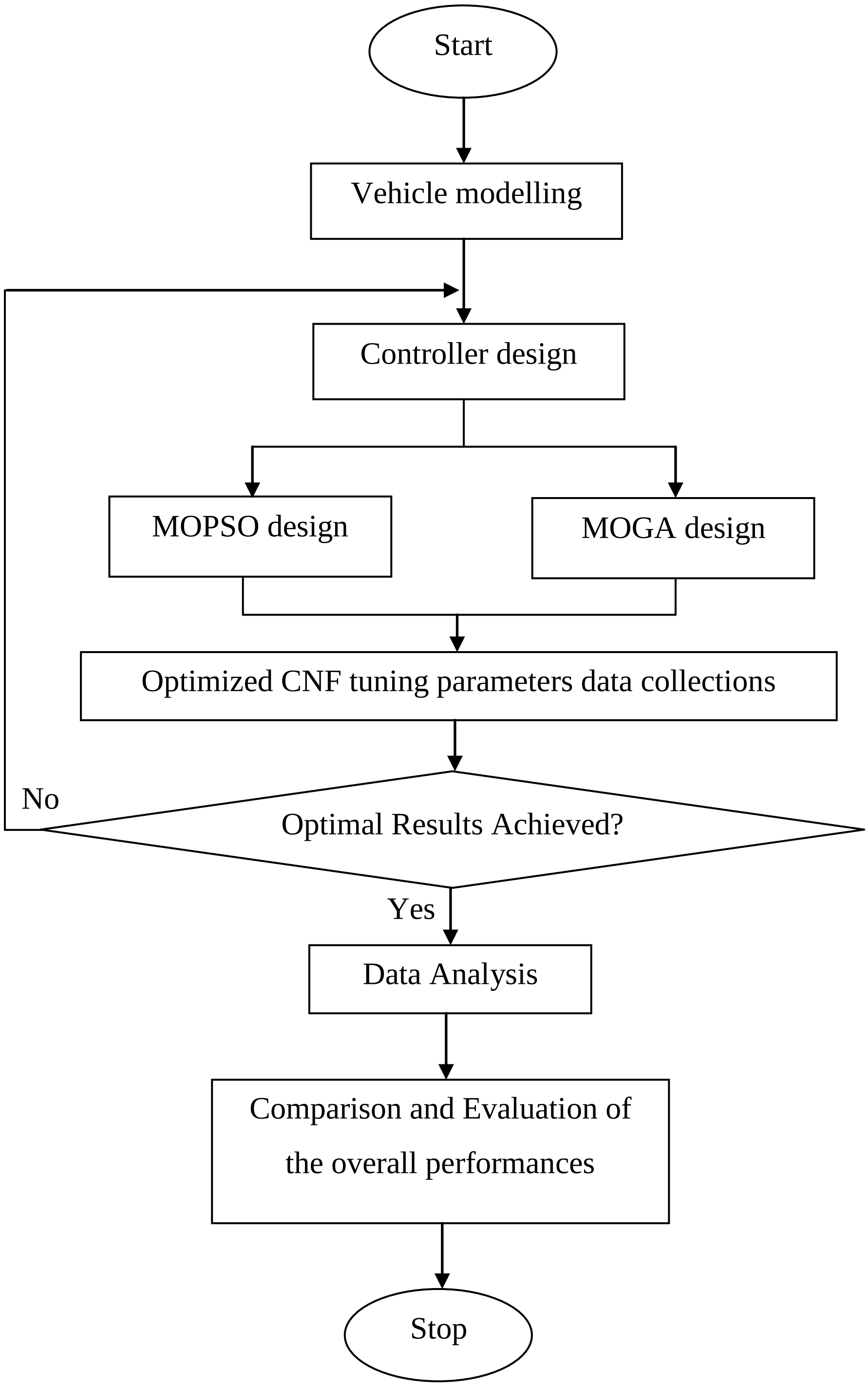


**Figure 1.2** Research methodology flowchart

The research started with the physic 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 over-steer 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

Ackermann, J. (1990). Robust car steering by yaw rate control. *Proceedings of the 1990 29th IEEE Conference on Decision and Control*. 5-7 Dec. 2033-2034.

Adel, T., and Abdelkader, C. (2013). A particle swarm optimization approach for optimum design of pid controller for nonlinear systems. *Proceedings of the 2013 International Conference on Electrical Engineering and Software Applications (ICEESA)*. 21-23 March. 1-4.

Adham, A. A. J., and Tahar, R. B. M. (2012). Enhancing efficiency of automobile assembly line using the fuzzy logical and multi-objective genetic algorithm. *Proceedings of the 2012 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*. 10-15 June. 1-7.

Aijun, H., and Baozhan, L. (2010). Study on mixed robust control for integrated active front steering and direct yaw moment. *Proceedings of the 2010 International Conference on Mechatronics and Automation (ICMA)*. 4-7 August. 29-33.

Aijun, H., and Fuying, H. (2011). Variable structure control for active front steering and direct yaw moment. *Proceedings of the 2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC)*. 8-10 August. 3587-3590.

Arai, K., Kapoor, S., and Bhatia, R. (2014). *Intelligent systems in science and information 2014* (Vol. 591): Springer.

Aripin, M. K., Sam, Y. M., Kumeresan, A. D., Peng, K., Hasan, M., and Ismail, M. (2013). A yaw rate tracking control of active front steering system using composite nonlinear feedback *Asiasim 2013*. (231-242): Springer Berlin Heidelberg.

Baltar, A. M. (2007). *Use of multi-objective particle swarm optimization in water resources management.* Thesis, Ph.D. Colorado State University. Ann Arbor.

Bandyopadhyay, B., Deepak, F., and Kim, K.-S. (2009). Integral sliding mode based composite nonlinear feedback control *Sliding mode control using novel sliding surfaces*. (83-95): Springer Berlin Heidelberg.

Başlamişli, S. Ç., Köse, İ. E., and Anlaç, G. (2010). Handling stability improvement through robust active front steering and active differential control. *Vehicle System Dynamics*. 49 (5), 657-683.

Beraud, B., Steyer, J. P., Lemoine, C., Latrille, E., Manic, G., and Printemps-Vacquier, C. (2007). Towards a global multi objective optimization of wastewater treatment plant based on modeling and genetic algorithms. *Water Science and Technology*. 56 (9), 109-116.

Bergh, F. V. D. (2002). *An analysis of particle swarm optimizers*. Thesis, University of Pretoria

Bin, L., and Fan, Y. (2009). Optimal model following control of four-wheel active steering vehicle. *Proceedings of the 2009 International Conference on Information and Automation (ICIA '09)*. 22-24 June. 881-886.

Castillo, O., and Melin, P. (2014). A review on interval type-2 fuzzy logic applications in intelligent control. *Journal of Information Sciences*. 279, 615-631.

Chen, Lee, T. H., Kemao, P., and Venkataramanan, V. (2003). Composite nonlinear feedback control for linear systems with input saturation: Theory and an application. *IEEE Transactions on Automatic Control*. 48 (3), 427-439.

Chen, Q., Li, L., Pei, L., and Du, P. (2014). Modeling and composite nonlinear feedback control of voice coil motor in high precision positioning system. *Proceedings of the 2014 17th International Conference on Electrical Machines and Systems (ICEMS)*. 22-25 October. 2242-2247.

Chen., Lee, T. H., and Venkataramanan, V. (2006). *Hard disk servo system* (2 ed.). London, U.K.: Springer-Verlag.

Chen., and Weiyao, L. (2007). On improving transient performance in tracking control for a class of nonlinear discrete-time systems with input saturation. *IEEE Transactions on Automatic Control*. 52 (7), 1307-1313.

Coello, C. (2001). A short tutorial on evolutionary multiobjective optimization. In E. Zitzler, L. Thiele, K. Deb, C. Coello Coello & D. Corne (Eds.), *Evolutionary multi-criterion optimization*. (21-40): Springer Berlin Heidelberg.

Di Cairano, S., Tseng, H. E., Bernardini, D., and Bemporad, A. (2013). Vehicle yaw stability control by coordinated active front steering and differential braking in the tire sideslip angles domain. *IEEE Transactions on Control Systems Technology*. 21 (4), 1236-1248.

Domínguez, M., Fernández-Cardador, A., Cucala, A. P., Gonsalves, T., and Fernández, A. (2014). Multi objective particle swarm optimization algorithm for the design of efficient ato speed profiles in metro lines. *Engineering Applications of Artificial Intelligence*. 29, 43-53.

Dorigo, M., Maniezzo, V., and Colorni, A. (1996). Ant system: Optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and Cybernetics*. 26 (1), 29-41.

Eberhart, R. C., and Shi, Y. (2000). Comparing inertia weights and constriction factors in particle swarm optimization. *Proceedings of the 2000 Evolutionary Computation, 2000. Proceedings of the 2000 Congress on*, 84-88.

Em Poh, P., Hudha, K., Harun, M. H. B., and Jamaluddin, H. (2010). Hardware-in-the-loop simulation of automatic steering control: Outer-loop and inner-loop control design. *Proceedings of the 2010 Control Automation Robotics & Vision (ICARCV), 2010 11th International Conference on*. 7-10 Dec. 2010. 964-969.

Engelbrecht, A. P. (2007). References *Computational intelligence*. (487-549): John Wiley & Sons, Ltd.

Eren, S., Pahlevaninezhad, M., Bakhshai, A., and Jain, P. K. (2013). Composite nonlinear feedback control and stability analysis of a grid-connected voltage source inverter with lcl filter. *IEEE Transactions on Industrial Electronics*. 60 (11), 5059-5074.

Falcone, P., Borrelli, F., Tseng, H. E., Asgari, J., and Hrovat, D. (2008). Linear time-varying model predictive control and its application to active steering systems: Stability analysis and experimental validation. *International Journal of Robust and Nonlinear Control*. 18 (8), 862-875.

Farahani, M. (2014). Design of pid controller using multi-objective genetic algorithm for load frequency control in interconnected power systems. *Journal of Intelligent and Fuzzy Systems*. 27 (2), 709-716.

Fdhila, R., Hamdani, T. M., and Alimi, A. M. (2010). A new hierarchical approach for mopso based on dynamic subdivision of the population using pareto fronts.

*Proceedings of the 2010 IEEE International Conference on Systems Man and Cybernetics (SMC)*. 10-13 Oct. 2010. 947-954.

Forkenbrock, G. J., Garrott, W. R., Heitz, M., and O'Harra, B. C. (2003). An experimental examination of j-turn and fishhook maneuvers that may induce on-road, untripped, light vehicle rollover. 3-6 March.

Fujimoto, H., Takahashi, N., Tsumasaka, A., and Noguchi, T. (2006). Motion control of electric vehicle based on cornering stiffness estimation with yaw-moment observer. *Proceedings of the 2006 9th IEEE International Workshop on Advanced Motion Control*. 0-0 0. 206-211.

Ghamisi, P., and Benediktsson, J. A. (2015). Feature selection based on hybridization of genetic algorithm and particle swarm optimization. *IEEE Geoscience and Remote Sensing Letters*. 12 (2), 309-313.

Gillespie, T. D. (1992). *Fundamentals of vehicle dynamics*: Society of Automotive Engineers Inc.

Goldberg, D. E. (1989). Genetic algorithms in search, optimization, and machine learning

Graham, J. K. (2005). *Combining particle swarm optimization and genetic programming utilizing lisp.* Thesis, M.S. Utah State University. Ann Arbor.

Guoqing, C., and Yanwei, H. (2014). Position control of permanent magnet synchronous motor via composite nonlinear feedback. *Proceedings of the 2014 Control Conference (CCC), 2014 33rd Chinese*. 28-30 July 2014. 7864-7868.

Guowei, C., Chen, B. M., Kemao, P., Miaobo, D., and Lee, T. H. (2008). Modeling and control of the yaw channel of a uav helicopter. *IEEE Transactions on Industrial Electronics*. 55 (9), 3426-3434.

Guoyang, C., and Kemao, P. (2007). Robust composite nonlinear feedback control with application to a servo positioning system. *IEEE Transactions on Industrial Electronics*. 54 (2), 1132-1140.

Guoyang, C., Kemao, P., Chen, B. M., and Lee, T. H. (2006). Generalized composite nonlinear feedback control technique to track non-step references. *Proceedings of the 2006 Intelligent Control and Automation, 2006. WCICA 2006. The Sixth World Congress on*. 0-0 0. 234-238.

Guoyang, C., Kemao, P., Chen, B. M., and Lee, T. H. (2007). Improving transient performance in tracking general references using composite nonlinear feedback control and its application to high-speed table positioning mechanism. *Industrial Electronics, IEEE Transactions on*. 54 (2), 1039-1051.

Guoyang, C., and Wenguang, J. (2006). Parameterized design of nonlinear feedback controllers for servo positioning systems. *Journal of Systems Engineering and Electronics*. 17 (3), 593-599.

Hamzah, N., Aripin, M. K., Sam, Y. M., Selamat, H., and Ismail, M. F. (2013). Vehicle stability enhancement based on second order sliding mode control. *Proceedings of the 2013 Proceedings - 2012 IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2012*, 580-585.

Hamzah, N., Sam, Y. M., Selamat, H., Aripin, M. K., and Ismail, M. F. (2012). Yaw stability improvement for four-wheel active steering vehicle using sliding mode control. *Proceedings of the 2012 IEEE 8th International Colloquium on Signal Processing and its Applications (CSPA)*. 23-25 March 2012. 127-132.

Hassan, M. H. C. (2013). *An active front steering control based on composite nonlinear feedback for vehicle yaw stability system.* Thesis, Master Universiti Teknologi Malaysia. Malaysia.

Hazra, J., and Sinha, A. K. (2007). Congestion management using multiobjective particle swarm optimization. *IEEE Transactions on Power Systems*. 22 (4), 1726-1734.

He, J. (2005). *Integrated vehicle dynamics control using active steering, driveline and braking.* Thesis, Ph.D. University of Leeds (United Kingdom). Ann Arbor.

He, J., Crolla, D. A., Levesley, M. C., and Manning, W. J. (2004). Integrated active steering and variable torque distribution control for improving vehicle handling and stability.

Holland, J. H. (1992). Adaptation in natural and artificial systems

Ismail, Sam, Y. M., Sudin, S., Peng, K., and Khairi Aripin, M. (2014). Modeling and control of a nonlinear active suspension using multi-body dynamics system software. *Jurnal Teknologi (Sciences and Engineering)*. 67 (1), 35-46.

Ismail, F. S. (2011). *Self organizing genetic algorithm for multi-objective optimization problems.* Thesis, Universiti Teknologi Malaysia

Ismail, M. F., Sam, Y. M., Peng, K., Aripin, M. K., and Hamzah, N. (2012). A control performance of linear model and the macpherson model for active suspension system using composite nonlinear feedback. *Proceedings of the 2012*

*Control System, Computing and Engineering (ICCSCE), 2012 IEEE International Conference on*. 23-25 Nov. 2012. 227-233.

Jaafar, H. I., Sulaima, M. F., Mohamed, Z., and Jamian, J. J. (2013). Optimal pid controller parameters for nonlinear gantry crane system via mopso technique. *Proceedings of the 2013 IEEE Conference on Sustainable Utilization and Development in Engineering and Technology (CSUDET)*. May 30 2013-June 1 2013. 86-91.

Jamian, J. J., Mustafa, M. W., Mokhlis, H., and Baharudin, M. a. (2012). Implementation of evolutionary particle swarm optimization in distributed generation sizing. *International journal of electrical and computer engineering (IJECE)*. 2, 137-146.

Jazar, R. N. (2008). *Vehicle dynamics: Theory and application*: Springer-Verlag New York.

Jin, N. (2008). *Particle swarm optimization in engineering electromagnetics.* Thesis, Ph.D. University of California, Los Angeles. Ann Arbor.

Jinzhong, L., Jintao, Z., Jiewu, X., Manhua, L., and Changxin, L. (2009). Research on grid workflow scheduling based on mopso algorithm. *Proceedings of the 2009 WRI Global Congress on Intelligent Systems (GCIS '09)* 19-21 May 2009. 199-203.

Kanghyun, N., Fujimoto, H., and Hori, Y. (2014). Advanced motion control of electric vehicles based on robust lateral tire force control via active front steering. *IEEE/ASME Transactions on Mechatronics*. 19 (1), 289-299.

Kanghyun, N., Sehoon, O., and Hori, Y. (2010). Robust yaw stability control for electric vehicles based on active steering control. *Proceedings of the 2010 IEEE Vehicle Power and Propulsion Conference (VPPC)*. 1-3 Sept. 2010. 1-5.

Kemao, P., Chen, B. M., Guoyang, C., and Lee, T. H. (2004). Friction and nonlinearity compensation in hard disk drive servo systems using robust composite nonlinear feedback control. *Proceedings of the 2004 Control Conference, 2004. 5th Asian*. 20-23 July 2004. 58-63 Vol.51.

Kemao, P., Chen, B. M., Guoyang, C., and Lee, T. H. (2005). Modeling and compensation of nonlinearities and friction in a micro hard disk drive servo system with nonlinear feedback control. *IEEE Transactions on Control Systems Technology*. 13 (5), 708-721.

Kennedy, J., and Eberhart, R. (1995). Particle swarm optimization. *Proceedings of the 1995 IEEE International Conference on Neural Networks*. Nov/Dec 1995. 1942-1948.

Khedr, S. F. M., Ammar, M. E., and Hassan, M. A. M. (2013). Multi objective genetic algorithm controller's tuning for non-linear automatic voltage regulator. *Proceedings of the 2013 International Conference on Control, Decision and Information Technologies (CoDIT)*. 6-8 May 2013. 857-863.

Kiencke, U., and Nielsen, L. (2010). *Automotive control systems for engine, driveline and vehicle* (second ed.): Springer-Verlag Berlin Heidelberg.

Kitamura, S., Mori, K., Shindo, S., Izui, Y., and Ozaki, Y. (2005). Multiobjective energy management system using modified mopso. *Proceedings of the 2005 IEEE International Conference on Systems, Man and Cybernetics*. 10-12 Oct. 2005. 3497-3503.

Le, W., Fang, F., and Yang, S. (2014). Adaptive backstepping-based composite nonlinear feedback water level control for the nuclear u-tube steam generator. *IEEE Transactions on Control Systems Technology*. 22 (1), 369-377.

Li, G., Zong, C.-f., Zheng, H.-y., and Hong, W. (2011). Vehicle active front steering and yaw moment integrated control. *Proceedings of the 2011 International Conference onTransportation, Mechanical, and Electrical Engineering (TMEE)*. 16-18 Dec. 2011. 787-790.

Lin, Z., Pachter, M., and Banda, S. (1998). Toward improvement of tracking performance nonlinear feedback for linear systems. *International Journal of Control*. 70 (1), 1-11.

Ltaief, A., Taieb, A., and Châari, A. (2013). Pid-pso control for takagi-sugeno fuzzy model. *Proceedings of the 2013 International Conference on Control, Decision and Information Technologies (CoDIT)*, 86-91.

Ma, D., Cao, Y., and Fan, D. (2010). Design and implementation of an electro-optical tracking servo system via composite nonlinear control approach. *Proceedings of the 2010 Intelligent Computation Technology and Automation (ICICTA), 2010 International Conference on*. 11-12 May 2010. 1139-1142.

Mahmoodabadi, M. J., Taherkhorsandi, M., and Bagheri, A. (2014). Optimal robust sliding mode tracking control of a biped robot based on ingenious multi-objective pso. *Neurocomputing*. 124, 194-209.

Marino, R., Scalzi, S., Orlando, G., and Netto, M. (2009). A nested pid steering control for lane keeping in vision based autonomous vehicles. *Proceedings of the 2009 American Control Conference (ACC '09)*. 10-12 June 2009. 2885-2890.

Mirzaei, M. (2010). A new strategy for minimum usage of external yaw moment in vehicle dynamic control system. *Transportation Research Part C: Emerging Technologies*. 18 (2), 213-224.

Ng, S. T., Chong, C. K., Choon, Y. W., Chai, L. E., Deris, S., Illias, R. M., et al. (2013). Estimating kinetic parameters for essential amino acid production in arabidopsis thaliana by using particle swarm optimization. *Jurnal Teknologi (Sciences and Engineering)*. 64 (1), 73-80.

Ohara, H., and Murakami, T. (2004). Tracking control of a compact electrical vehicle trailer based on equivalent dynamics model. *Proceedings of the 2004 The 8th IEEE International Workshop on Advanced Motion Control (AMC '04)*. 25-28 March 2004. 183-186.

Ohara, H., and Murakami, T. (2008). A stability control by active angle control of front-wheel in a vehicle system. *IEEE Transactions on Industrial Electronics*. 55 (3), 1277-1285.

Pacejka, H. B. (2002). *Tyre and vehicle dynamics*. Oxford: Butterworth-Heinemann.

Pang, X., and Rybarcyk, L. J. (2014). Multi-objective particle swarm and genetic algorithm for the optimization of the lansce linac operation. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 741, 124-129.

Parrott, D., and Li, X. (2004). A particle swarm model for tracking multiple peaks in a dynamic environment using speciation. *Paper presented at the Evolutionary Computation CEC2004*. 98 - 103.

Qian, D., Yi, J., Liu, X., and Li, X. (2010). Ga-based fuzzy sliding mode governor for hydro-turbine. *Paper presented at the Intelligent control and information processing*. Chine, 382 - 387.

Qiang, L., Guobiao, S., Jie, W., and Yi, L. (2009). Yaw stability control of active front steering with fractional-order pid controller. *Proceedings of the 2009 International Conference on Information Engineering and Computer Science (ICIECS)*. 19-20 Dec. 2009. 1-4.

Qiang, L., Guobiao, S., Yi, L., and Jie, W. (2010). Yaw rate control of active front steering based on fuzzy-logic controller. *Proceedings of the 2010 Second*

*International Workshop on Education Technology and Computer Science (ETCS)*. 6-7 March 2010. 125-128.

Rajamani, R. (2012). *Vehicle dynamics and control* (Second ed.): Springer.

Sahnehsaraei, M. A., Mahmoodabadi, M. J., and Taherkhorsandi, M. (2013). Optimal robust decoupled sliding mode control based on a multi-objective genetic algorithm. *Proceedings of the 2013 IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA)*. 19-21 June 2013. 1-5.

Sanaye, S., and Hajabdollahi, H. (2015). Thermo-economic optimization of solar cchp using both genetic and particle swarm algorithms. *Transactions of the ASME Journal of Solar Energy Engineering*. 137 (1).

Saoudi, K., Harmas, M. N., and Bouchama, Z. (2014). Design of a robust and indirect adaptive fuzzy sliding mode power system stabilizer using particle swarm optimization. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*. 36 (15), 1670-1680.

Seungkyu, O., Hyoungsoo, K., and Jinhee, J. (2009). Proposals for improvement of afs system using hil simulation. *Proceedings of the 2009 ICCAS-SICE, 2009*. 18-21 Aug. 2009. 555-559.

Sharaf, A. M., and El-Gammal, A. A. A. (2009). A novel discrete multi-objective particle swarm optimization (mopso) of optimal shunt power filter. *Proceedings of the 2009 IEEE/PES Power Systems Conference and Exposition (PSCE '09)*. 15-18 March 2009. 1-7.

Solmaz, S., Corless, M., and Shorten, R. (2007). A methodology for the design of robust rollover prevention controllers for automotive vehicles: Part 2-active steering. *Proceedings of the 2007 American Control Conference (ACC '07)*. 9-13 July 2007. 1606-1611.

Stephant, J., Charara, A., and Meizel, D. (2004). Virtual sensor: Application to vehicle sideslip angle and transversal forces. *IEEE Transactions on Industrial Electronics*. 51 (2), 278-289.

Taeib, A., Ltaief, A., and Chaari, A. (2013). Pid control based on modified particle swarm optimization for nonlinear process. *Proceedings of the 2013 World Congress on Computer and Information Technology (WCCIT 2013),*

Talukder, S. (2011). *Mathematical modelling and applications of particle swarm optimization.* Thesis, Blekinge Institute of Technology. Sweden.

Tang, X.-H., Chang, X., and Fang, Z.-F. (2012). A multi-objective genetic algorithm based on simulated annealing. *Proceedings of the 2012 Fourth International Conference on Multimedia Information Networking and Security (MINES)*. 2-4 Nov. 2012. 413-416.

Turner, M. C., Postlethwaite, I., and Walker, D. J. (2000). Non-linear tracking control for multivariable constrained input linear systems. *International Journal of Control*. 73 (12), 1160-1172.

Venkataramanan, V., Kemao, P., Chen, B. M., and Lee, T. H. (2003). Discrete-time composite nonlinear feedback control with an application in design of a hard disk drive servo system. *IEEE Transactions on Control Systems Technology*. 11 (1), 16-23.

Wai, R. J., Lin, Y. F., and Chuang, K. L. (2014). Total sliding-mode-based particle swarm optimization control for linear induction motor. *Journal of the Franklin Institute*. 351 (5), 2755-2780.

Wei, L., and Fang, F. (2012). Adaptive backstepping composite nonlinear control for utility boiler-turbine units. *Proceedings of the 2012 Control Conference (CCC), 2012 31st Chinese*. 25-27 July 2012. 6900-6906.

Weiyao, L., and Chen, B. M. (2007). On selection of nonlinear gain in composite nonlinear feedback control for a class of linear systems. *Proceedings of the 2007 46th IEEE Conference on Decision and Control*. 12-14 Dec. 2007. 1198-1203.

Weiyao, L., Thum, C. K., and Chen, B. M. (2010). A hard-disk-drive servo system design using composite nonlinear-feedback control with optimal nonlinear gain tuning methods. *IEEE Transactions on Industrial Electronics*. 57 (5), 1735-1745.

Wu, Y., Song, D., Hou, Z., and Yuan, X. (2007). A fuzzy control method to improve vehicle yaw stability based on integrated yaw moment control and active front steering. *Proceedings of the 2007 International Conference on Mechatronics and Automation (ICMA)*. 5-8 Aug. 2007. 1508-1512.

Yacoub, A. H. Y., Buyamin, S., and Wahab, N. A. (2011). Integral time absolute error minimization for pi controller on coupled-tank liquid level control system based on stochastic search techniques. *Jurnal Teknologi (Sciences and Engineering)*. 54, 381-402.

Yen, G. G., and Wen-Fung, L. (2009). Dynamic multiple swarms in multiobjective particle swarm optimization. *IEEE Transactions on Systems, Man and Cybernetics*. 39 (4), 890-911.

Ying, G., Lei, S., and Pingjing, Y. (2000). Study on multi-objective genetic algorithm. *Proceedings of the 2000 Proceedings of the 3rd World Congress on Intelligent Control and Automation*. 2000. 646-650 vol.641.

Yingjie, H., Chen, B. M., and Chao, W. (2003). Composite nonlinear control with state and measurement feedback for general multivariable systems with input saturation. *Proceedings of the 2003 42nd IEEE Conference on Decision and Control*. 9-12 Dec. 2003. 4469-4474.

Yuhui, S., and Eberhart, R. C. (1999). Empirical study of particle swarm optimization. *Proceedings of the 1999 Congress on Evolutionary Computation (CEC 99)* 1999. 1950 Vol. 1953.

Yujia, W., Xue, Y., and Chaogang, Y. (2011). Multiobjective particle swarm optimization based on preference ordering optimality criterion. *Proceedings of the 2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC)*. 8-10 Aug. 2011. 4088-4090.

Zhang, J. Y., Kim, J. W., Lee, K. B., and Kim, Y. B. (2008). Development of an active front steering (afs) system with qft control. *International Journal of Automotive Technology*. 9 (6), 695-702.

Zhao, S. Z., Iruthayarajan, M. W., Baskar, S., and Suganthan, P. N. (2011). Multi-objective robust pid controller tuning using two lbests multi-objective particle swarm optimization. *Information Sciences*. 181 (16), 3323-3335.

Zheng, Z., Sun, W., Chen, H., and Yeow, J. T. W. (2014). Integral sliding mode based optimal composite nonlinear feedback control for a class of systems. *Control Theory and Technology*. 12 (2), 139-146.