STATE AND PARAMETER ESTIMATOR DESIGN FOR CONTROL OF VEHICLE SUSPENSION SYSTEM

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To my family, especially my wife for the nice cuppas of latte and espressos every now and then. Forget bout putting you steady. You may marry someone else. Just a waste of space.

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ABSTRACT

Modern vehicle stability and navigational systems are mostly designed using inaccurate bicycle models to approximate the full-car models. This results in incomplete models with various unknown parameters and states being neglected in the controller and navigation system design processes. Earlier estimation algorithms using the bicycle models are simpler but have many undefined parameters and states that are crucial for proper stability control. For existing vehicle navigation systems, direct line of sight for satellite access is required but is limited in modern cities with many high-rise buildings and therefore, an inertial navigation system utilizing accurate estimation of these parameters is needed. The aim of this research is to estimate the parameters and states of the vehicle more accurately using a multivariable and complex full-car model. This will enhance the stability of the vehicle and can provide a more consistent navigation. The proposed method uses the kinematics estimation model formulated using special orthogonal SO_3 group to design estimators for vehicles velocity, attitude and suspension states. These estimators are used to modify the existing antilock braking system (ABS) scheme by incorporating the dynamic velocity estimation to reduce the stopping distance. Meanwhile the semi-active suspension system includes suspension velocity and displacement states to reduce the suspension displacements and velocities. They are also used in the direct yaw control (DYC) scheme to include mass and attitude changes to reduce the lateral velocity and slips. Meanwhile in the navigation system, the 3-dimensional attitude effects can improve the position accuracy. With these approaches, the stopping distance in the ABS has been reduced by one meter and the vehicle states required for inertial navigation are more accurately estimated. The results for high speed lane change test indicate that the vehicle is 34% more stable and 16% better ride comfort on rough terrains due to the proposed DYC and the active suspension system control. The methods proposed can be utilized in future autonomous car design. This research is therefore an important contribution in shaping the future of vehicle driving, comfort and stability.

ABSTRAK

Sistem keseimbangan dan navigasi pengemudian kenderaan moden kebanyakannya direka dengan menggunakan model dua tayar yang tidak tepat untuk menganggarkan model-model kereta-penuh. Ini akan menghasilkan model yang tidak lengkap dengan pelbagai parameter dan keadaan yang tidak diketahui diabaikan di dalam proses merekabentuk pengawal dan sistem navigasi. Algoritma awal penganggaran menggunakan model dua tayar adalah lebih ringkas tetapi mempunyai banyak parameter dan keadaan yang penting yang tidak ditakrifkan untuk kawalan kestabilan yang sepatutnya. Untuk sistem navigasi kenderaan yang sedia ada, garis penglihatan langsung untuk capaian satelit diperlukan tetapi ia terhad di dalam bandar yang mempunyai banyak bangunan tinggi. Oleh itu, sistem pengemudian inersia yang memberikan anggaran lebih tepat bagi parameter-parameter tersebut adalah diperlukan. Matlamat penyelidikan ini adalah untuk menganggarkan parameter-parameter dan keadaan kenderaan tersebut secara lebih tepat dengan menggunakan model berbilang pemboleh ubah dan kereta-penuh. Ini akan menambahkan kestabilan kenderaan dan memberikan pengemudian yang lebih konsisten. Kaedah yang dicadangkan menggunakan model penganggaran kinematik yang dirumuskan menggunakan kumpulan SO_3 ortogonal khas untuk penganggaran halaju, sikap dan keadaan ampaian kenderaan. Penganggar ini digunakan untuk mengubah skema sistem brek antikunci (ABS) dengan menggabungkan penganggar dinamik halaju untuk mengurangkan jarak berhenti. Sementara itu, sistem ampaian separa aktif dengan menyertakan halaju dan sesaran digunakan bagi mengurangkan sesaran dan halaju ampaian. Ia juga digunakan dalam skema pengawalan rewang terus (DYC) dengan menyertakan perubahan jisim dan sikap untuk mengurangkan halaju dan gelincir sisi. Dalam sistem navigasi pula, kesan sikap ini boleh meningkatkan kejituan posisi. Dengan pendekatan ini, jarak berhenti dalam ABS telah dikurangkan sebanyak 1 meter dan keadaan kenderaan diperlukan untuk navigasi inersia dianggarkan dengan lebih tepat. Keputusan bagi perubahan lorong ketika halaju tinggi ialah 34% lebih seimbang dan 16% lebih selesa di atas permukaan kasar hasil dari DYC dan pengawalan sistem ampaian aktif yang dicadangkan. Kaedah yang dicadangkan boleh digunakan dalam merekabentuk kenderaan autonomi pada masa hadapan. Penyelidikan ini adalah sumbangan penting dalam membentuk masa depan pemanduan, keselesaan, dan keutuhan kestabilan.

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LIST OF ABBREVIATIONS

BM – Bicycle Model

CG – Center of gravity

$diag$ – Diagonal matrix, a matrix with all non parameters defined in the diagonal column only

$DMHE$ – Direct Moving Horizon Estimator

EKF – Extended Kalman Filter

$EKBF$ – Extended Kalman Bucy Filter

EPF – Extended Particle Filter

FCM – Full Car Model

FL – Fuzzy Logic

GPS – Global Positioning System

$GINS$ – Global Inertial Navigational System

$GLONASS$ – Global Navigation and Observatory System

INS – Inertial Navigation System

IMU – Inertial Measurement Unit

KF – Kalman Filter

KM – Kinematics Model

KBF – Kalman Bucy Filter

LMS – Least Mean Square

MR – Magnetorheological

MH – Moving Horizon Estimator

MMS – Multiple model and switching method

NLO – Nonlinear Observer

PF – Particle Filter

RLS	–	Recursive Least Square
$RLSF$	–	Recursive Least Square with Forgetting Factor
$RTLSF$	–	Recursive Time varying Least Square with Forgetting Factor
SDC	–	State Dependent Coefficient Form
$SDRE$	–	State Dependent Ricatti Equation
LQR	–	Linear Quadratic Recursion

LIST OF SYMBOLS

Vehicle Physical Parameters

A_p – Wind Drag Coefficient

e – Lateral Width of the vehicle [m]

f – Frequency of the source

h – Distance of C.G from roll axis [m]

h_{cg} – Height of center of gravity from level ground [m]

I – Moment of Inertia along x,y,z axis[Kgm^2][I_x,I_y,I_z].

l_a – Distance of C.G from front axle [m]

l_b – Distance of C.G from rear axle [m]

l – Wheel Base(a + b) [m]

M – Vehicle Mass [Kg]

M_1 – Roll Compensated Vehicle Mass [Kg]

m – Lower suspension mass [Kg]

$\mathbb{M}$ – Vector of masses [M,m_1,m_2,m_3,m_4]

r_{11} – Longitudinal distance from front left damper to wheel joint [m]

r_{12} – Lateral distance from front left damper to wheel joint [m]

r_{21} – Longitudinal distance from front right damper to wheel joint [m]

r_{22} – Lateral distance from front right damper to wheel joint [m]

r_{31} – Longitudinal distance from rear left damper to wheel joint [m]

r_{32} – Lateral distance from rear left damper to wheel joint [m]

r_{41} – Longitudinal distance from rear left damper to wheel joint [m]

r_{42} – Lateral distance from rear left damper to wheel joint [m]

R_e – Radius of the Earth [m]

R_c – Radius of Curvature during turning [m]

t_f – Distance between front tires [m]

t_r – Distance between rear tires [m]

θ_{bank} – Banking angle of road surface

μ – Nominal friction coefficient of the road surface

Sensor Parameters

A_{NL} – Accelerometer Nonlinearity

aab – Accelerometer beam coefficients[aa_1,ab_1]

a_{bcx} – x-axis accelerometer constant potential for running

a_{brx} – x-axis accelerometer random potential for running

ae_1 – Accelerometer demodulator filter effects

ah_1 – Output filter Coefficient 1/(6.28×50)

aFS – Accelerometer Range Selectable (2g/4g/8g/16g)

A_m – Accelerations measurement Vector[$\mathbf{Ax}$, $\mathbf{Ay}$, $\mathbf{Az}$]

A_{maxGPS} – operational Limits (Acceleration) [g]

A_R – Satellite Received Signal Amplitude

b_{ai} – Accelerometer bias[b_{ax},b_{ay},b_{az}]

b_{ari} – Random bias of accelerometer[b_{arx},b_{ary},b_{arz}]

b_{aci} – Constant Accelerometer bias[b_{acx},b_{acy},b_{acz}]

b_{gci} – Constant Gyro bias[b_{gcx},b_{gcy},b_{gcz}]

b_{gci} – Constant Gyro bias[b_{gcx},b_{gcy},b_{gcz}]

b_{grri} – Random x-axis run-to-run gyro bias[b_{grrx}, b_{grry}, b_{grrz}]

a_{gcbx} – x-axis gyro constant potential for running

a_{grbx} – x-axis gyro random potential for running

δt^i – Residual satellite clock error after performing the corrections

δ_g – Anomalous gravity

$\epsilon(\omega)$ – gyro error noise

$\epsilon(a)$ – Accelerometer error noise

$e_g(t)$ – Error in Gyroscope

f_1 – L1 Band frequency

f_2 – L2 Band frequency

F_{slant} – VCO clock slant correction factor

g_{gbin} – Biasing when the gyroscope is running

gT_{comp} – Gyro Temperature Compensation

G_s – gyro scale factor

gDV_{off} – Gyro Digital Zero Rate Level [dps]

g_{NL} – gyro Non-Linearity [% FS]

g_{ODR} – Gyro rate level change vs Temp [dps/C]

gR_n – Gyro rate Noise Density [dps / $\sqrt{Hz}$]

g_FS – Gyro Range [dps]

GPS_{AC} – GPS Accuracy

h_{maxGPS} – operational Limits (Altitude) [m]

$I^{i}{}_{r}$ – Error due to dispersion atmospheric effects

I_r – Mobile signal recieved signal struength

k_{a1} – Accelerometer amplifier Gain [V/V]

m_{FS} – Magnetometer Range [Gauss]

m_DFS – magnetometer dynamic range [Gauss]

$M^i_{\rho i}$ – Pseudo-range multiple path errors on the L$_i$ pseudo-range measurements[$M^i_{\rho 1}$,$M^i_{\rho 2}$]

M_g – Magnetometer Sensitivity [LSB/Gauss]

M_N – Magnetomter Noise Floor [milli-Gauss]

M_{res} – Magnetometer Resolution in [milli-Gauss/bit]

Np – Pressure Sensor RMS Noise [m]

N – Non-Orthogonalities

$\aleph$ – Sensor and Process random white gaussian noise[$\aleph$,$\wp$]

ω_{gbias} – Process noise driving the gyroscope bias [rad/s][ω_{xbias},ω_{ybias},ω_{zbias}]

ω_{abias} – Process noise driving the accelerometer bias [m/s^2]

Ω – Gyro measurements Vector $[\Omega_x, \Omega_y, \Omega_z]$[radians/s]

ψ_{GPS} – GPS Heading [radians]

θ_{GPS} – GPS Roll [radians]

ψ_m – Magnetometer yaw [radians]

ψ_{INS} – INS yaw [radians]

ψ_{MARG} – MARG yaw [radians]

KF – Magnetometer confidence factor

p_{GPS} – Position measured using GPS

V_{GPS} – Velocity measured using GPS[V_{GPS}^{east}, V_{GPS}^{north}, V_{GPS}^{up}]

P_{AC} – Pressure Sensor Absolute Accuracy Pressure [hPa]

$p_F S$ – Pressure Sensor Resolution [hPa]

PT_{res} – Pressure Sensor Temp Resolution [$^{\circ}C$]

Q_{bias} – Sensor bias covariance

ρ – Pseudorange at position p(x)

σ_{gps} – Standard deviation of GPS noise [radians/Hz]

σ_{accel} – Standard deviation of accelerometer noise [radians/Hz]

σ_{gyro} – Standard deviation of gyro noise [radians/Hz]

σ_N – Random white Gaussian sensor noise density [W/$\sqrt{Hz}$]

σ_{Na} – Random white Gaussian Accelerometer noise density [W/$\sqrt{Hz}$]

σ_{Ng} – Random white Gaussian Gyroscope noise density [W/$\sqrt{Hz}$]

σ_R – Random white Gaussian Process noise density [W/$\sqrt{Hz}$]

S_{gps} – GPS sensitivity [dBm]

S_a – Accelerometer Sensitivity [LSB/g]

S_g – Gyro sensitivity [mdps/digit]

S_2 – Accelerometer frequency sensitivity factor

Sg_{ODR} – Sensivity deration per degrees [mg/deg]

$T^i{}_r$ – Error due to non-dispersion atmospheric effects

τ_{bias} – Markov Time Constant

T_{gps} – Sampling Rate of GPS [s]

T_s – Sampling Rate of Inertial sensors [s]

T_R – Received signal period [s]

v_{gyro} – Gyro sensor noise

v_{accel} – Accelerometer sensor noise

v_{gps} – GPS sensor noise

$v^i{}_{\rho i}$ – random measurement noise on the L_i pseudo-range measurements[$v^i_{\rho 1}$, $v^i_{\rho 2}$]

V_{maxGPS} – operational Limits (Velocity) [m/s]

$V_{\psi_{gps}}$ – standard deviation of GPS heading noise [radians]

$V_{\theta_{gps}}$ – standard deviation of GPS grade noise [radians]

Tire Parameters

α_i – Lateral tire slip angle [radians][α_f,α_r]

κ – Tire slip ratio

C_α – Tire Coefficient along tire slip angle

C_σ – Tire Coefficient along tire density

C_i – Tire Coefficient along longitudinal and lateral axis [C_x,C_y]

C_α – Front and Rear Tire Cornering Stiffness [Nm] [$C_{\alpha f}$, $C_{\alpha r}$]

E – Tire Curvature Factor

γ – slip switching function

ϱ – Lateral Tire Slip Function

K_t – Tire Spring Constant [N/m]

λ – Slip in tire

M_z – Tire Braking Force[N]

S_i – Tire Horizontal and Vertical Shift [S_H, S_v]

T_b – Braking torque [N/m]

T_d – Traction Torque[N/m]

ς – Tire Peak Value

Υ – Tire Stiffness Factor

ϖ – Tire Shape Factor

Wheel Parameters

I_w – Wheel moment of inertia [Kgm/s^2]

J – Tire Horizontal Slip Function

ω_w – Wheel Angular velocity of wheel [rad/s]

R_w – Radius of Wheel [m]

V_w – Wheel Linear Velocity [m/s]

Vehicle Dynamic Parameters

α – Kinematic model based observer design parameter

A_c – Actual linear accelerations vector $[a_x, a_y, a_z]$ [m/s^2]

$\mathbb{A}$ – Attitude Vector [θ,ϕ,ψ][Radians]

β – Sideslip angle [radians]

δ – Steering angle [rad]

δ_c – Steering input from controller for assistance [rad]

δ_{max} – Maximum steering angle [rad]

F_x – Longitudinal Force Component [N]

F_y – Lateral Force Component [N]

F_z – Vertical Force Component [N]

F_ϕ – Force causing vehicle roll [N]

$\hbar$ – Odd submatrix of Rotation Matrix

$\mathbb{J}$ – Cost Function

K_p – Proportional Gain

ω_c – Actual Angular velocity vector $[\omega_x, \omega_y, \omega_z]$[Radians/s]

p – position of the vehicle[x,y,z][m]

θ – Roll angle [radians]

ϕ – Pitch Angle [radians]

ψ – Yaw angle [radians]

$\mathfrak{r}$ – Coefficient of rotation matrix

$\mathbb{R}$ – Rotation Matrix using direction cosines

S – Sliding Surface

τ_δ – Steer system time constant [s]

τ_c – Actuator time constant [s]

τ_{CAN} – Steer system time constant [s]

τ_{I2C} – Steer system time constant [s]

V – Velocity of the vehicle [m/s][V$_x$,V$_y$,V$_z$]

$\mathbb{W}$ – Lyapunov Energy Function

Suspension Physical Parameters

b_ϕ – Damping Coefficient of damper along roll axis [Ns/m][$b_{\phi f}$,$b_{\phi r}$]

B – Vector of Damping Coefficient of the MR Dampers [b$_{0_{FL}}$,b$_{0_{FR}}$,b$_{0_{RL}}$,b$_{0_{RR}}$][Ns/rad]

k_ϕ – Spring Constant along roll axis [N/m][$k_{\phi f}$,$k_{\phi r}$]

K – Vector of spring constants $[k_1, k_2, k_3, k_4]$

$\Re_i$ – Damper Coefficients matrix[$\Re_1$,$\Re_2$,$\Re_3$]

MR Damper

$m\alpha_i$ – Fixed and variable MR fluid factor

A_m – MR damper piston surface area [m^2]

β_m – MR fluid factor

bm_0 – Fixed and variable Bingham damping coefficients [Ns/m][b$_0a$,b$_0b$]

bm_1 – Fixed and variable Hysteresis damping coefficients [Ns/m][b$_1a$,b$_1b$]

η_m – Response time of the MR fluid

γ_m – MR fluid factor

System Matrices

A – State Matrix

A_N – Nominal State Matrix

B – Input State Matrix[B_1, B_2]

B_N – Nominal Input State Matrix

$B(x,t)$ – Nonlinear input state dependent function

C – Output State Matrix

C_N – Nominal Output State Matrix

CCR – Submatrix of the state matrix

χ – Linear and nonlinear composite controller control effort[χ_N, χ_L]

D – Feedforward State Matrix

D_N – Nominal Feedforward State Matrix

$EngineType$ – DOHC DVVT [K3VE]

$f(x,t)$ – Nonlinear system state dependent function

F – Linear substate state matrix in composite control scheme

G – Linear substate input matrix in composite control scheme

Γ – Bias Augmented state matrix

I – Identity Matrix

K_∞ – Measurement error gain Covariance Matrix

$\Im$ – Estimator Gain matrix

KK – Submatrix of the state matrix

$\Omega_\times$ – Special orthogonal rate matrix

O – Zero Matrix

Ψ – Observability Matrix

Π – Bias Augmented input matrix

Φ – Bias Augmented feedforward matrix

P – Covariance Matrix

P_∞ – Steady state kalman error Covariance Matrix

Q – Process Noise Covariance Matrix[Q_i,Q_j]

R – Sensor Noise Covariance Matrix

Θ – Bias Augmented output matrix

Ξ – Controllability Matrix

$u(t)$ – Input vector[u_1,u_2]

$\mathbb{U}$ – Second moment of distance submatrix

$\mathbb{V}$ – First moment of distance submatrix

ξ – Subfunction in sliding mode controller

$x(t)$ – State vector

$y(t)$ – Output vector

y_m – System output measurements vector

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CHAPTER 1

INTRODUCTION

1.1 Background

Since the early 19th century, the cars has passed through a number of improvements (Bevly and Cobb, 2010; Leung *et al.*, 2011; Oh and Choi, 2013; Farrell, 2008). During the early days, clutch system and variable speed gear system was introduced to improve the vehicle handling (Lee *et al.*, 2014; davidL, 2000). Similarly flexible suspension system using spring mass damper system and air filled tires were introduced to improve the ride comfort and long term reliability (Lin and Kanellakopoulos, 1997). These innovations were introduced using bulky mechanical system and conceived on paper using expert knowledge; as there were no means of doing simulations (Stensson *et al.*, 1994; Fallah *et al.*, 2009). Earlier introduction of electromechanical systems in the form of motors for engine starting, encouraged the car engineers to replace the bulky mechanical assemblies with electromechanical systems to reduce weight and improve system performance (Bevly and Cobb, 2010; Farrell, 2008). Most of the earlier electromechanical systems used simple drive-by-wire technology for control. The improvements in digital control theory and microprocessors lead to the use of computer for driver assistance in collision avoiding system, like antilock braking system (ABS), and driver assisting systems, like assisted direct yaw control (DYC) (Jagtman and Wiersma, 2003; Abdulrahim, 2006; Aripin *et al.*, 2014; Suzuki and Takeda, 2016). When designing driver assisted control systems, the focus was mainly on improving the specific component of the car. For example, the automatic transmission system design process was focused on how to change the drive train by including electromechanical valves coupled with a large array of speed sensors and a digital controller for gear shift (Ackermann and Buente, 1997; Lee *et al.*, 2014). It did not include the engine block in the design process to optimize speed and torque. Similarly, the antilock braking system (Khachane and Shrivastav, 2016; Rizzi *et al.*, 2016; Boopathi and Abudhahir, 2016) included the speed obtained from the wheels speed sensors (Madau *et al.*, 1993; Mauer, 1995; Suraci *et al.*, 2006) and did not include the linear accelerations (Bowman and Law, 1993) and angular velocities acting on the vehicle when developing the controller (Peric *et al.*, 2016; Antic *et al.*, 2016; Tang *et al.*, 2016).

The use of electromechanical systems for steering control and navigational system for autonomous driving, is another application which is being developed and refined (Inoue *et al.*, 2016; Zhao *et al.*, 2017). The use of electromechanical systems for direct steering, by using drive-by-wire technology has resulted in the reduction of weight, by reducing heavy mechanical linkages used in the ackermann shaft. It has also resulted in the improvement of the system response time, since direct control with lightening response and very low torque requirements are needed. High torque requirements for turning are common in bigger car, trucks and buses. Excessively high torque requirements had forced the car engineers to design power steering systems. With drive-by-wire technology, power steering systems become irrelevant. The drive-by-wire technology, reduces engine load required by power steering, reduces the weight and converts torque requirements into systems response inputs. The drive-by-wire technology also helps in placing digital controllers to assist the driver by changing the steering input habits of the driver for better control and reduce accident chances (Zhao *et al.*, 2017).

Recently, the drive-by-wire steering system, the automatic cruise control system and the braking system has been integrated with a reliable navigational system to provide the driver with a fully autonomous or partially autonomous system. The aim of this system has been in replacing or comforting the driver by employing various sensors and controllers. These systems have shown promising results under various test conditions. Since these systems have not gone through strenuous testing, they are considered less reliable and their accuracy is also limited. The reliability of these systems has created a sense of uncertainty in the car industry. The industry is also looking for systems which are simpler, since simpler systems are more reliable, have better accuracy and good component and system reliability. A good component reliability can result in higher component service life, which results in lesser maintenance (Dhahri *et al.*, 2012).

When considering the reliability of such systems, the reliability of each component is important. Hence each component is being tested and refined to improve its reliability. The amount of energy consumed is one important factors for judging the reliability of a component, subsystem or system. Some safety and comfort related systems have thus been graded as unreliable or uneconomical. One such system is the active suspension system, which consumes a lot of power and its components have a very limited operational life. They are thus replaced by sub-optimal semi-active suspension systems, which are much more reliable and consume less energy (Chen *et al.*, 2015). Similarly, in semi-autonomous systems, the global positioning system, because of its direct line of sight requirements and limited 3D accuracy, is considered less reliable. There is a need to have navigational systems which can provide reliable accuracy (Wu *et al.*, 2016; Lin *et al.*, 2016; Sarbishei, 2016).

1.2 Problem Statement

The research work aims to address the following problems:

i. Most of the current vehicle stability control systems incorporate essential and measurable parameters and states. Essential but non-measurable parameters are either estimated using complex estimation schemes, or are neglected (Sandu *et al.*, 2010; Crivellaro and Alves, 2006; Qazi *et al.*, 2014). The resultant control scheme is therefore, not robust enough or has high computational cost. Earlier control systems did not use expensive sensors or fast processing computers due to their higher cost (Cherouat *et al.*, 2005; Hac and Simpson, 2000). Current technologies has made the cost of sensors to reduce considerably and high end processors are also becoming cheaper. Therefore parameters and states which were neglected must be included to have more robustness and reliability (Chen *et al.*, 2015; Qazi *et al.*, 2014).

ii. Current navigational systems use direct line of sight satellite communications, which are easily obstructed by underground bridges, sky scrapers and overhead bridges (Cohen *et al.*, 1994; Jwo *et al.*, 2012; Farina *et al.*, 2002). The system has to do a lot of computations to provide accurate 3D positional and velocity accuracy, which makes the system unsuitable for real time navigation (Wu *et al.*, 2016). The inertial navigation system can provide data in real time but does not have high accuracy. It does not require direct line of sight. A fusion of GPS with INS, as used in existing systems, cannot overcome the direct line of sight problem with GPS, without sacrificing the system accuracy. By fusing the inertial navigation system with other sensors to achieve redundancy and by using better algorithms, the INS accuracy can be improved without any direct line of sight problems (Sarbishei, 2016).

iii. Newer and better control schemes must be provided to improve the stability and control of the vehicle to overcome general problems with existing control schemes.

1.3 Objectives

The objectives of this research are listed as follows:

i. To estimate the important states and parameters of vehicles for better control of the vehicle.

ii. To design a simple and robust controller that can improve the longitudinal, lateral and vertical stability of the vehicle.

iii. To develop a navigational system that has no dependency on GPS.

1.4 Scope of Work

The scope of work in this research are

i. The systems were tested using hatchback car model, since it has the ability to loose traction during turning. The real time systems were tested on test car since its structure is hatch back with good weight to torque settings for a utility car.

ii. The important data for states and parameters were obtained using Carsim^{TM} (a nonlinear vehicle simulator) and used for comparison in real time estimation, since those states and parameters were not possible to physically measure them.

iii. The proposed controllers were only simulated with tests in Carsim^{TM}.

iv. The proposed navigational algorithm was tested on practical environment and the attitude states were compared with simulated results obtained from Carsim^{TM} since they were not possible to measure in practical environment.

1.5 Dissertation Organization

The research is divided into several chapters. Following is the list of chapters with a brief detail of each chapters.

i. Chapter 1: This chapter gives a brief introduction of the work. It consists of the problem statement, the objectives of this research, the scope of the work and important contributions of this work.

ii. Chapter 2: This chapter describes the theory of existing systems. This chapter clearly defines the important parameters, models and states used to build the foundation of this research.

iii. Chapter 3: This chapter briefly describes the literature review of existing systems. It revisits certain models to introduce important missing parameters. It also revisits the existing observers and controllers to suggest improvements and new control and estimation algorithms.

iv. Chapter 4: The proposed changes are discussed with elaborate mathematical justification in this chapter. The method used for testing the proposed changes and its implementation are also discussed. The chapter thus includes the methodology of the proposed works. The proposed changes and the method used to test the changes and evaluate them in comparison to the existing methods is also done in this chapter.

v. Chapter 5: The chapter presents all the test results and provides a comprehensive analysis of each test result, that are compared with existing results. The chapter thus provides the results and analysis of the research.

vi. Chapter 6: This chapter concludes the work done in this research. It gives all the conclusions drawn from the research. Based on the conclusions, it also suggests recommendations for further research.

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