isabe 2019

6th - 8th August 2019
Makassar, Indonesia

The 3rd International Symposium on Agricultural and Biosystems Engineering 2019

Organized by:

UNIVERSITAS HASANUDDIN
DEPT. OF AGRICULTURAL TECHNOLOGY

UNIVERSITAS GADJAH MADA
DEPT. OF AGRICULTURAL & BIOSYSTEMS ENGINEERING

The role of Agricultural and Biosystems Engineering in Sustainable Development Goals 2030: Food, Water, Energy and Environment

Sub Theme

- **Postharvest and food engineering**
- **Energy and agricultural machinery**
- **Land and water resources engineering**
- **Agricultural structures and environmental engineering**
- **Biophysics engineering**
- **Other agricultural and biosystems topics**

Speakers

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Minister of Agriculture of the Republic Indonesia

Invited Speakers :

Prof. Bart Nicolai
Ku Leuven, Belgium

Prof.Armando Apan
University of Southern Queensland, Australia

Prof. Yu Pin Lin
National Taiwan University, Taiwan

Prof. Jong Hoon Chung
Seoul National University, South Korea

Dr. Katharina Keiblinger
University of Natural Resources and Life Sciences, Austria

Dr. Bayu Dwi Apri Nugroho
Dept. Agricultural and Biosystems Engineering
Universitas Gadjah Mada

Proceeding will be published in SCOPUS - indexed publisher

Abstract submission deadline has been EXTENDED

Important Dates

Abstract Submission deadline	April 26th 2019
Early bird registration	May 20th 2019
Full Paper submission deadline	July 5th 2019
Registration	July 8th 2019

Venue

Faculty of Agriculture - Hasanuddin University
Jl. Perintis Kemerdekaan Km. 10, Kampus Unhas Tamalarea
Makassar, South Sulawesi,90245

Registration Fee

Attendee	International Participant	Indonesian Participant
Presenter (Oral + Poster)	USD 200	IDR 2.000.000
Non-Presenter	USD 35	IDR 500.000

Registration

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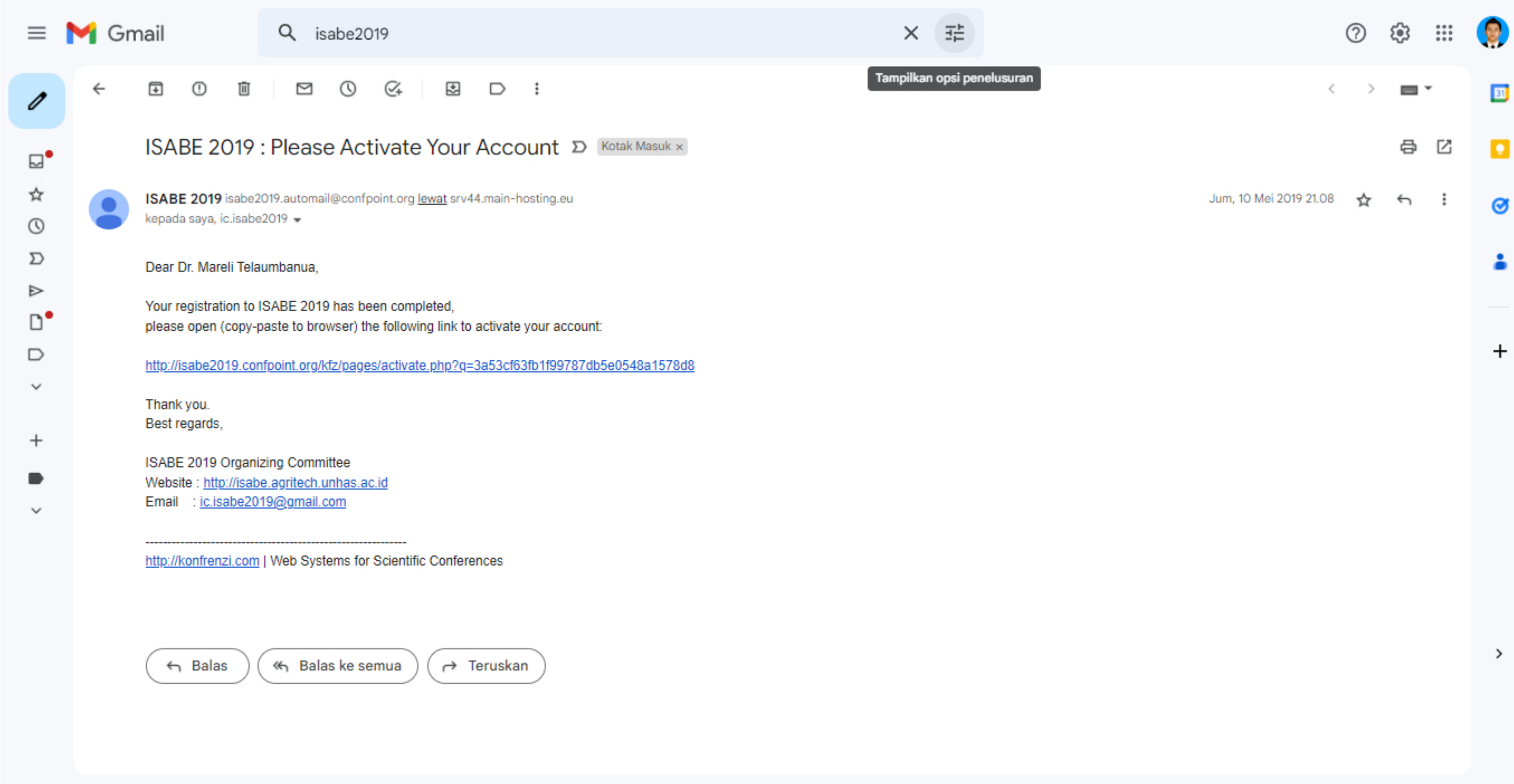
The 3rd International Symposium on Agricultural and Biosystems Engineering 2019

Judul : Simulation of Kalman-Bucy Filter Based Optimal Yaw Rate Control System for Autonomous Tractor

- SUBMIT (10 Mei 2019)
- NASKAH REVISI (22 Juli 2019)
- ACCEPTED PAPER (20 September 2019)
- TERBIT DI IOP (19 November 2019)

Daftar Lampiran



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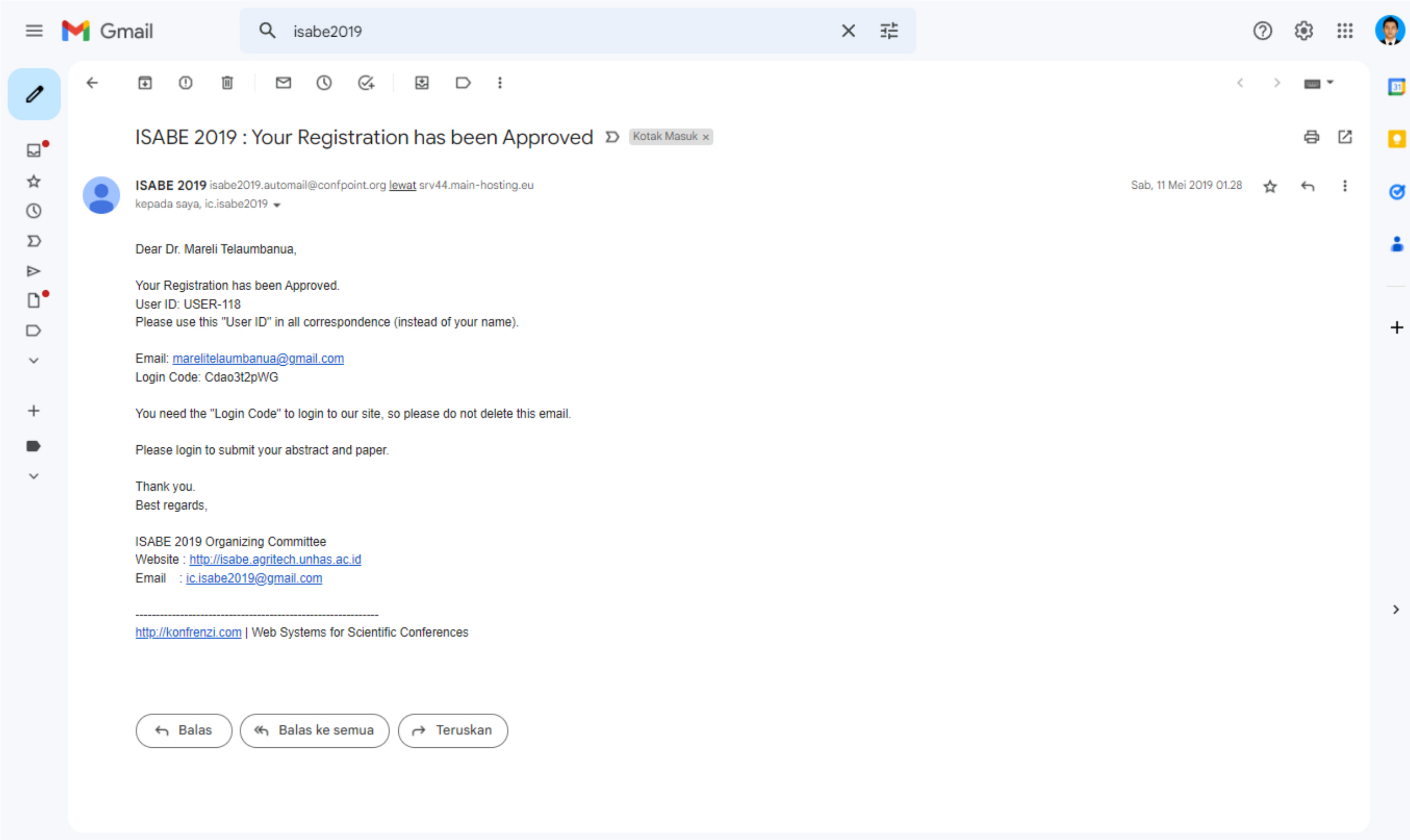
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Request for ISABE full paper submission   Kotak Masuk ×

isabe 2019   Sab, 25 Mei 2019 09.42
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3

Darma -   Sel, 11 Jun 2019 09.49
Dear organizing committee, Thank you for the information. In addition, the full paper submission deadline is 14 June or 15 July 2019? With best regards, Darma,

Y Aris Purwanto <arispurwanto@apps.ipb.ac.id>   Sel, 11 Jun 2019 19.15
kepada Darma, 89chalvia, Aris, Guyup, I, saya, NOORAKMAR, Nofri, Rudiati, WAN, agus.haryanto, amin.geotep, anakemala, andi.raehana.muchlis, andi.rahmayanti28, andre0402, andrew, anomsw, anoraga_584, ansar72, an:

Dear Committee,

It is written in website that the full paper submission deadline will be on July 5, 2019.

Regards,
Aris
IPB University

On Tue, 11 Jun 2019 at 09.49 Darma - <darmabond@gmail.com> wrote:

> Dear organizing committee,
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> With best regards,
>
> Darma,
> Papua University
>
> Pada tanggal Sen, 10 Jun 2019 pukul 06.32 WAN NOR ZANARIAH BT. ZAINOL @ ABDULLAH / BTU <wnzz@upm.edu.my> menulis:
>
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> > Wan Nor Zanariah bt. Zainol @ Abdullah, PhD.
> > Senior lecturer and Industrial training coordinator.
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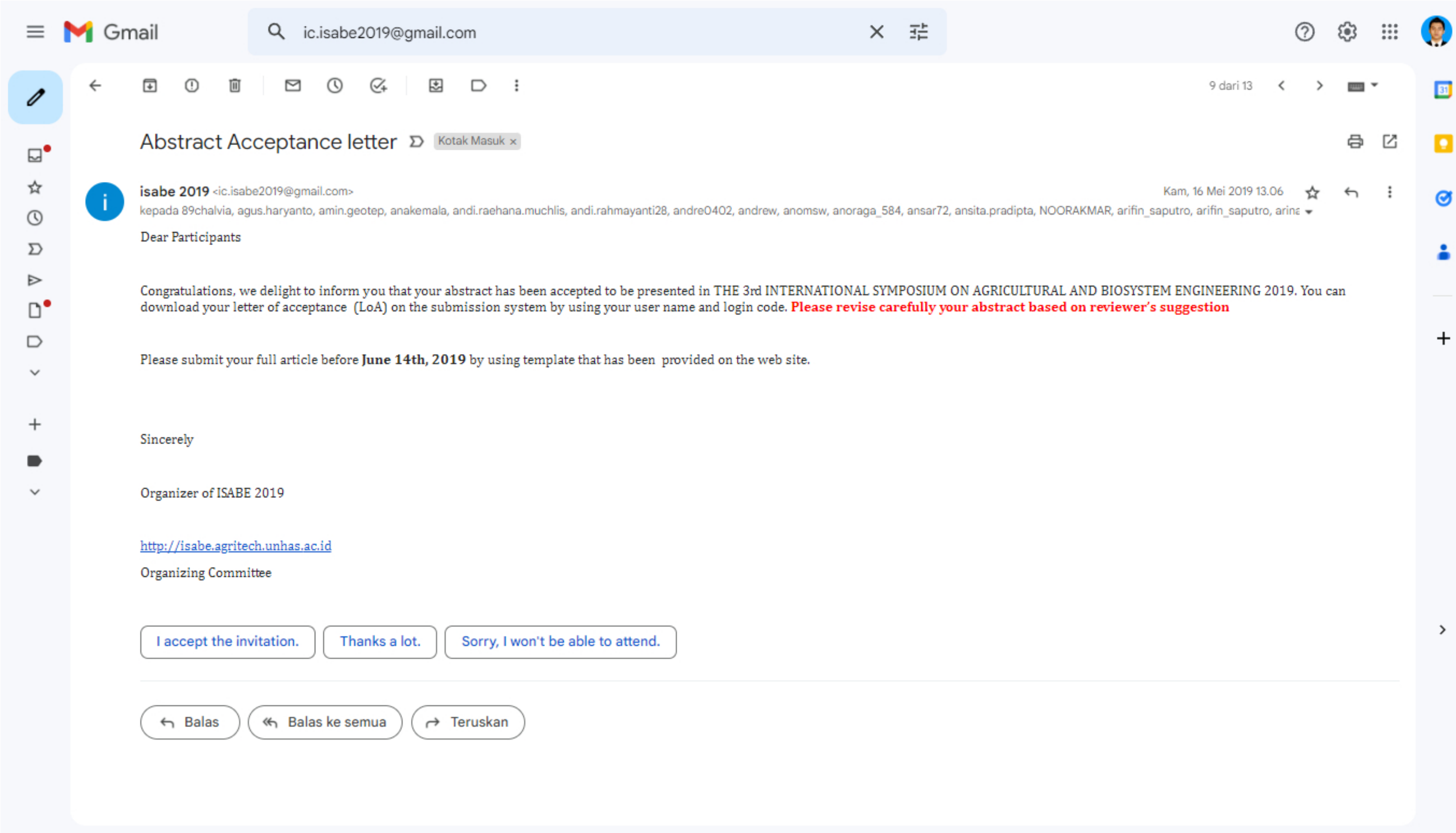

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Abstract Acceptance letter

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Congratulations, we delight to inform you that your abstract has been accepted to be presented in THE 3rd INTERNATIONAL SYMPOSIUM ON AGRICULTURAL AND BIOSYSTEM ENGINEERING 2019. You can download your letter of acceptance (LoA) on the submission system by using your user name and login code. **Please revise carefully your abstract based on reviewer's suggestion**

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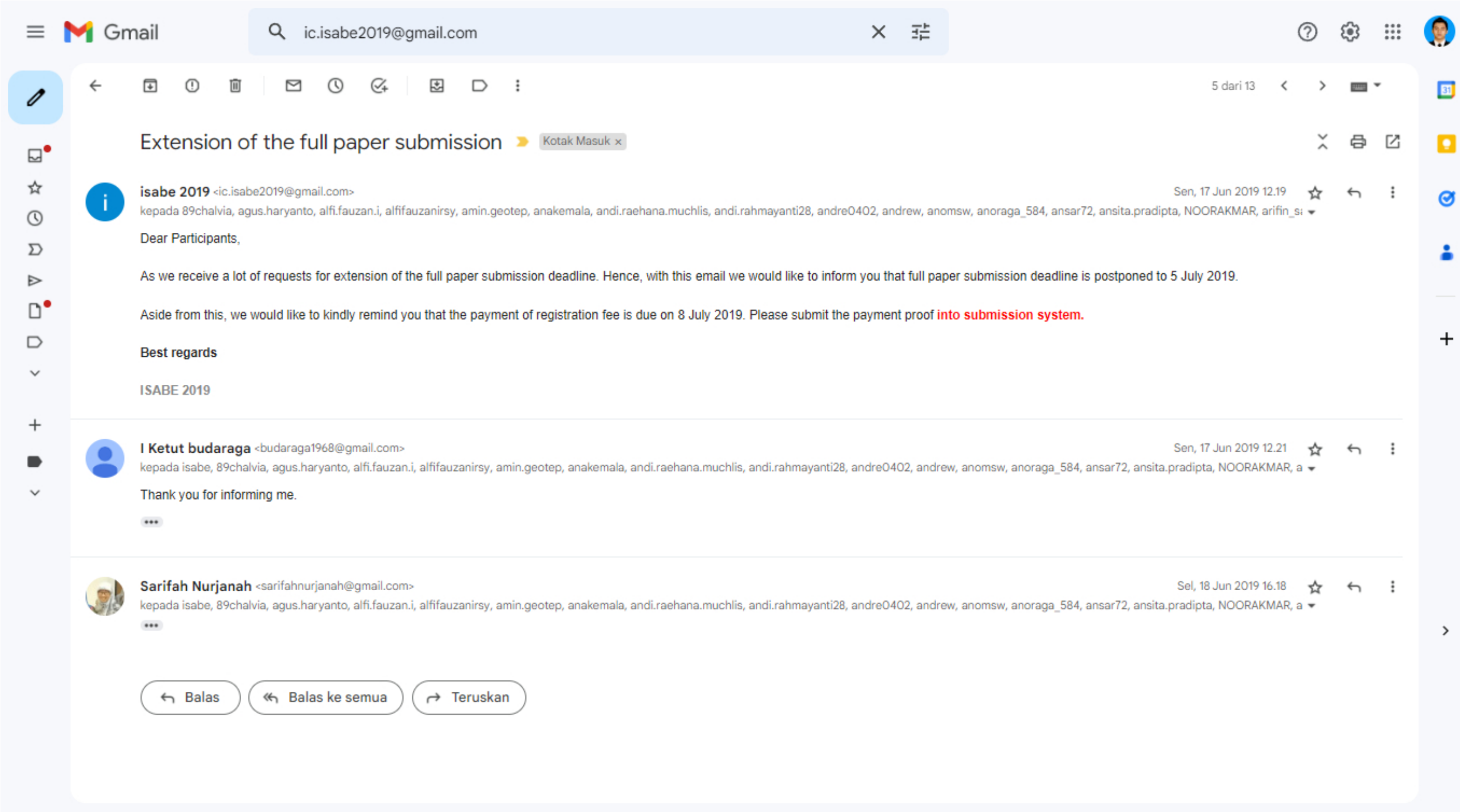

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Extension of the full paper submission   Kotak Masuk ×

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Aside from this, we would like to kindly remind you that the payment of registration fee is due on 8 July 2019. Please submit the payment proof **into submission system.**

Best regards

ISABE 2019

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Thank you for informing me.

Sarifah Nurjanah <sarifahnurjanah@gmail.com>   Sel, 18 Jun 2019 16.18
kepada isabe, 89chalvia, agus.haryanto, alfi.fauzan.i, alfifauzanirsy, amin.geotep, anakemala, andi.raehana.muchlis, andi.rahmayanti28, andre0402, andrew, anomsw, anoraga_584, ansar72, ansita.pradipta, NOORAKMAR, a

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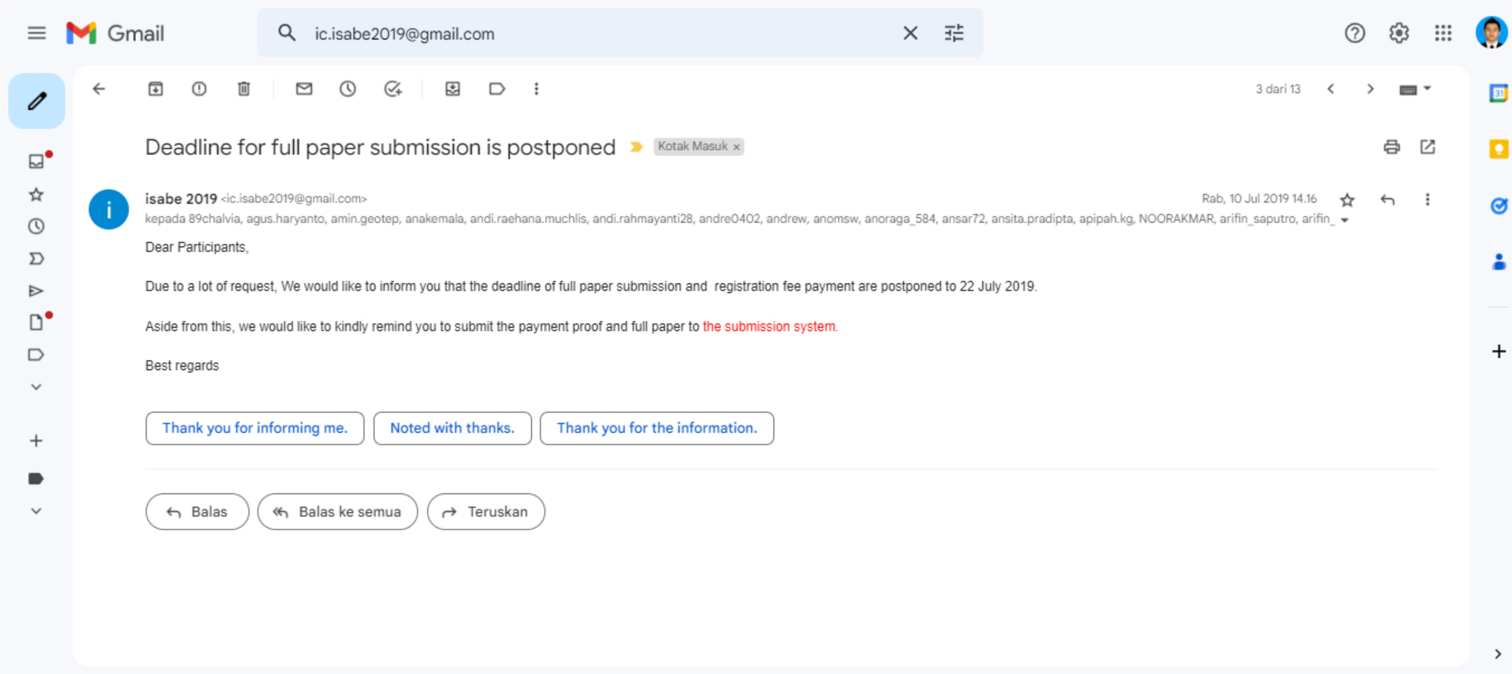

Deadline for full paper submission is postponed

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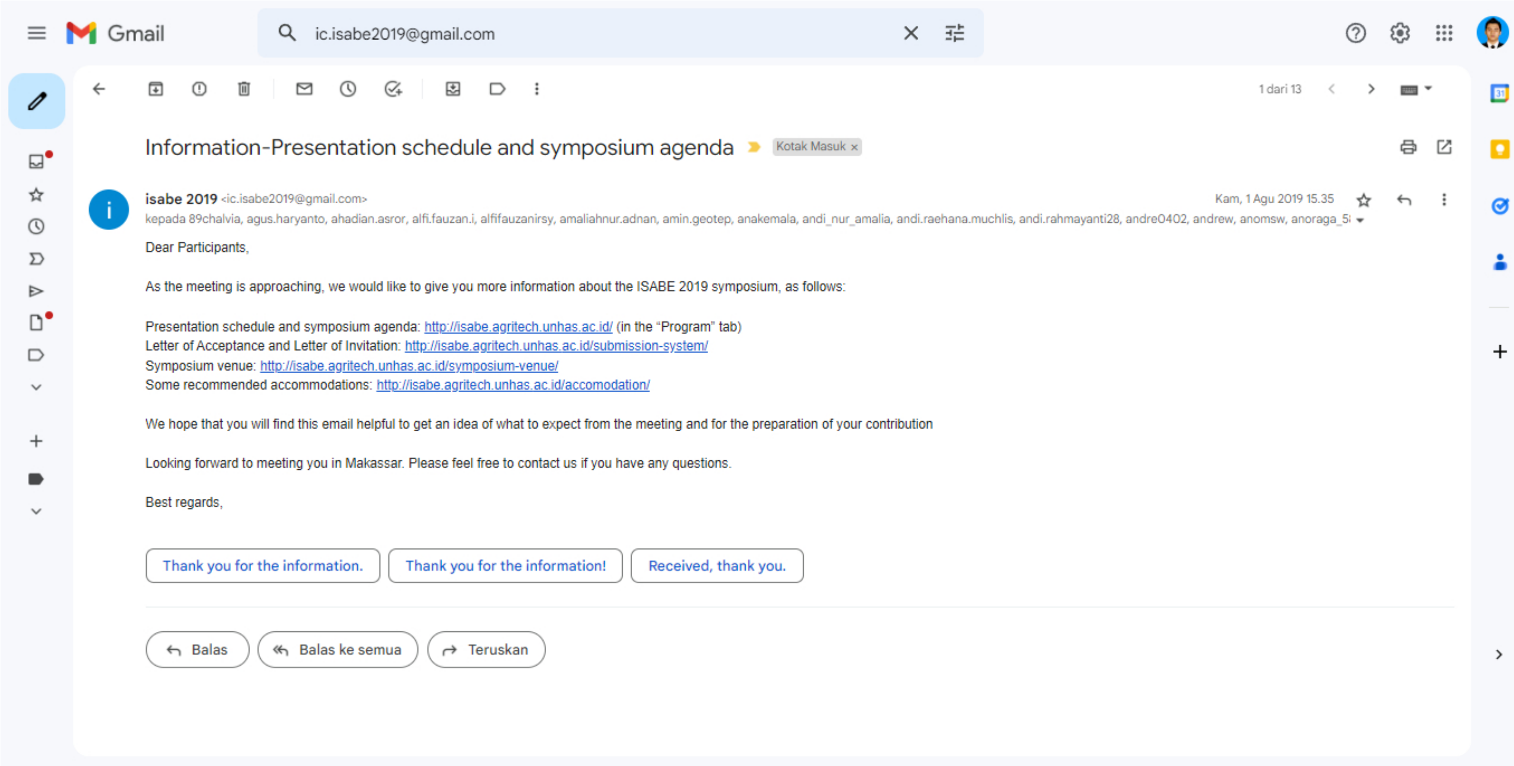
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Information-Presentation schedule and symposium agenda

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isabe 2019 <ic.isabe2019@gmail.com>

Kam, 1 Agu 2019 15.35

kepada 89chalvia, agus.haryanto, ahadian.asror, alfi.fauzan.i, alfifauzanirsy, amaliahnur.adnan, amin.geotep, anakemala, andi_nur_amalia, andi.raehana.muchlis, andi.rahmayanti28, andre0402, andrew, anomsw, anoraga_5i

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Letter of Acceptance and Letter of Invitation: http://isabe.agritech.unhas.ac.id/submission-system/
Symposium venue: http://isabe.agritech.unhas.ac.id/symposium-venue/
Some recommended accommodations: http://isabe.agritech.unhas.ac.id/accomodation/

We hope that you will find this email helpful to get an idea of what to expect from the meeting and for the preparation of your contribution

Looking forward to meeting you in Makassar. Please feel free to contact us if you have any questions.

Best regards,

Thank you for the information. | Thank you for the information! | Received, thank you.

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DRAFT REVISI AKHIR

Simulation Study of Kalman-Bucy filter Based Optimal Yaw Rate Control System for Autonomous Tractor

Widagdo Purbowaskito[1], Mareli Telaumbanua[2]

[1]Department of Industrial Engineering, Universitas Atma Jaya Yogyakarta, Jl. Babarsari, No. 43, Yogyakarta 55281, Indonesia
[2]Deparment of Agricultural Engineering, University of Lampung, Jl. Sumantri Brodjonegoro No. 1, Gedongmeneng, Bandar Lampung 35145, Indonesia

widagdo.purbowaskito@uajy.ac.id, mareli.telaumbanua@fp.unila.ac.id

Abstract. Unstructured agricultural field environment and varying jobs need to be done by a tractor bring the autonomous tractor subjected into the changes of its system dynamics. Due to this condition, development of autonomous tractor yaw rate dynamics control system is a challenging study. An observer based optimal controller is employed to control the autonomous tractor yaw rate dynamics control system in this simulation study. Linear quadratic regulator (LQR) is used as the optimal control algorithm, while the Kalman Bucy filter is used as the state observer of the autonomous tractor. This Kalman based LQR method works by combination of optimization and state estimation approaches. Based on the proposed method, the LQR control algorithm provides satisfactory yaw rate controller results, while the Kalman-Bucy filter provides satisfactory estimation results.

1. Introduction

As the human population continues to grow while the availability space for food production is limited, the efficient usage of the agricultural resources such as biomass and machinery becomes the primary concern. A solution proposed by researchers are smart farming where autonomous tractor is one of the solution to improve the agricultural machinery usage efficiency. Developing an autonomous tractor is a challenging study. Steering and trajectory control become one of the difficulties in the autonomous tractor development. The tractor generally subjected into unstructured agricultural field environments. There are several factors that can be associated with tractor working environment such as soil types, soil irregularities, varying driving speed according to the type of tractor job, and varying implement loads in which tractors have many types of implement depended on which job is tractor operating [1].

Trying to overcome these challenges, a tractor adaptive steering controller is developed. A model reference adaptive control (MRAC) is developed on a tractor to compensate the yaw rate dynamics by using adaptive the feed-forward yaw rate control system [2]. A self-tuning regulator is also developed to control the tractor yaw rate dynamics with variations in speed and implement forces [1]. The method proposed in the study in [1] is developed based on the pole placement control system design with a minimum-degree pole placement. Understanding the yaw rate dynamics model is important so that in such way a controller can be designed properly. Tractor yaw rate dynamics are modelled and identified in order to develop a tractor speed controller [3] and to understand the relationship between tractor and the agricultural field conditions [4]. New approach of tractor yaw rate modelling is proposed by considering also the implement carried by the tractor during the job [1].

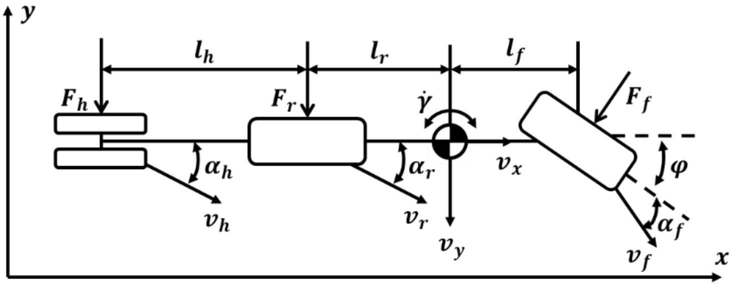

Figure 1. Tractor-implement bicycle free body diagram

A novel approach of yaw rate dynamic control system is proposed by using an optimal control algorithm based on state observer. Linear quadratic regulator is proposed as the optimal control algorithm while the Kalman-Bucy filter is proposed as the autonomous tractor states observer. This paper consists of four more sections. The second section describes the dynamic modelling and open-loop step response analyses. The third section describes the proposed methodology in this study. The fourth section describes the results and discussion. While the fifth section describes the conclusion from this study.

2. Tractor-Implement Analysis

2.1. Tractor Yaw Rate Dynamic Modelling

Understanding the tractor dynamics and kinematics is important to develop a proper controller. The tractor-implement model is shown in Figure 1. Where, $\dot{\gamma}$ is the yaw rate tractor in centre of gravity, φ is the steering angle, α_f is the front wheel slip angle, α_r is the rear wheel slip angle, and α_h is the implement slip angle. l_f and l_r are distances from front and rear axis to the tractor center of gravity respectively, while l_h is distance from rear axis to the implement. F_f, F_r, and F_h are lateral force at front, rear, and implement respectively. In this condition the longitudinal velocity v_x is constant, therefore no longitudinal acceleration a_x in which the longitudinal forces are neglected. Hence, the tractor yaw rate dynamics can be expressed by equation of motions as follows,

$$\sum F_y = m\, a_y \quad (1)$$

$$\sum M_{CG} = I_{zz}\, \ddot{\gamma} \quad (2)$$

As the tractor longitudinal acceleration is null, the lateral acceleration is expressed as,

$$a_y = \dot{v}_y + \dot{\gamma}\, v_x \quad (3)$$

Assuming constant and proportional to the slip angles, the lateral forces are described as follows,

$$F_f = -C_{\alpha f}\alpha_f \quad (4)$$

$$F_r = -C_{\alpha r}\alpha_r \quad (5)$$

$$F_h = -C_{\alpha h}\alpha_h \quad (6)$$

with $C_{\alpha f}$, $C_{\alpha r}$, and $C_{\alpha h}$ are the front wheel, rear wheel, and implement cornering stiffness with values are varying depended on the working environment and the agricultural job performed.

Based on Figure 1 with assumption that the tractor model as a rigid body, the relationship between slip angle, steering angles, yaw rate, and linear velocity can be described as follows,

$$\tan(\alpha_f + \varphi) = \frac{v_y + \dot{\gamma} l_f}{v_x} \quad (7)$$

$$\tan(\alpha_r) = \frac{v_y - \dot{\gamma} l_r}{v_x} \quad (8)$$

$$\tan(\alpha_h) = \frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x} \quad (9)$$

Using small angle approximation, the nonlinear terms of tractor model can be linearized in which the slip angles are described as follows,

$$\alpha_f = \frac{v_y + \dot{\gamma} l_f}{v_x} - \varphi \tag{10}$$

$$\alpha_r = \frac{v_y - \dot{\gamma} l_r}{v_x} \tag{11}$$

$$\alpha_h = \frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x} \tag{12}$$

Substituting Eq. (3) to (6) and Eq. (10) to (12) into Eq. (1) and (2), the equation of motion can be expanded as,

$$m\left(\dot{v}_y + \dot{\gamma}\, v_x\right) = -C_{\alpha f}\left(\frac{v_y + \dot{\gamma} l_f}{v_x} - \varphi\right) - C_{\alpha r}\left(\frac{v_y - \dot{\gamma} l_r}{v_x}\right) - C_{\alpha h}\left(\frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x}\right) \tag{13}$$

$$I_{zz}\,\ddot{\gamma} = -l_f\, C_{\alpha f}\left(\frac{v_y + \dot{\gamma} l_f}{v_x} - \varphi\right) + l_r\, C_{\alpha r}\left(\frac{v_y - \dot{\gamma} l_r}{v_x}\right) + (l_r + l_h)\, C_{\alpha h}\left(\frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x}\right) \tag{14}$$

Based on Eq. (13) and (14) the state space representation can be described as follows,

$$\dot{x}(t) = Ax(t) + Bu(t) + Bw(t) \tag{15}$$

$$y = Cx(t) + Du(t) + v(t) \tag{16}$$

where $w(t)$ is disturbance, $v(t)$ is measurement noise, while $x(t), u(t), A, B, C, D$ are as follows,

$$x(t) = [v_y\,, \dot{\gamma}]^T \tag{17}$$

$$u(t) = \varphi \tag{18}$$

$$A = \begin{bmatrix} \frac{-(C_{\alpha f} + C_{\alpha r} + C_{\alpha h})}{m\, v_x} & \frac{-l_f\, C_{\alpha f} + l_r\, C_{\alpha r} + (l_r + l_h)\, C_{\alpha h}}{m\, v_x} - v_x \\ \frac{-l_f\, C_{\alpha f}\alpha_f + l_r\, C_{\alpha r}\alpha_r + (l_r + l_h)\, C_{\alpha h}\alpha_h}{I_{zz}\, v_x} & \frac{{l_f}^2\, C_{\alpha f} + l_r\, C_{\alpha r} + (l_r + l_h)\, C_{\alpha h}}{I_{zz}\, v_x} \end{bmatrix} \tag{19}$$

$$B = \begin{bmatrix} \frac{C_{\alpha f}}{m} \\ \frac{l_f\, C_{\alpha f}}{I_{zz}} \end{bmatrix} \tag{20}$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{21}$$

$$D = [0] \tag{22}$$

Based on the state space matrix described in Eq. (17) to (22) and by using the Laplace Transform, the tractor steering angle and yaw rate continuous time transfer function can be derived as follows,

$$G(s) = \frac{\dot{\gamma}(s)}{\varphi(s)} = \frac{B_{21}s + (B_{11}A_{21} - B_{21}A_{11})}{s^2 - (A_{11} + A_{22})s + (A_{11}A_{22} - A_{12}A_{21})} \tag{23}$$

where A_{ij} with i = 1,2 and j = 1,2 and B_{mn} with m = 1 and n = 1,2 are the matrix elements of state space matrix in Eq. (19) and (20).

2.2. Open-loop System Step Response Analysis

As it is described before that the autonomous tractor system implement cornering stiffness $C_{\alpha h}$ is changed dynamically according to the working environment and the agricultural job performed, the open-loop autonomous tractor transfer function step response analysis helps to understand how the system behaves according to the condition described. In this simulation, the open-loop step response analysis is done based on the condition that the implement cornering stiffness and tractor longitudinal velocity are varying. By using Eq. (23), the analysis is done by using two longitudinal velocity (tractor working speed) v_x variations such as, 2.5 m/s and 10 m/s representing the low and high working speed, and eight cornering stiffness $C_{\alpha h}$ variations generated by random integer number between 0 to 5000 N/deg representing the variations of tractor agricultural jobs. Approximated geometric and dynamic parameters of a 130-170 HP tractor and implement are used in this simulation shown in Table 1.

Table 1. Tractor-Implement Parameters

Tractor Parameters		
Data	**Value**	**Unit**
l_f	1.57	m
l_r	3.2	m
l_h	2.1	m
m	11000	Kg
I_{zz}	18500*	Kg.m
$C_{\alpha f}$	2400*	N/deg
$C_{\alpha r}$	5000*	N/deg
$C_{\alpha h}$	0-5000	N/deg
v_x	0-10	m/s

*parameters are obtained from [2]

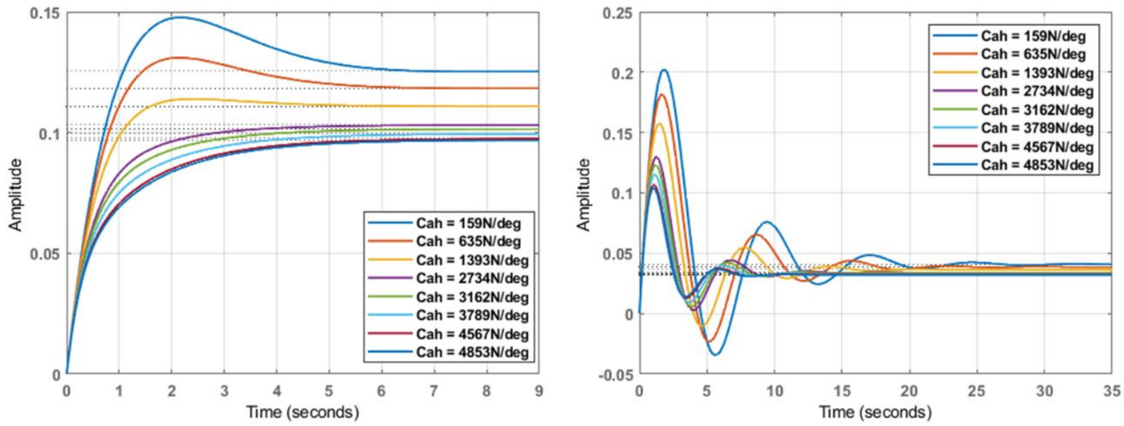

Figure 2. Tractor open-loop system step response: low (left) and high (right) working speed

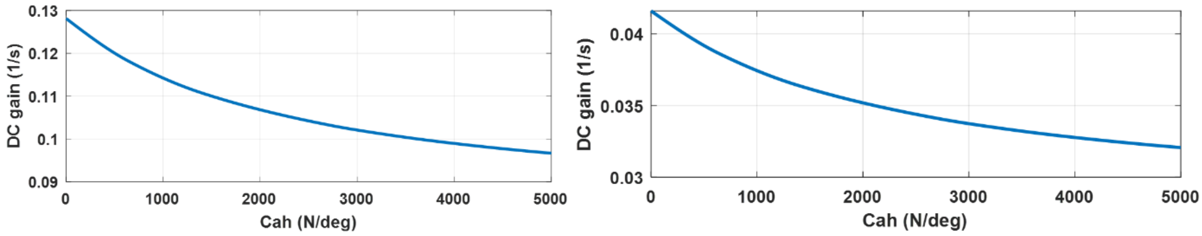

Figure 3. DC gain vs $C_{\alpha h}$: low (left) and high (right) working speed

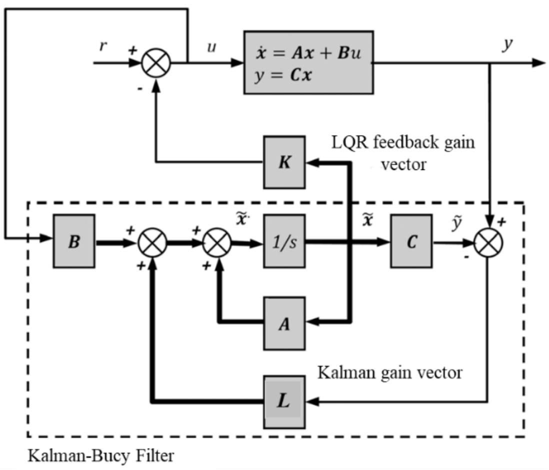

Figure 4. Kalman-Bucy filter based LQR control diagram

Based on the open-loop step response in Figure 2, at both low and high working speed the higher the cornering stiffness the higher the steady state error. While at the high working speed the system transient response showing the high oscillatory behavior. A plot in Figure 3 shows the dc gain of the open-loop system transfer function response with respect to the cornering stiffness variations. According to the Figure 2 and 3, it can be concluded that the yaw rate response is directly affected by the variations of cornering stiffness. This simply can be translated as the tractor maneuverability is affected by the types of working environment and agricultural job performed. Hence, according to the described phenomenon, an optimal control method is proposed with Kalman-Bucy filter to observe the changing autonomous tractor states due to the changing of the working environment and the agricultural job performed.

3. Methodology

The yaw rate control system has to be designed with satisfactory performance, fast response, no overshoot or oscillatory behaviour, and accurate response with minimum steady-state error. To achieve those requirements, a linear quadratic regulator (LQR) algorithm with Kalman-Bucy filter is proposed. Figure 4 shows the Kalman based LQR control diagram. This combination estimator state-feedback controller is adapted from [5].

3.1. Linear Quadratic Regulator

LQR is an optimal control strategy that allows us to apply a full-state feedback to a dynamic system in such that the satisfactory performance is achieved. The objective of LQR is to place the poles of the system in optimal location so that the system closed-loop will minimize the cost function below,

$$J = \int (x^T Q x + u^T R u) dt \qquad (24)$$

where $Q \in \mathbb{R}^{n\,x\,n}$ is a positive semidefinite matrix as the system states weight, and $R \in \mathbb{R}^{m\,x\,m}$ is a positive definite matrix as the system controller input weight. The system states weight is obtained by $Q = CC^T$, and the system controller input weight is obtained by $R = \lambda I$ with $\lambda > 0$ and I as the identity matrix. In order to tune the Q and R weight there is a trade-off. If in some cases the system states are more considered then the Q should be tuned higher than R, and this is called cheap control method. While in some cases that the system control effort is more considered then the R should be tuned higher than Q, and this is called as expensive control method.

The input controller is described as follows,

$$u(t) = -Kx(t) \qquad (25)$$

where K is LQR gain matrix obtained by using described equation,

$$K = R^{-1} B^T P \qquad (26)$$

with P is obtained by solving this following Algebraic Riccati Equations,

$$\dot{P} = A^T P + PA - PBR^{-1} B^T P + Q \qquad (27)$$

Matrix A and B are the dynamic system model state-space in Eq. (19) and (20).

3.2. Kalman-Bucy filter

In this study, the dynamic of the system keeps changing according to working environment conditions and types of agricultural job, and this condition may bring a reality that the system states will not always be measurable. So, a Kalman-Bucy filter is employed to estimate the full states ($x(t)$) of the system and provide accurate estimated states for the control effort by the LQR. The Kalman-Bucy filter is described by the following equation,

$$\dot{\tilde{x}}(t) = A\tilde{x}(t) + Bu(t) + L(y(t) - \tilde{y}(t)) \qquad (28)$$

where the Kalman gain L can be obtained by this following equation,

$$L = PC^T R_v^{-1} \qquad (29)$$

with R_v is a measurement noises covariance and P is obtained by solving this following Algebraic Riccati Equations,

$$\dot{P} = AP + PA^T - PC^T R_v^{-1} CP + BR_w B^T \quad (30)$$

with R_w is a disturbance covariance. Both R_w and R_v are tuned manually. Matrix A, B, and C are the dynamic system model state-space in Eq. (19), (20), and (21).

4. Results and Discussions

As our simulation study, two sets of tractor working condition simulation are performed: one is low working speed at 2.5 m/s with two variations of cornering stiffness at 500 N/deg and 4500 N/deg, and one is high working speed at 10 m/s with two variations of cornering stiffness at 500 N/deg and 4500 N/deg. Based on these sets of simulation closed-loop step response analyses are done. Figure 5 and 6 show the closed-loop step response of the tractor yaw rate dynamics at low and high working speed respectively. It can be seen that the LQR control algorithm results track the reference with satisfactory, while the Kalman-Bucy filter can estimate the response also with satisfactory. Both at low and high working speed with low and high cornering stiffness show the stable response without overshoot oscillation in transient response and with minimum steady state error.

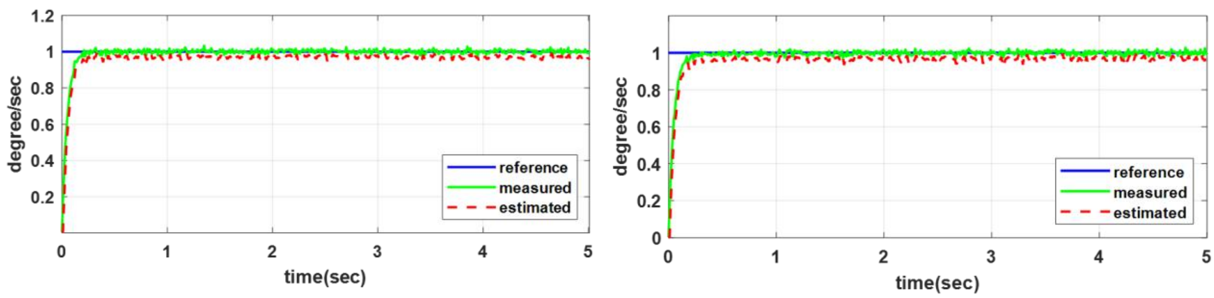

Figure 5. Closed-loop yaw rate controller step response at low working speed: $C_{\alpha h}$ = 500 N/deg (left) and $C_{\alpha h}$ = 4500 N/deg (right)

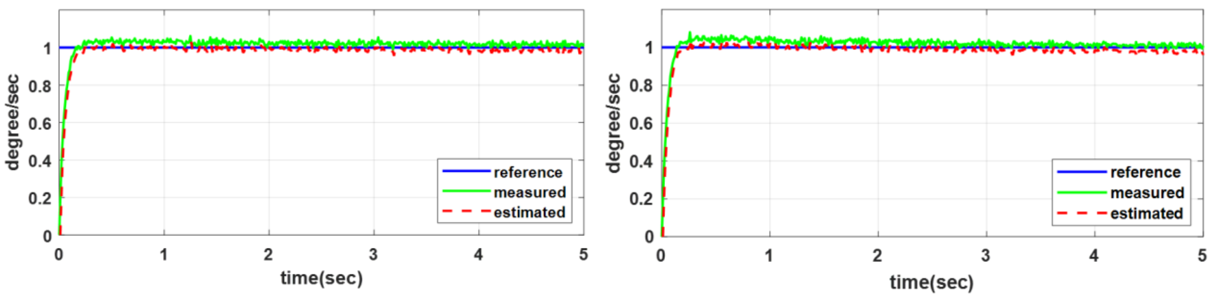

Figure 6. Closed-loop yaw rate controller step response at high working speed: $C_{\alpha h}$ = 500 N/deg (left) and $C_{\alpha h}$ = 4500 N/deg (right)

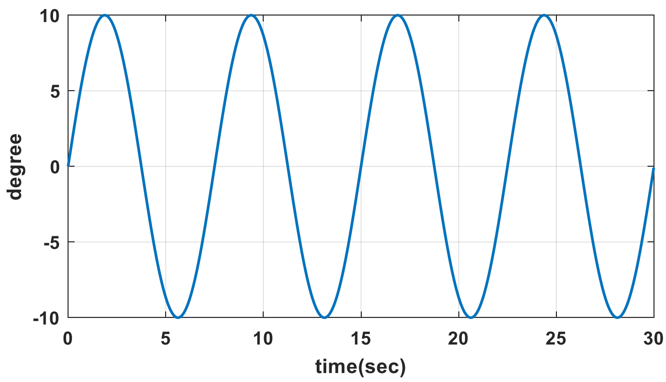

Figure 7. Tractor steering angle as controller input

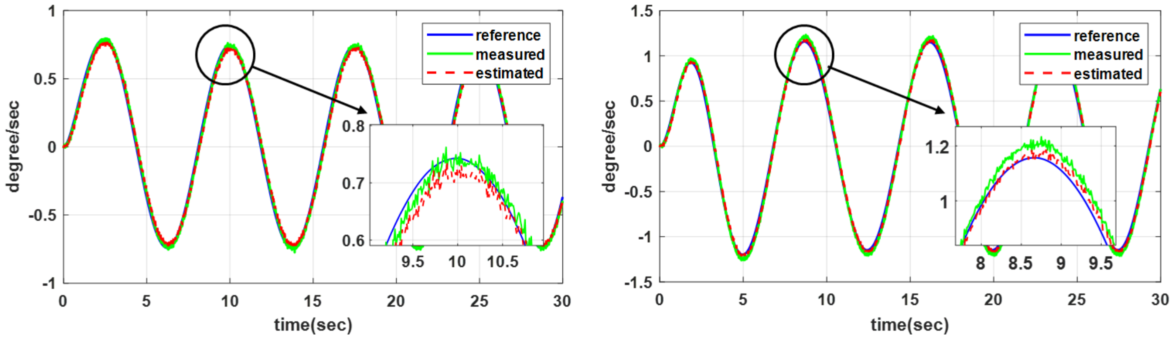

Figure 8. Yaw rate controller output tracking response at $C_{\alpha h}$ = 4500 N/deg: low working speed at v_x = 2.5 m/s (left) and high working speed at v_x = 10 m/s (right)

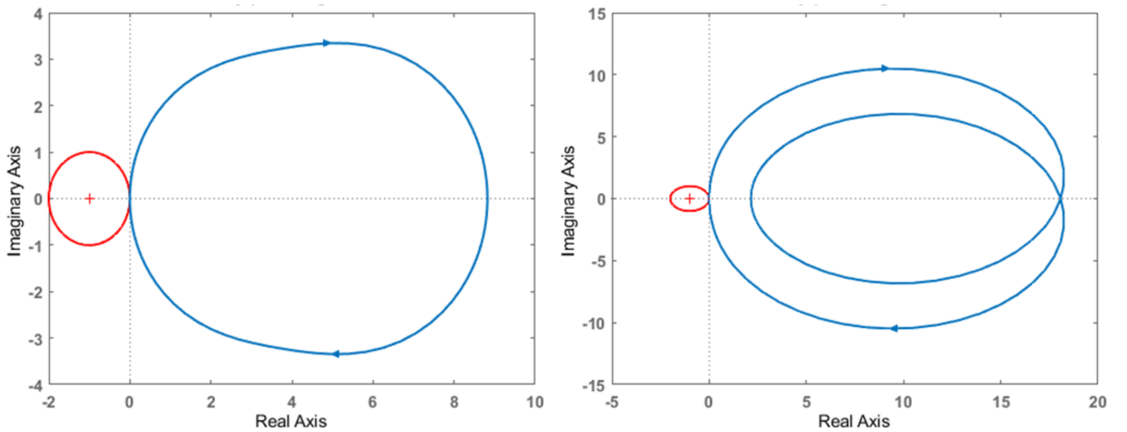

Figure 9. Nyquist plot of yaw rate controller: low working speed at v_x = 2.5 m/s (left) and high working speed at v_x = 10 m/s (right)

Besides the step response, the tracking response analysis of tractor yaw rate dynamics is done as well. In this tracking response low and high working speed are performed with only high cornering stiffness at 4500 N/deg. This tracking analysis is done by giving a steering angle as the controller input shown in Figure 7. The tracking responses are shown in Figure 8. The tracking responses show that the LQR control algorithm provides satisfactory tracking result with respect to the reference signal while the Kalman-Bucy filter provides satisfactory estimation with respect to the measurement signal. The stability of proposed controller method is shown by the Nyquist plot in Figure 9. In which the Nyquist plot for both low and high working speed avoid the unit circle centered in -1.

5. Conclusions

A Kalman-Bucy filter linear quadratic regulator control algorithm is implemented to control the autonomous tractor yaw rate dynamics as the simulation based study. By using the small angle approximation, the nonlinear terms of tractor dynamics model are linearized in which the linear control theory advantages can be applied. Since the tractor states are subjected to the dynamic changing with respect to the working environment and its types of agricultural job performed, a cheap control method is used for the linear quadratic regulator control algorithm in which the states of the system are more considered. While the Kalman-Bucy filter is employed to provide the full states estimation. According to the Nyquist plot, the proposed control system is stable in any working conditions. This presented results are limited in simulation study, a further real-time application with real measured tractor parameters might need to be done in order to verify the proposed method.

References

[1] B. Fernandez, P. J. Herrera, and J. A. Cerrada, “Self-tuning regulator for a tractor with varying speed and hitch forces,” *Comput. Electron. Agric.*, vol. 145, pp. 282–288, 2018.

[2] J. B. Derrick and D. M. Bevly, “Adaptive Steering Control of a Farm Tractor with Varying Yaw Rate Properties,” *J. F. Robot.*, vol. 26, no. 6, pp. 519–536, 2009.

[3] D. M. Bevly, J. C. Gerdes, and B. W. Parkinson, “A New Yaw Dynamic Model for Improved High Speed Control of a Farm Tractor,” *J. Dyn. Syst. Meas. Control*, vol. 124, no. 4, pp. 659–667, 2002.

[4] E. Kayacan, E. Kayacan, H. Ramon, and W. Saeys, “Modeling and identification of the yaw dynamics of an autonomous tractor,” in *2013 9th Asian Control Conference (ASCC)*, pp. 1–6.

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SIMULATION STUDY OF KALMAN-BUCY FILTER BASED OPTIMAL YAW RATE CONTROL SYSTEM FOR AUTONOMOUS TRACTOR

3rd ISABE 2019 International Symposium on Agricultural and Biosystem Engineering

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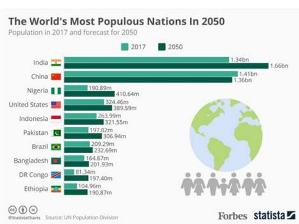
CONTENTS

INTRODUCTION

WORLD POPULATION

As the human population continues to grow while the availability space for food production is limited, the efficient usage of the agricultural resources such as biomass and machinery becomes the primary concern

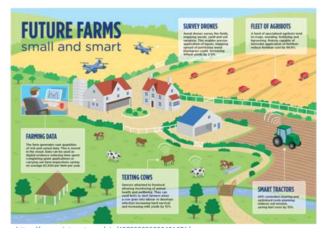


https://www.forbes.com/sites/niallmccarthy/2017/06/22/the-worlds-most-populous-nations-in-2050-infographic/#50a800e239f6

INTRODUCTION (Cont'd)

SMART FARMING

A solution proposed by researchers is smart farming where autonomous tractor is one of the solution to improve the agricultural machinery usage efficiency. One of the smart farming solutions is the smart tractor or autonomous tractor.



https://www.pinterest.com/pin/457959855838481671/

INTRODUCTION (Cont'd)

AUTONOMOUS TRACTOR

Developing an autonomous tractor is a challenging study. The tractor generally subjected into unstructured agricultural field environments.

https://www.nesta.org.uk/feature/precision-agriculture/smart-tractors/

INTRODUCTION (Cont'd)

WORKING ENVIRONMENT

Several factors associated with tractor working environment (Fernandez et al., 2018):

- Soil types
- Soil irregularities
- Varying driving speeds
- Varying implement loads

http://clipart-library.com/farming-field-cliparts.html

B. Fernandez, P.J. Herrera, J.A. Cerrada, Self-tuning regulator for a tractor with varying speed and hitch forces Comput. Electron. Agric., 145 (2018), pp. 282-288

INTRODUCTION (Cont'd)

STEERING CONTROLLER

Hence before developing a full autonomous path tracking tractor, it is important to build a simulation model of the steering response controller with respect to the types of tractor job and working environment.

https://www.nesta.org.uk/feature/precision-agriculture/smart-tractors/

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INTRODUCTION (Cont'd)

EXISTING LITERATURES

A self-tuning steering regulator is developed to control the tractor yaw rate dynamics with variations in speed and cornering stiffness (Fernandez et al., 2018)

A model reference adaptive control (MRAC) is developed on a tractor to compensate the yaw rate dynamics (Derrick and Bevly, 2009)

B. Fernandez, P.J. Herrera, J.A. Cerrada, Self-tuning regulator for a tractor with varying speed and hitch forces Comput. Electron. Agric., 145 (2018), pp. 282-288
J. B. Derrick and D. M. Bevly, "Adaptive Steering Control of a Farm Tractor with Varying Yaw Rate Properties," J. F. Robot., vol. 26, no. 6, pp. 519–536, 2009.

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TRACTOR IMPLEMENT ANALYSIS

SECOND NEWTON'S LAW OF MOTION

Equation of Motions

In this condition the longitudinal velocity v_x is constant, therefore no longitudinal acceleration a_x in which the longitudinal forces are neglected

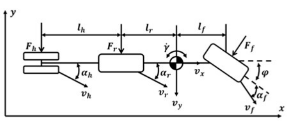
$$\sum F_y = m\, a_y \quad (1)$$

$$\sum M_{CG} = I_{zz}\, \ddot{\gamma} \quad (2)$$

$$a_y = \dot{v}_y + \dot{\gamma}\, v_x \quad (3)$$

Lateral acceleration

As the tractor longitudinal acceleration is null, the lateral acceleration is expressed as Eq. (3)



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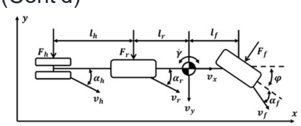
TRACTOR IMPLEMENT ANALYSIS (Cont'd)

KINEMATICS AND DYNAMICS RELATIONSHIPS



Assuming constant and proportional to the slip angles, the lateral forces are described as follows,

$$F_f = -C_{\alpha f}\alpha_f \quad (4)$$

$$F_r = -C_{\alpha r}\alpha_r \quad (5)$$

$$F_h = -C_{\alpha h}\alpha_h \quad (6)$$

with $C_{\alpha f}$, $C_{\alpha r}$, and $C_{\alpha h}$ are the front wheel, rear wheel, and implement cornering stiffness with values are varying depended on the working environment and the agricultural job performed.

Based on free body diagram with assumption that the tractor model as a rigid body, the relationship between slip angle, steering angles, yaw rate, and linear velocity can be described as follows,

$$\tan(\alpha_f + \varphi) = \frac{v_y + \dot{\gamma} l_f}{v_x} \quad (7)$$

$$\tan(\alpha_r) = \frac{v_y - \dot{\gamma} l_r}{v_x} \quad (8)$$

$$\tan(\alpha_h) = \frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x} \quad (9)$$

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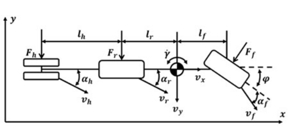
TRACTOR IMPLEMENT ANALYSIS (Cont'd)

LINEARIZATION



Linearization

Using small angle approximation, the nonlinear terms of tractor model can be linearized in which the slip angles are described as follows,

$$\alpha_f = \frac{v_y + \dot{\gamma} l_f}{v_x} - \varphi \quad (10)$$

$$\alpha_r = \frac{v_y - \dot{\gamma} l_r}{v_x} \quad (11)$$

$$\alpha_h = \frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x} \quad (12)$$

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TRACTOR IMPLEMENT ANALYSIS (Cont'd)

VEHICLE DYNAMICS

Eq. (3) – (6) and Eq. (10) – (12)
Substitute into

Eq. (1) and (2)
Yields

Equation of Motions

$$m\left(\dot{v}_y + \dot{\gamma}\, v_x\right) = -C_{\alpha f}\left(\frac{v_y + \dot{\gamma} l_f}{v_x} - \varphi\right) - C_{\alpha r}\left(\frac{v_y - \dot{\gamma} l_r}{v_x}\right) - C_{\alpha h}\left(\frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x}\right) \quad (13)$$

$$I_{zz}\,\ddot{\gamma} = -l_f\, C_{\alpha f}\left(\frac{v_y + \dot{\gamma} l_f}{v_x} - \varphi\right) + l_r\, C_{\alpha r}\left(\frac{v_y - \dot{\gamma} l_r}{v_x}\right) + (l_r + l_h)\, C_{\alpha h}\left(\frac{v_y - \dot{\gamma}(l_r + l_h)}{v_x}\right) \quad (14)$$

TRACTOR IMPLEMENT ANALYSIS (Cont'd)

STATE SPACE

Based on Eq. (13) and (14) the state space representation can be described as follows,

$$\dot{x}(t) = Ax(t) + Bu(t) + Bw(t) \quad (15)$$
$$y = Cx(t) + Du(t) + v(t) \quad (16)$$

Where,
$w(t)$ is disturbance,
$v(t)$ is measurement noise,

$$x(t) = [v_y, \dot{\gamma}]^T \quad (17)$$
$$u(t) = \varphi \quad (18)$$
$$A = \begin{bmatrix} \frac{-(C_{\alpha f}+C_{\alpha r}+C_{\alpha h})}{m\, v_x} & \frac{-l_f\, C_{\alpha f}+l_r\, C_{\alpha r}+(l_r+l_h)\, C_{\alpha h}}{m\, v_x} - v_x \\ \frac{-l_f\, C_{\alpha f}\alpha_f+l_r\, C_{\alpha r}\alpha_r+(l_r+l_h)\, C_{\alpha h}\alpha_h}{I_{zz}\, v_x} & \frac{l_f^2\, C_{\alpha f}+l_r\, C_{\alpha r}+(l_r+l_h)\, C_{\alpha h}}{I_{zz}\, v_x} \end{bmatrix} \quad (19)$$
$$B = \begin{bmatrix} \frac{C_{\alpha f}}{m} \\ \frac{l_f\, C_{\alpha f}}{I_{zz}} \end{bmatrix} \quad (20)$$
$$C = [0 \quad 1] \quad (21)$$
$$D = [0] \quad (22)$$

TRACTOR IMPLEMENT ANALYSIS (Cont'd)

TRANSFER FUNCTION

Eq. (15) to (22) → *Laplace Transform* →

$$G(s) = \frac{\dot{\gamma}(s)}{\varphi(s)} = \frac{B_{21}s+(B_{11}A_{21}-B_{21}A_{11})}{s^2-(A_{11}+A_{22})s+(A_{11}A_{22}-A_{12}A_{21})} \quad (23)$$

where A_{ij} with i = 1,2 and j = 1,2 and B_{mn} with m = 1 and n = 1,2 are the matrix elements of state space matrix in Eq. (19) and (20).

TRACTOR IMPLEMENT ANALYSIS (Cont'd)

OPEN LOOP SYSTEM ANALYSIS PROCEDURES

Table 1. Tractor-Implement Parameters

Tractor Parameters		
Data	Value	Unit
l_f	1.57	m
l_r	3.2	m
l_h	2.1	m
m	11000	Kg
I_{zz}	18500*	Kg.m
$C_{\alpha f}$	2400*	N/deg
$C_{\alpha r}$	5000*	N/deg
$C_{\alpha h}$	0-5000	N/deg
v_x	0-10	m/s

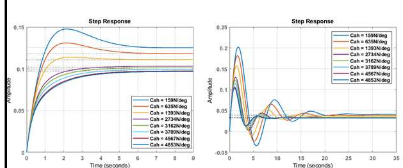
*parameters are obtained from (Derrick and Bevly, 2009)

Require: Tractor parameters from Table 1
Analysis: Open-loop system
MAIN:
0 Calculate Eq. (19) and (20)
1 Using *Laplace Transform* convert Eq. (15) to (22) into Eq. (23)
2 Find system *step response* by using *step function* and apply it to Eq. (23)
3 Plot system *open-loop step response*
4 Plot system *open-loop DC gain response*
END

J. B. Derrick and D. M. Bevly, "Adaptive Steering Control of a Farm Tractor with Varying Yaw Rate Properties," J. F. Robot., vol. 26, no. 6, pp. 519–536, 2009.

TRACTOR IMPLEMENT ANALYSIS (Cont'd)

OPEN LOOP STEP RESPONSE ANALYSIS

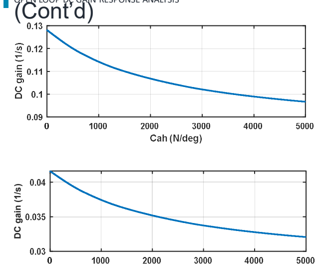


At low working speed v_x= 2.5 m/s (left) the open loop step response more stable than at high working speed v_x= 10 m/s (right) with more oscillatory behaviour

The higher the implement cornering stiffness $C_{\alpha h}$ the lower the tractor overshoot, transient, and oscillatory responses.

TRACTOR IMPLEMENT ANALYSIS (Cont'd)

OPEN LOOP DC GAIN RESPONSE ANALYSIS



At low working speed v_x= 2.5 m/s (top) the open loop DC gain response value is higher than at high working speed v_x= 10 m/s (bottom)

The higher the implement cornering stiffness $C_{\alpha h}$ the lower the DC gain response.

It means that the tractor steady state error is getting higher as the working speed and cornering stiffness increasing

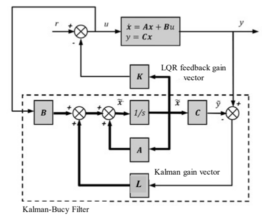
ADDRESSED PROBLEMS

- From the tractor open loop analysis, changing in type of job and working environment resulting in overshoot, oscillatory behaviors, and steady state errors
- While requirements of steering controller should provide good performance, this includes fast response, absence of overshoot or oscillatory behavior, and good accuracy with minimal steady-state error.
- Existing adaptive steering controllers require gain look up table for every type of tractor jobs and working environment. This results in time consuming and less robust design

OBJECTIVES OF THE STUDY

- Design an optimal steering controller which provides fast response, absence of overshoot or oscillatory behavior, and good accuracy with minimal steady-state error.
- Implement an observer based controller to estimate the states of the tractor to overcome the need of look up table for changing tractor type of jobs and working environment
- Build a simulation platform for autonomous tractor steering control system

METHODOLOGY



As the yaw rate or steering control system has to be designed with satisfactory performance, fast response, no overshoot or oscillatory behavior, and accurate response with minimum steady-state error. To achieve those requirements, a linear quadratic regulator (LQR) algorithm with Kalman-Bucy filter is proposed. Figure in left shows the Kalman based LQR control diagram. This combination estimator state-feedback controller is adapted from (Roman et al., 2017).

Aly M, Roman M, Rabie M, Shaaban S. Observer-Based Optimal Position Control for Electrohydraulic Steer-by-Wire System Using Gray-Box System Identified Model. ASME. *J. Dyn. Sys., Meas., Control.* 2017;139(12):121002-121002-9

METHODOLOGY (Cont'd)

LINEAR QUADRATIC REGULATOR

The objective of LQR is to place the poles of the system in optimal location so that the system closed-loop will minimize the cost function below,

$$J = \int (x^T Qx + u^T Ru)dt \quad (24)$$

With controller input is described as follows,

$$u(t) = -Kx(t) \quad (25)$$

where K is LQR gain matrix obtained by using described equation,

$$K = R^{-1}B^T P \quad (26)$$

with P is obtained by solving this following Algebraic Riccati Equations,

$$\dot{P} = A^T P + PA - PBR^{-1}B^T P + Q \quad (27)$$

Matrix A and B are the dynamic system model state-space in Eq. (19) and (20).

where $Q \in \mathbb{R}^{n\,x\,n}$ is a positive semidefinite matrix as the system states weight, and $R \in \mathbb{R}^{m\,x\,m}$ is a positive definite matrix as the system controller input weight. The system states weight is obtained by $Q = CC^T$, and the system controller input weight is obtained by $R = \lambda I$ with $\lambda > 0$ and I as the identity matrix. In order to tune the Q and R weight there is a trade-off.

METHODOLOGY (Cont'd)

KALMAN-BUCY FILTER

The objective of LQR is to place the poles of the system in optimal location so that the system closed-loop will minimize the cost function below,

$$\dot{\tilde{x}}(t) = A\tilde{x}(t) + Bu(t) + L(y(t) - \tilde{y}(t)) \quad (28)$$

where L is Kalman gain obtained by using described equation,

$$L = PC^T R_v^{-1} \quad (29)$$

with R_v is a measurement noises covariance and P is obtained by solving this following Algebraic Riccati Equations,

$$\dot{P} = AP + PA^T - PC^T R_v^{-1} CP + BR_w B^T \quad (30)$$

with R_w is a disturbance covariance. Both R_w and R_v are tuned manually. Matrix A, B, and C are the dynamic system model state-space in Eq. (19), (20), and (21).

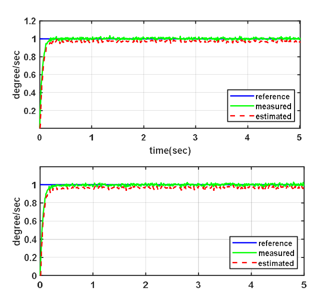
In this study, the dynamic of the system keeps changing according to working environment conditions and types of tractor job, and this condition may bring a reality that the system states will not always be measurable. So, a Kalman-Bucy filter is employed to estimate the full states ($x(t)$) of the system and provide accurate estimated states for the control effort by the LQR.

METHODOLOGY (Cont'd)

SIMULATION ALGORITHM

Require: Tractor parameters from Table 1
Ensure: The system is controllable and observable
0 Check controllability by using Eq. (19) and (20)
  IF `rank(ctrb(A,B))` is full rank
    system is controllable
  ELSE
    system is uncontrollable
1 Check observability by using Eq. (19) and (21)
  IF `rank(obsv(A,C))` is full rank
    system is observable
  ELSE
    system is unobservable
2 Execute control algorithm
  IF system is controllable and observable
    execute **MAIN** command
  ELSE
    stop

MAIN:
LQR Algorithm
0 Tune $Q \in \mathbb{R}^{n\,x\,n}$ and $R \in \mathbb{R}^{m\,x\,m}$ by using $Q = CC^T$ and $R = \lambda I$
1 Solve P from *Algebraic Riccati* Eq. (27)
2 Calculate gain K by using Eq. (26)
3 Calculate controller input by using Eq. (25)
4 Apply *4th Order Runge-Kutta Method* on Eq. (15) and (16)
Kalman-Bucy Algorithm
5 Tune R_w and R_v based on disturbance and noise *covariance*
6 Solve P from *Algebraic Riccati* Eq. (30)
7 Calculate gain L by using Eq. (29)
8 Apply *4th Order Runge-Kutta Method* on Eq. (28) and (16)
Postprocess results and visualizations
END



RESULTS

LOW WORKING SPEED STEP RESPONSE

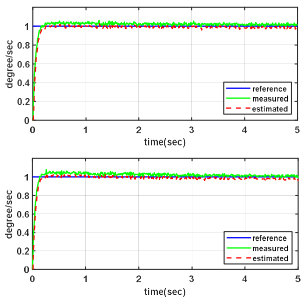
Simulation:

Low working speed v_x= 2.5 m/s

Low and high cornering stiffness $C_{\alpha h}$ = 500 N/deg (top) and $C_{\alpha h}$ = 4500 N/deg (bottom)

Results:

The step response show fast response, no overshoot and oscillatory behaviour, and accurate estimation. There is the same response for low and high cornering stiffness.



RESULTS (Cont'd)

HIGH WORKING SPEED STEP RESPONSE

Simulation:

High working speed v_x= 10 m/s

Low and high cornering stiffness $C_{\alpha h}$ = 500 N/deg (top) and $C_{\alpha h}$ = 4500 N/deg (bottom)

Results:

The step response show the similar response as low working speed response such as fast response, no overshoot and oscillatory behaviour, and accurate estimation. There is the same response also for low and high cornering stiffness.

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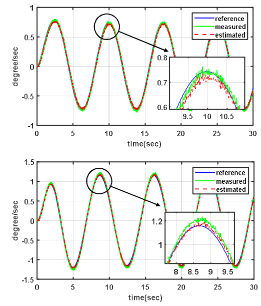

RESULTS (Cont'd)

STEERING TRACKING RESPONSE

Simulation:

High cornering stiffness $C_{\alpha h}$ = 4500 N/deg

Low and high working speed v_x= 2.5 m/s (top) and v_x= 10 m/s (bottom)

Results:

The sinewave tracking response for both low and high working speed also shows the satisfactory tracking performance with satisfactory estimation result. This shows that the proposed steering controller provides good yaw rate or steering performance of autonomous tractor.

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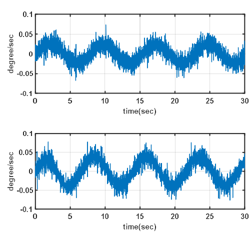

RESULTS (Cont'd)

ERROR STEERING ESTIMATION RESULTS

Simulation:

High cornering stiffness $C_{\alpha h}$ = 4500 N/deg

Low and high working speed v_x= 2.5 m/s (top) and v_x= 10 m/s (bottom)

Results:

The yaw rate or steering response estimation error which is ranged at ± 0.05 deg/sec proves that Kalman-Bucy filter provides satisfactory estimation results.

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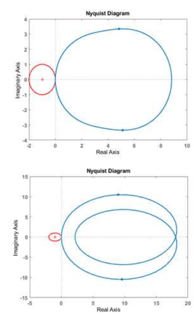

RESULTS (Cont'd)

NYQUIST STABILITY ANALYSIS

Simulation:

Low and high working speed v_x= 2.5 m/s (top) and v_x= 10 m/s (bottom)

Results:

Nyquist plot for both low and high working speed avoid the unit circle centered in -1. This means that the steering controller design is stable in any condition.

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CONCLUSIONS

- A Kalman-Bucy filter linear quadratic regulator control algorithm is implemented to control the autonomous tractor yaw rate dynamics as the simulation based study.
- Based on the simulation results, the linear quadratic regulator provides satisfactory control output while the Kalman-Bucy filter provides accurate estimation results
- The proposed algorithm show the similar response for low and high working speed and for low and high cornering stiffness which represents various tractor job and working environment
- This presented results are limited in simulation study, a further real-time application with real measured tractor parameters might need to be done in order to verify the proposed method.

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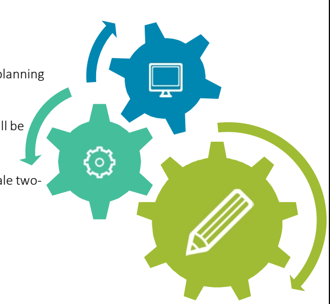
FUTURE WORKS

- The tractor kinematics and dynamics for path planning model will be developed
- Tractor path planning appropriate controller will be developed
- Real approach will be implemented in small scale two-wheeled hand tractor



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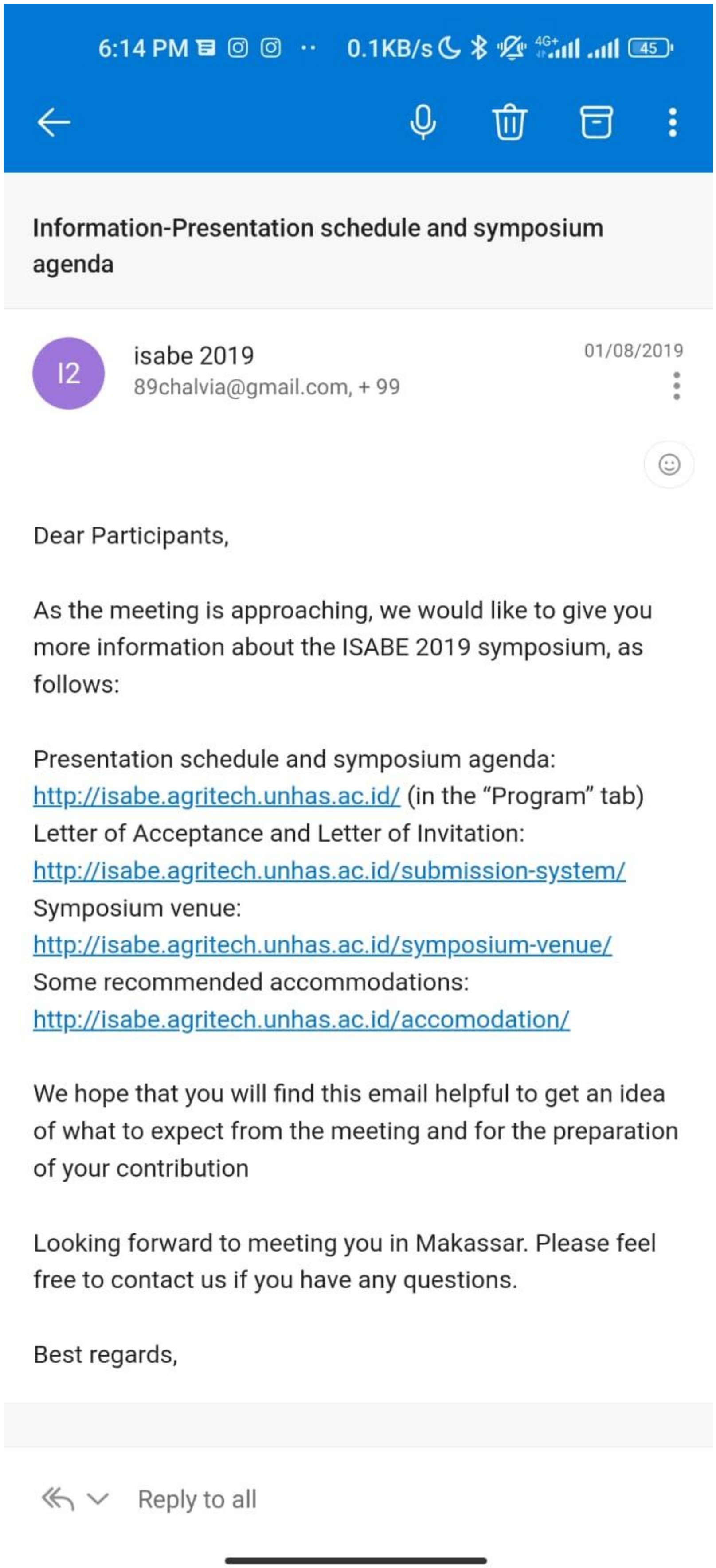

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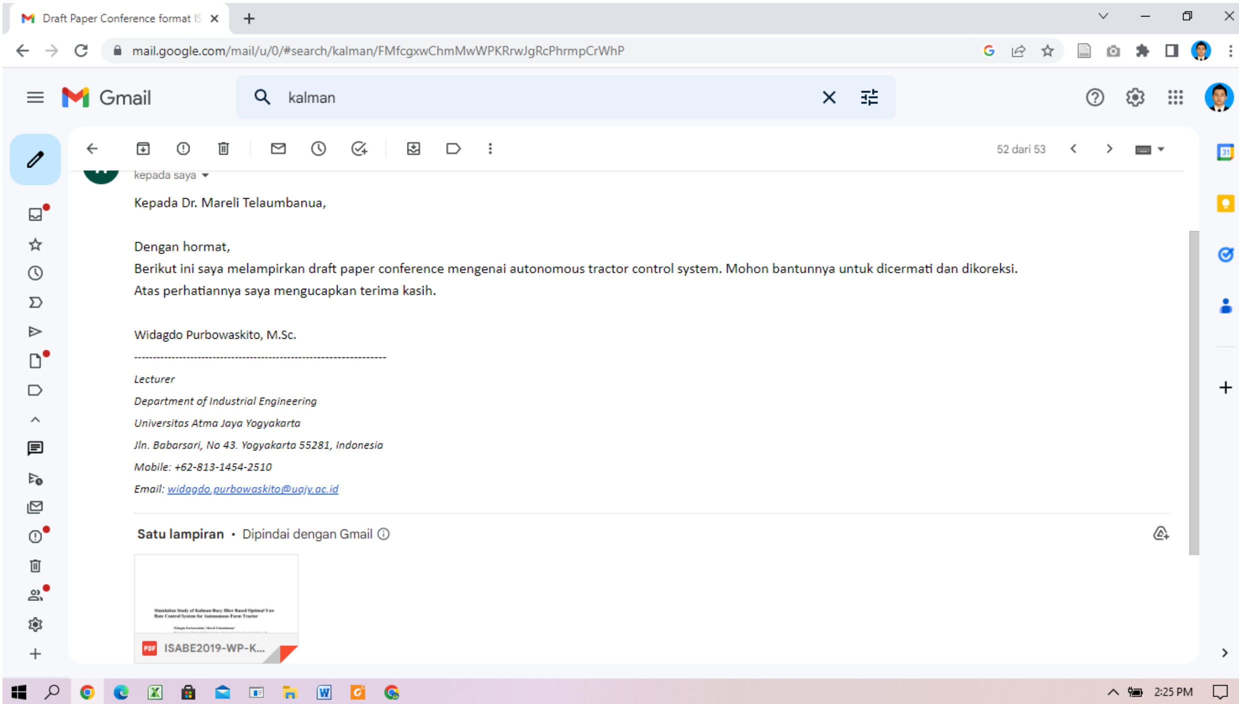
We hope that you will find this email helpful to get an idea of what to expect from the meeting and for the preparation of your contribution

Looking forward to meeting you in Makassar. Please feel free to contact us if you have any questions.

Best regards,

Reply to all



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Kepada Dr. Mareli Telaumbanua,

Dengan hormat,
Berikut ini saya melampirkan draft paper conference mengenai autonomous tractor control system. Mohon bantunnya untuk dicermati dan dikoreksi.
Atas perhatiannya saya mengucapkan terima kasih.

Widagdo Purbowaskito, M.Sc.

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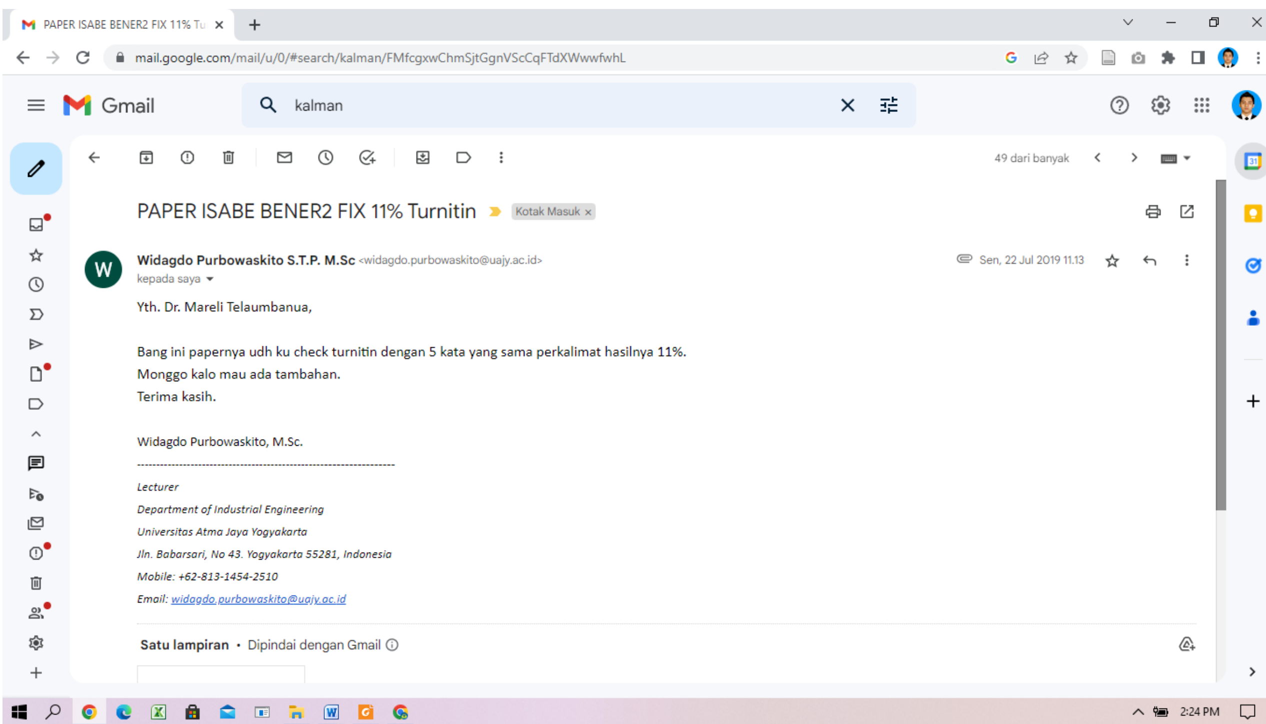

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