Comparison between Kalman Filter and Exponential Filter on IMU Data Acquisition

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ABSTRACT

IMU (Inertial Measurement Unit) is the main component of inertial guidance systems used in aircraft, spacecraft, and watercraft, including guided missiles. The IMU works by sensing the motion, including the rate and direction of that motion, using the combination of accelerometers and gyroscopes. The data are collected from these sensors allowing a computer to track a craft’s position and rotation, using a method known as dead reckoning. One part of the IMU detects the current rate of acceleration by using accelerometers, and the others the changes in rotational attributes like pitch, roll, and yaw by using gyroscopes. These data are transferred into the computer which calculates the current speed rotation and position, under a known initial position.

In this paper, we report our effort to utilize properly the acquired data from those detectors. The result of two scrutinizing digital filters, namely the Kalman and exponential ones as well as the angle and position estimations base on microcontroller. The average error of rotation estimation using the exponential filter is smaller than by using the Kalman filter, which are around 4.98% and 1.73% respectively. On the other hand, the average error of position estimation using Kalman filter is about 2.24% whereas the error average using exponential filter is about 5%.

Keywords: exponential filter, Kalman filter, accelerometer, gyroscope, and IMU.

1. INTRODUCTION

Analog filters in the sensor’s output can not guarantee optimal filtering of noise. Therefore some digital filters are needed to remove the noise better. A good filtering algorithm should remove the noise from any signal and gives the valid information with minimum error. A comparison between exponential filter and FIR filter on accelerometer data acquisition has been done [5]. The results have shown that the average error on three axis of position estimation using the exponential filter were smaller than using the FIR filters designs and applications of the exponential filters on rotation estimations using the angular rate sensor (Gyroscope) and the application of double exponential smoothing on IMU have been done [2][6]. The exponential filters have better performances. Some other papers used Kalman filter on IMU system, e.g. the application of self-adaptive Kalman filter in NGIMU/GPS Integrated Navigation System and a Kalman filter-based algorithm for IMU-camera calibration [1][3]. These papers present the comparison between exponential filter and Kalman filter on IMU system. Block diagram of IMU system is shown in Figure 1.

![Figure 1: Block diagram of IMU system](image_url)
2. DIGITAL FILTER

The Kalman filter is used to solve the problem of state estimation of a process that can be written as a linear difference equation and measurement as follows. [7]

\[ x_{k+1} = A_k x_k + B_k u_k + w_k \]  
(1)

Where the output is

\[ y_k = H_k x_k + v_k \]

The random variables \( w_k \) and \( v_k \) represent the process and measurement noises, respectively. They are assumed to be independent (of each other), white, and with normal probability distributions, where:

\[ p(w) = N(0,Q) \quad \text{and} \quad p(v) = N(0,R) \]

and

\[ E[w_i w_j] = \begin{cases} Q_i & \text{if } i = j \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad E[v_i v_j] = \begin{cases} R_i & \text{if } i = j \\ 0 & \text{otherwise} \end{cases} \]

In general, the process noise covariance \( Q \) and measurement noise covariance \( R \) matrices might change each time step or measurement, however in our case we assume they are constant.

The value of state estimate \( \hat{x}_k \) of Kalman filter is determined by the posteriori estimation \( \hat{x}_k \), the true measurement \( y_k \) and measurement estimation \( H_k \hat{x}_k \) as the following.

\[ \hat{x}_k = \hat{x}_k + K_k (y_k - H_k \hat{x}_k) \]

\[ \hat{x}_k = \hat{x}_k + K_k (y_k - H_k \hat{x}_k) \]

The difference between \( y_k \) and \( H_k \hat{x}_k \) is called as the residual of measurement or the innovation. If the value of the residual is zero, the output of the estimation is the result of the measurement. The value of \( K_k \) is the gain factor of Kalman filter. The gain of Kalman filter is chosen so that the result based on the optimal posteriori estimation give minimum error. The value of \( P_k \) is minimum when the estimation has minimum covariance. In turn, the value of \( K_k \) is minimum the equation below, following.

\[ K_k = P_k H_k^T (H_k P_k H_k^T + R_k)^{-1} \]

(3)

The minimum value of \( P_k \) is therefore

\[ P_k = I - K_k H_k P_k \]

(4)

Because no noise correlation, the priori estimation and the error covariance are, respectively,

\[ \hat{x}_{k+1} = A_k \hat{x}_k + B_k u_k \]

(5)

\[ P_{k+1} = A_k P_k A_k^T + Q_k \]

(6)

The Kalman filter process is shown in Figure 2 [7]. There are two steps of this process, a priori calculation and the calculation of Kalman gain.

---

**Figure 2**: The operation of Kalman filter
The exponential filter is a simple IIR (Infinite Impulse Response) filter. Realizable IIR digital filter are characterized by the following recursive equation.

\[ y(n) = \sum_{k=0}^{N} a_k x(n-k) - \sum_{k=0}^{M} b_k y(n-k) \]  

(7)

Where the impulse response h(k) of the filter which is theoretically infinite in duration, \( a_k \) and \( b_k \) are the coefficients of the filter, and \( x(n) \) and \( y(n) \) are the input and output to the filter respectively. The transfer function of the IIR filter is given as below.

\[ H(z) = \frac{\sum_{k=0}^{N} a_k z^{-k}}{1 + \sum_{k=0}^{M} b_k z^{-k}} \]

An important part of the IIR filter design process is to find suitable value for the coefficient \( a_k \) and \( b_k \) such that some aspects of the filter characteristics, such as the frequency response can be constructed. In practice exponential filter can be a simple recursive filter, for example the first order of exponential filter as shown below [2].

\[ y(t) = (1 - a) y(t-1) + a x(t) \]  

(8)

Where \( x(t) \) and \( y(t) \) are input and output of filter, the value of coefficient \( a \) is between 0 to 1. The value of coefficient \( a \) can be calculated as below.

\[ a = \frac{1}{(1 + 2\pi \cdot \frac{f_c}{f_s})} \]  

(9)

Where \( f_c \) is the cut off frequency and \( f_s \) is the sampling frequency. The second order of exponential filter is shown as below.

\[ y(t)^2 = (1 - a) y(t-1)^2 + a y(t) \]

(10)

3. DESIGN OF FILTER

The output of gyroscope sensor is a voltage that represents the angular rate. The angle data of the sensor’s output can be calculated by integrating, so the relationship between the angular rate signal and the angle shown in Figure 3.

![Figure 3: The relationship between the angular rate and the angle](image)

The Laplace form of the relationship between angular rate and angle is shown in the following equation.

\[ s \theta(s) = u \]  

This equation is changed to the time domain and to the discrete form:

\[ \frac{d\theta(t)}{dt} = u \]

\[ \theta_{k+1} - \theta_k = \frac{u_k}{T} \]

\[ \theta_{k+1} - \theta_k = T u_k \]

\[ \theta_{k+1} = \theta_k + T u_k \]

The state equation of gyroscope sensor on three-axis as follow:

\[ x_{k+1} = \begin{bmatrix} 1 & 1 & \frac{T}{2} \\ \frac{T}{2} & 1 & T \\ T & \frac{T}{2} & 1 \end{bmatrix} x_k + \begin{bmatrix} u_{k,x} \\ u_{k,y} \\ u_{k,z} \end{bmatrix} + \begin{bmatrix} w_k \\ w_k \\ w_k \end{bmatrix} \]
\[ y_k = \begin{bmatrix} 1 \ 1 \ 1 \ \frac{v_k}{v_k} \ \frac{v_k}{v_k} \end{bmatrix} \]

Where the state vector \( x_k = \begin{bmatrix} \theta_{x_k} \\ \theta_{y_k} \\ \theta_{z_k} \end{bmatrix} \)

The output of accelerometer sensor is a voltage that represents the acceleration. The relationship between the acceleration signal and the position is shown in Figure 4.

![Figure 4: The relationship between the acceleration signal and the position](image)

The Laplace form of the relationship between acceleration and velocity is shown in the following equation.

\[ sV(s) = u \]

This equation is changed to the time domain and to the discrete form:

\[ \frac{dv(t)}{dt} = u \]

\[ v_{k+1} - v_k = \frac{u_k}{T} \]

\[ v_{k+1} = v_k + Tu_k \]

In the similar manner, the relationship between position and velocity due to acceleration is shown in the following equation.

\[ s_{k+1} = s_k + Tv_k + 0.5T^2u_k \]

The state equation of accelerometer sensor on three-axis as follow:

\[ x_{k+1} = \begin{bmatrix} 1 & T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} x_k + \begin{bmatrix} 0.5T^2 & T & 0.5T^2 & T \end{bmatrix} u_k + \begin{bmatrix} w_k \\ w_k \\ w_k \\ w_k \\ w_k \\ w_k \end{bmatrix} \]

Where the state vector \( x_k = \begin{bmatrix} \theta_{x_k} \\ \theta_{y_k} \\ \theta_{z_k} \end{bmatrix} \)

The parameter \( a \) of exponential filter can be obtained using equation 9. The exponential filter is used on the cutoff frequency 40 Hz and the sampling frequency 31250 Hz, so we got the value of \( a = 0.9 \). The second order of exponential filter is shown as below:

```c
// single exponential filter
y1=(1 - a)*in;
y2=a*out1;
ym1=y1+y2;
out1=ym1;
// double exponential filter
y12=(1 - a)*ym1;
y22=a*out2;
ym2=y12+y22;
out2=ym2;
```
To obtain the angle data of gyroscope and the position data of accelerometer, the second order of runge-kutta integration is used.

// second order integration
integration := integration + (T/2)*(input+input_before);
input_before := input;

4. EXPERIMENT DATA

Every table presents four the original value on every axis. The experiment data of the estimate distance and the estimate angle are average of ten data. The experiment data of the estimate distance using Kalman filter is presented in Table 1 and the experiment data of the estimate distance using exponential filter is presented in Table 2.

<p>| Table 1: The experiment data of the estimate distance using Kalman filter. |
|---------------------------|-------------------|-------------------|</p>
<table>
<thead>
<tr>
<th>No</th>
<th>Original distance (cm)</th>
<th>Estimate distance (°)</th>
<th>Average of error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
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<tr>
<td>1</td>
<td>15</td>
<td>14.96</td>
<td>15.28</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>30.95</td>
<td>29.17</td>
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<tr>
<td>3</td>
<td>45</td>
<td>46.11</td>
<td>43.91</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>61.77</td>
<td>58.3</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>2.22</td>
<td>2.47</td>
</tr>
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<p>| Table 2: The experiment data of the estimate distance using exponential filter. |
|---------------------------|-------------------|-------------------|</p>
<table>
<thead>
<tr>
<th>No</th>
<th>Original distance (cm)</th>
<th>Estimate distance (°)</th>
<th>Average of error (%)</th>
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<td>1</td>
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<td>30.82</td>
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<tr>
<td>4</td>
<td>60</td>
<td>66.83</td>
<td>54.06</td>
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<td></td>
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<td>5.28</td>
<td>6.12</td>
</tr>
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</table>

Table 1 and Table 2 show that the average of error using Kalman filter in every axis smaller than using exponential filter. The average of error on three axes using Kalman filter is about 2.24 % and using exponential filter is about 5 %.
The experiment data of the estimate angle using Kalman filter on clockwise and counter clockwise are presented in Table 3 and Table 4. The error average on clockwise rotation of three axes is about 4.51 % and the error average on counterclockwise rotation of three axes is about 5.44 %. The error average of the estimate angle using Kalman filter is about 4.98 %.

<p>| Table 3: The experiment data of the estimate angle using Kalman filter (clockwise). |
|---------------------------|-------------------|-------------------|</p>
<table>
<thead>
<tr>
<th>No</th>
<th>Original angle (°)</th>
<th>Estimate angle (°)</th>
<th>Average of error (%)</th>
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<td>30.81</td>
<td>32.96</td>
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<td>93.34</td>
<td>97.96</td>
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<td>140.35</td>
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<tr>
<td>4</td>
<td>180</td>
<td>193.66</td>
<td>180.81</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>5.50</td>
<td>4.85</td>
</tr>
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</table>

<p>| Table 4: The experiment data of the estimate angle using Kalman filter (counterclockwise). |
|---------------------------|-------------------|-------------------|</p>
<table>
<thead>
<tr>
<th>No</th>
<th>Original angle (°)</th>
<th>Estimate angle (°)</th>
<th>Average of error (%)</th>
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<tr>
<td></td>
<td>Roll</td>
<td>Pitch</td>
<td>Yaw</td>
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<tr>
<td>1</td>
<td>-30</td>
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<td>2</td>
<td>-90</td>
<td>-93.26</td>
<td>-84.67</td>
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</table>
The experiment data of the estimate angle using exponential filter on clockwise and counter clockwise are presented in Table 5 and Table 6. The error average on clockwise rotation of three axes is about 1.29 % and the error average on counterclockwise rotation of three axes is about 2.16 %. The error average of the estimate angle using exponential filter is about 1.73 %.

Table 5: The experiment data of the estimate angle using exponential filter (clockwise).

<table>
<thead>
<tr>
<th>No</th>
<th>Original angle</th>
<th>Estimate angle (°)</th>
<th>Average of error (%)</th>
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<tr>
<td>1</td>
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<td>30.18</td>
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<tr>
<td>2</td>
<td>90</td>
<td>89.28</td>
<td>90.77</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
<td>139.38</td>
<td>141.37</td>
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<tr>
<td>4</td>
<td>180</td>
<td>178.82</td>
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</tr>
<tr>
<td></td>
<td>Average</td>
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Table 6: The experiment data of the estimate angle using exponential filter (counter-clockwise).

<table>
<thead>
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<th>Estimate angle (°)</th>
<th>Average of error (%)</th>
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<tr>
<td></td>
<td>Average</td>
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<td></td>
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5. CONCLUSION

Comparison of Kalman filter and exponential filter on data acquisition of IMU has been developed. Design of IMU used the accelerometer sensor on three axes and the gyroscope sensor on three axes. The design process of exponential filter is to find parameter (a). The exponential filter is used on the cutoff frequency 40 Hz and the sampling frequency 31250 Hz, so the parameter (a) is 0.9. The design process of Kalman filter is to find of state estimation of a process. The error average of rotation estimation using the exponential filter is smaller than by using the Kalman filter. The average error of rotation estimation using the exponential filter is smaller than by using the Kalman filter, which are around 4.98 % and 1.73 % respectively. On the other hand the average error of position estimation using Kalman filter is about 2.24 % whereas the error average using exponential filter is about 5 %.

REFERENCES

WELCOME FROM THE RECTOR OF UNIVERSITAS INDONESIA

I am honoured to have the opportunity to officially welcome you to the 12th International Conference on QIR (Quality in Research) 2011. As we are all aware that the impact of globalization has resulted in a very competitive business environment; a condition that makes the fulfillment of the needs of customer/clients’ ever-sophisticated project, product, or service most challenging. Without any doubt, a sustainable design and technology is the key factors in assisting our industries to enhance their contributions to the future development of humanity. Therefore, it is our hope that this conference will be able to provide an international forum for exchanging knowledge and research expertise as well as creating a prospective collaboration and networking in various fields of sustainable engineering and architecture.

In order to achieve business objectives and benefits, engineering products or projects require various resources, skills, and technology. Accordingly, we need an application of knowledge, tools, and techniques necessary to develop sustainable products or projects, which are environmentally friendly, produced through efficient processes, and adapted to local conditions. And this may be achieved by eco-technology. Eco-technology is a technology that will give consumers what they want: lower cost, convenience, save money and deliver what people everywhere needs; less waste, less pollution, and green environment. Eco-technology practices can facilitate to conserve and restore the environment through the integration of engineering and ecological principles. However, eco-technology requires multidisciplinary synthesis of knowledge and skills; and the development and application of this technology in the sector of industry and services is therefore a crucial requirement for sustainable development process. For this reason, we urgently need new technologies and practical applications to be further developed based on the current knowledge.

Accordingly, I hope this conference can be a kick-off for the strengthened action and partnerships on creating a platform for us: national and international thinkers, academics, government officials, business executives and practitioners, to present and discuss the pivotal role of engineers in creating sustainable development.

I would like to thank the Faculty of Engineering of Universitas Indonesia for organizing this meaningful and timely event, and supporting organizations for their participation and contributions. I am sure that you will all find this conference stimulating and rewarding and with this, I wish you all a fruitful conference.

Prof. Dr. der. Soz. Gumilar Rusliwa Somantri
Rector
Universitas Indonesia
WELCOME FROM THE DEAN OF FACULTY OF ENGINEERING
UNIVERSITAS INDONESIA

On behalf of the Faculty of Engineering, University of Indonesia, it is my greatest pleasure to extend our warmest welcome to all of you to the 12th International Conference on QiR (Quality in Research) 2011. As we know that this conference is conducted to cover a wide range of sustainable design and technology issues, I hope this two days-conference will be spent in interesting discussions and exchange of ideas. I also hope that this conference will be able to provide a state-of-the-art information and knowledge in this challenging world of sustainable design and technology. The growing success of our institutions and expertise should urge us to develop our competitive capabilities, especially when we face certain challenges which should be overcome with hard work, cooperation, and working together hand in hand. We will work together to develop a common path and develop collaboration opportunities for future action and research on multi-disciplinary engineering areas for quality of life and humanity.

I am delighted that you have accepted our invitation to this conference in such a large numbers as indicated and that we will have many international speakers and papers from various countries to be presented and discussed in these two days. We will explore various issues on sustainable development and we must widen the scope of sustainability from a product-, system-, or an individual building-scale to the whole community-scale. At the same time, we have to widen the focus from ecological aspects to social and economic aspects. This means that environmental solutions should always be considered from the aspects of human health and well-being, safety, and economic point of view. This conference provides an excellent forum for engineering professionals, business executives, industry practitioners, and academicians to exchange ideas and to share their experience, knowledge and expertise to each other.

I would like to thank our sponsors, supported bodies, and various contributors for their generous support of this conference. I would also like to thank our distinguished speakers for agreeing to share their insights with us. To our friends from overseas and other provinces of Indonesia, I would also like to extend a warm welcome to you and wish you an enjoyable stay in Bali. Last but not least, I would invite you to join me in thanking the committed staff that made this conference happen and to make it success.

I wish us much success in the deliberations, discussions, and exchange of ideas which we will have within this conference and I wish you a very pleasant and enjoyable stay here in Bali.

Prof. Dr. Ir. Bambang Sugiarto, M.Eng
Dean Faculty of Engineering
Universitas Indonesia
WELCOME FROM THE QiR 2011 ORGANIZING COMMITTEE

On behalf of the Organizing Committee, it is my greatest pleasure to extend our warmest welcome to all of you to the 12th International Conference on QiR (Quality in Research) 2011. The selected theme for this year's conference is "Integrated Design in Urban Eco-Technology for Quality of Life and Humanity". With this theme, the conference focuses on the scientific analysis and design of the key factors explaining the success applications of integrated design in urban eco-technology, their market perspectives, and their contributions to the existing and future development of humanity. In line with this theme, it is our utmost pleasure to hold the QiR 2011 in conjunction with the 2nd International Conference on Saving Energy in Refrigeration and Air Conditioning (ICSEAR 2011).

With its continuous presence for 12 years, QiR has become an icon for Faculty of Engineering Universitas Indonesia in serving the objectives to provide engineering excellence for both national and international in all aspects of engineering, design, and architecture. For the first time, the QiR 2011 is held in a famous beautiful island of Indonesia - Bali. The QiR 2011 is supported by Universitas Udayana, in the spirit of strengthening of cooperation and mutual growth to be world class institution. I am delighted to inform you that we have such a large number of participants today, as indicated, that we will have 21 invited speaker presentation and more than 520 papers from more than 20 countries to be presented and discussed during these two days-conference. We are fortunate to have a lot of good quality papers belong to:

32 papers on ICSERA
39 papers on Chemical Engineering
115 papers on Electrical Engineering
37 papers on Mechanical and Naval Architecture Engineering
101 papers on Materials Engineering
54 papers on Architecture & Planning
75 papers on Industrial Engineering
72 papers on Civil Engineering

I would like to thank all contributors, speakers and participants for your generous support to this conference. It is my pleasant duty to thank all the members of Organizing Committee and the International Board of Reviewers for their advices and help. We are grateful to all Sponsors, Supporters, Exhibitors, Partner Universities and Professional Associations, for their spontaneous response and encouragement through committing funds and extending help in kind. I would like to sincerely thank the Rector of Universitas Indonesia and the Dean of Faculty of Engineering, for fully supporting the Committee and providing all supports to make this conference happen and to make it a success.

I wish you a very pleasant stay here in Bali; and finally, let me wish all of you a meaningful and fruitful conference. Thank you and we hope to see you again at the QiR 2013.

Prof. Dr. Ir. Bondan T. Sofyan, M.Si.
Chairman of QiR 2011 Organizing Committee
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