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Fuzzy Logic Based EKF for Mobile Robot Navigation: An Analysis of Different Fuzzy Membership Functions

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ABSTRACT

This paper deals with the analysis of different Fuzzy membership type performance for Extended Kalman Filter (EKF) based mobile robot navigation. EKF is known to be incompetent in non-Gaussian noise condition and therefore the technique alone is not sufficient to provide solution. Motivated by this shortcoming, a Fuzzy based EKF is proposed in this paper. Three membership types are considered which includes the triangular, trapezoidal and Gaussian membership types to determine the best estimation results for mobile robot and landmarks locations. Minimal rule design and configuration are also other aspects being considered for analysis purposes. The simulation results suggest that the Gaussian memberships surpassed other membership type in providing the best solution in mobile robot navigation.

Keywords: Fuzzy logic, Kalman Filter, Membership, Mobile robot, Navigation

INTRODUCTION

In achieving a truly autonomous mobile robot, several factors must be taken into account such as computational complexity of the designed model, the environmental conditions, noise characteristics and uncertainties. These issues are among the big challenges in mobile robot navigation and had an enormous attention from researcher.

Navigation covers a broad range of applications such as path planning, localization and mapping. Between those three main areas, localization and mapping has gained high research interest. Both of those fields can be tolerate individually or solved simultaneously. Combining both research themes, the problem can also be called as Simultaneous Localization and Mapping (SLAM). One of the famously been used technique to solve SLAM is Extended Kalman Filter (EKF) (Abdelnour, Chand, Chiu & Kido, 1993; Ahmad & Namerikawa,

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2013; Ahmad & Othman, 2015). Unfortunately, EKF is only known to be accurate to operate in a Gaussian noise environment. Such demerit demands further improvement or new solution. To this extend, particle filter (Asadian, Moshiri & Sedigh, 2005), unscented kalman filter, graph-SLAM and other techniques have been available for non-Gaussian noise environment. Unfortunately, all of the techniques still infeasible due to high computational cost, complexity and other unavoidable issues. As a result, researcher still relies heavily on EKF to perform navigation as it is can guarantee some good results in estimation (Huang & Dissayanake, 2007).

Motivated by the above series of research, this paper attempts to analyze the performance of EKF based SLAM with the aid of Fuzzy Logic. The research mainly considered a condition of non-Gaussian noise which exists in various environments. In fact this research is expected to improve the normal EKF performance in SLAM and at the same time offers better solution to any available techniques.

Three main membership types performance are observed and assessed to obtain the best configurations. Combination between EKF and Fuzzy Logic has been proposed in a number of research (Abdelnour et al., 1993; Ahmad, Othman, Razali, & Daud, 2016; Kobayashi, Cheok, Watanabe, & Munekata, 1998; Raimond, & Melusso, 2006; Wang, Park & Huh, 2014). But none of them has ever investigated the differences of having various type of membership type. In Ahmad et al. (2016), the research introduced the performance of a single Gaussian membership type performance with EKF and has proved that EKF with Fuzzy Logic can guarantee better estimation results. Other research such in (Kobayashi et al., 1998) demonstrated the triangular membership performance. Therefore, there is a need to determine which membership type is suitable and meet the research expectation. In (Wang et al., 2014), the simulation of Fuzzy EKF also proved that the method has better results than the normal EKF. Several papers have combined neural-network and fuzzy (Amitava & Fumitoshi, 2007; Thanh, Manh, Thuan, & Quang, 2012). Even though this approach could improve the performance, the computational cost will be increased. This research aim to distinguish in general about the performance of three membership types: the Gaussian, Trapezoidal and Triangular memberships about the estimation error. The assessment criteria's are based on the covariance characteristics and estimation error.

This paper is organized as follow. Section 2 presents the EKF mathematical formulation with a brief explanation about the general localization and mapping technique. Fuzzy Logic technique is then being introduced in further subsection to provide description about its role in providing an alternative way to improve estimation error. The simulation results and its analysis are then shown in section 3. Finally, section 4 concludes the paper.

There are two main steps to determine the mobile robot motions and landmarks conditions Thurn, Burgard, & Fox, 2000; 2005). The first model is the kinematic model and also known as the process model which defines the mobile robot movements. The latter model is known as the observation or measurement model that explains the measurement of the relative distance and angle between mobile robot and any landmarks. For the process model, the condition of mobile robot from time k to time $k + 1$ is described as

$$X_{k+1} = F_{k+1}X_k + G_{k+1}u_{k+1} + w_{k+1} \tag{1}$$

where X_k is the state of the mobile robot and landmarks, F_{k+1} is the state transition matrix, G_{k+1} is the control matrix that mapped the control inputs u_{k+1} into the state space, and w_{k+1} is the zero-mean Gaussian process noise with covariance Q_{k+1}. Whereas the observation model is define as

$$z_{k+1} = \begin{bmatrix} r_i + \upsilon_r \\ \phi_i + \upsilon_\phi \end{bmatrix} = H_{k+1}X_{k+1}^{-} + v_{k+1} \tag{2}$$

where H_{k+1} is the observation matrix.

EKF has a prediction and an update stages as shown below.

Predicted stage

$$\hat{X}_{k+1} = f(\hat{X}_k, \omega_k, v_k, 0, 0) \tag{3}$$

$$P_{k+1|k} = fP_{k|k}f^T + g\Sigma_{k|k}g^T \tag{4}$$

f = jacobian of mobile robot motion,
Σ = control noise covariance,
g = jacobian of the control noise,
P = state covariance.

Update stage

$$P_{k+1|k+1} = P_{k+1|k} - KH_iP_{k+1|k} \tag{5}$$

$$K = P_{k+1|k}H_i^T\left(H_i\,P_{k+1|k}H_i^T + R\right)^{-1} \tag{6}$$

$$\hat{X}_{k+1|k+1} = f\hat{X}_{k+1|k} + KH_i\left(X_{k+1|k} - \hat{X}_{k+1|k}\right)^{-1} \tag{7}$$

K = Kalman gain of EKF.

MATERIALS AND METHODS

Fuzzy Logic Design

The design of Fuzzy Logic is based on the measurement innovation characteristics when managing the information obtained from the mobile robot observation. This is shown indirectly on equation(7) on the second right hand side equation. The inputs to the Fuzzy logic are designed to be the angle and distance errors. The outputs are also the same as the Fuzzy logic tend to decrease the error of both parameters affected by the unknown measurement noise. As what equation (7) defines, smaller error can be obtained if the second part of right hand side equation is smaller. This explains directly on what this research is attempted to improve.

Consider a case where a stationary mobile robot is observing a specific landmark many times. The theoretical analysis proposed that if the exteroceptive sensors are working well, the measurement will yield smaller error (Huang & Dissayanake, 2007). In a non-Gaussian noise, this property are still not investigated and left with undefined conditions. As an alternative solution, the Fuzzy logic approach aims to reduce the estimation error by modifying the measurement innovation.. The approach is almost similar to Kobayashi et al., (Cheok, 1998) whose proposed that by selecting the *P, Q*, and *R* from Fuzzy logic, smaller uncertainties is achieved. Wang et al. (2014) has also configured that Kalman gain is related to the measurement noises and therefore needs to be carefully considered in mobile robot navigation.

The proposed design used the Mamdani technique for analysis purposes. The general design is illustrated in Figures 1-3 based on the triangular membership type. Other type of membership follows the same configuration as what triangular holds. The following describes the rules of Fuzzy logic that are used to define the output of the measurement innovation. The number of rules is minimized to save computational cost.

- IF angle error is negative and distance error is negative, THEN angle is negative
- IF angle error is negative and distance error is normal, THEN angle is normal
- IF angle error is negative and distance error is positive, THEN angle is negative, distance is normal
- IF angle error is positive and distance error is normal, THEN angle is negative
- IF angle error is positive and distance error is negative, THEN distance is normal
- IF angle error is positive and distance error is positive, THEN angle is negative, distance is normal

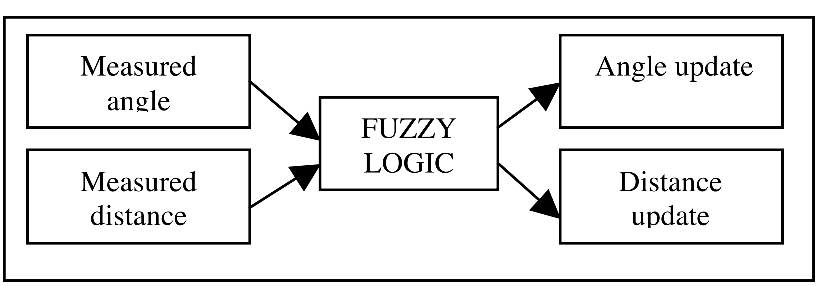
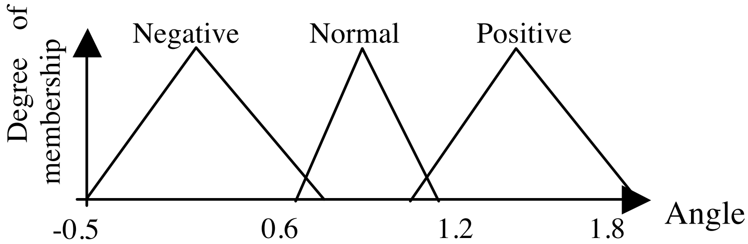


Figure 1. Fuzzy Logic with inputs and outputs



(a)

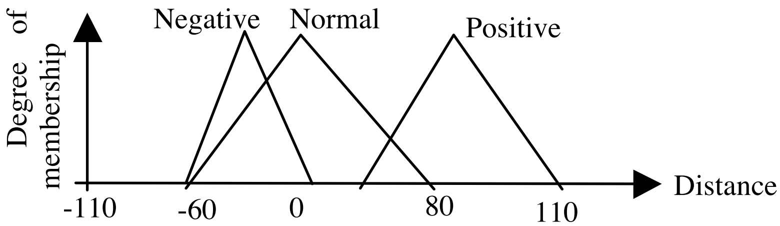


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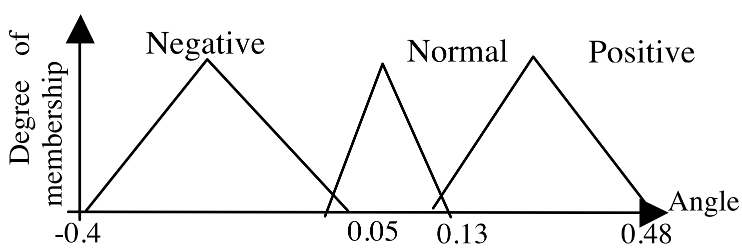
Figure 2. (a) Angle measurement (b) Distance measurement



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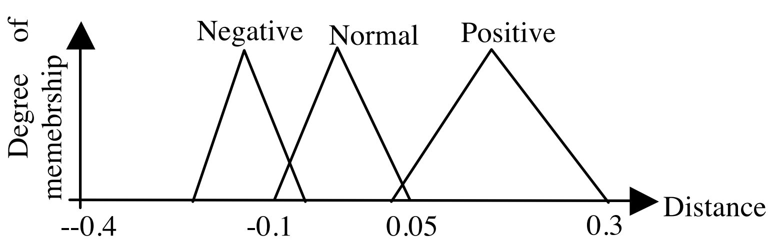

(b)

Figure 3. (a) Fuzzified angle (b) Fuzzified distance measurement

RESULTS AND DISCUSSIONS

The simulations analysis is carried by assuming all the parameters have the value presented in Table 1. These parameters are defined based on the previous research paper (Thrun et al., 2005; Honglei, Li, & Xingli, 2012) and literatures which can be found in the references.

Table 1
Simulation parameters

Variables	Parameter values
Process noise; Q_{min}, Q_{max}	-0.002, 0.001
Measurement noise; $R_{\theta min}$, $R_{\theta max}$	-0.04, 0.01
$R_{dist\text{-}min}$, $R_{dist\text{-}max}$	-0.15,0.3
Initial covariance; P_{robot},$P_{landmark}$	0.001, 100
Simulation time	1000[s]

The simulation analysis is configured to be able to model an indoor environment that has a small environment. There are no dynamic objects available during the testing. The noises on the mobile robot odometry is also assumed to be small at all time compared to the sensor noise. Taking into account these assumptions, the simulation and analysis are carried and the results are presented in Figures 4-6. As demonstrated in Fig.4, the combination between Fuzzy Logic and EKF has surpassed the performance on normal EKF estimation. This result agrees with the previous suggested findings and defines that EKF with Fuzzy Logic can provide better results of estimation. Observing between three types of membership, the Gaussian membership has almost similar estimation as the truth mobile robot motions and the landmark estimation compared to the other two memberships. The figure also suggest that the trapezoid has the lowest efficiency compared to Gaussian and Triangular memberships.

Different mobile robot motions are also investigated to obtain consistency of results. As the trapezoid is not providing a good estimation results, only triangular and Gaussian memberships will be considered for further analysis. Figures 5(a) and 5(b) demonstrates different mobile robot motions. Figure 5(a) still support the Gaussian membership than the triangular. However, if the mobile robot is doing a very narrow turns, then Gaussian shows opposite results and produced higher errors than the triangular membership. Further examinations have also showing the same characteristics in which defines the Gaussian membership is suitable for smooth motions whereas the Triangular memberships for rough motions. Figure 6 shows another robot motions and the results proposed the Gaussian as the best solution for the membership types.

The tuning process in Fuzzy Logic has also taken place during the simulation results. It is not recommended to add the number of rules as it will increase the computation cost. Therefore, only the fuzzy sets are tune to provide the best solution. This step is probably the most challenging stage in finding the best configuration of the Fuzzy Logic technique and must be done carefully. Tuning is done on the output fuzzy sets with reference to the error obtained from simulations e.g if distance error is smaller, then the fuzzy sets of distance will be modified to define smaller distance.

The updated state covariance is also analyzed to find any differences on the properties. As shown in figure 6, the state covariance has almost the same performance compared to the normal EKF. In other word, the estimation is not too optimistic even though the EKF is being combined with additional technique for inference. Both of the covariance is converging after some period of time i.e still preserving the same EKF characteristics.

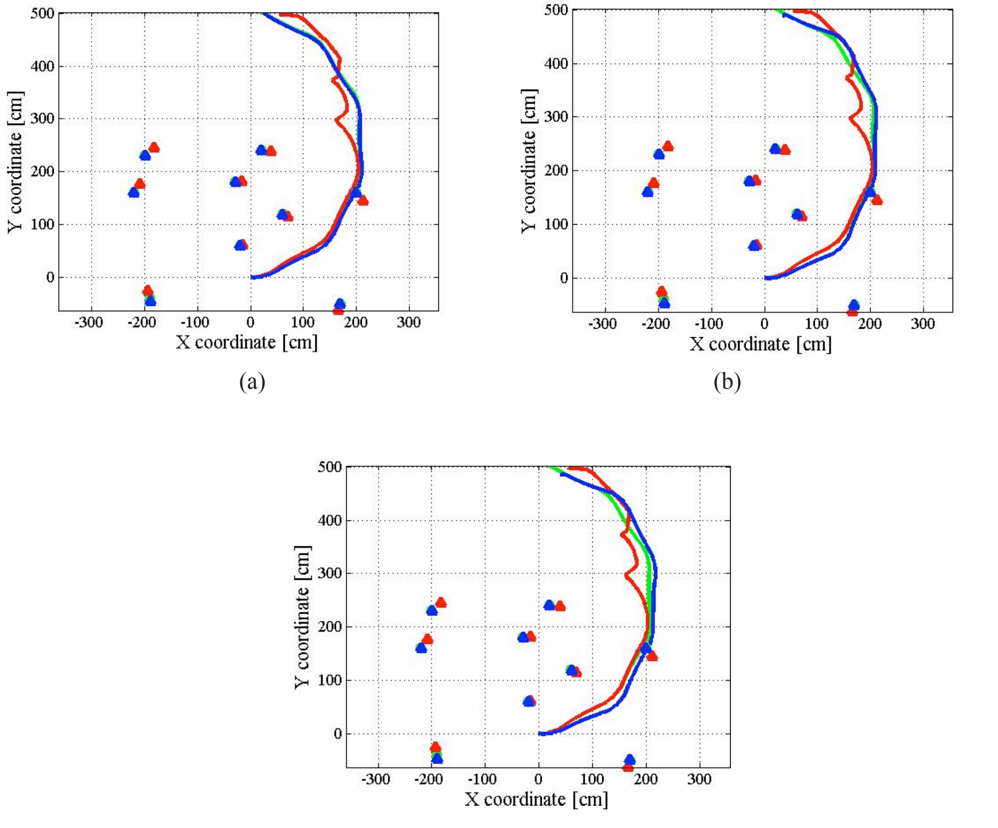

Figure 4. Comparison with different mobile robot movements; truth position (green), EKF estimation (red) (a) Performance of Fuzzy EKF-SLAM(blue) with Gaussian membership (b) Performance of Fuzzy EKF-SLAM(blue) with Triangular membership (c) Performance of Fuzzy EKF-SLAM(blue) with Trapezoid membership

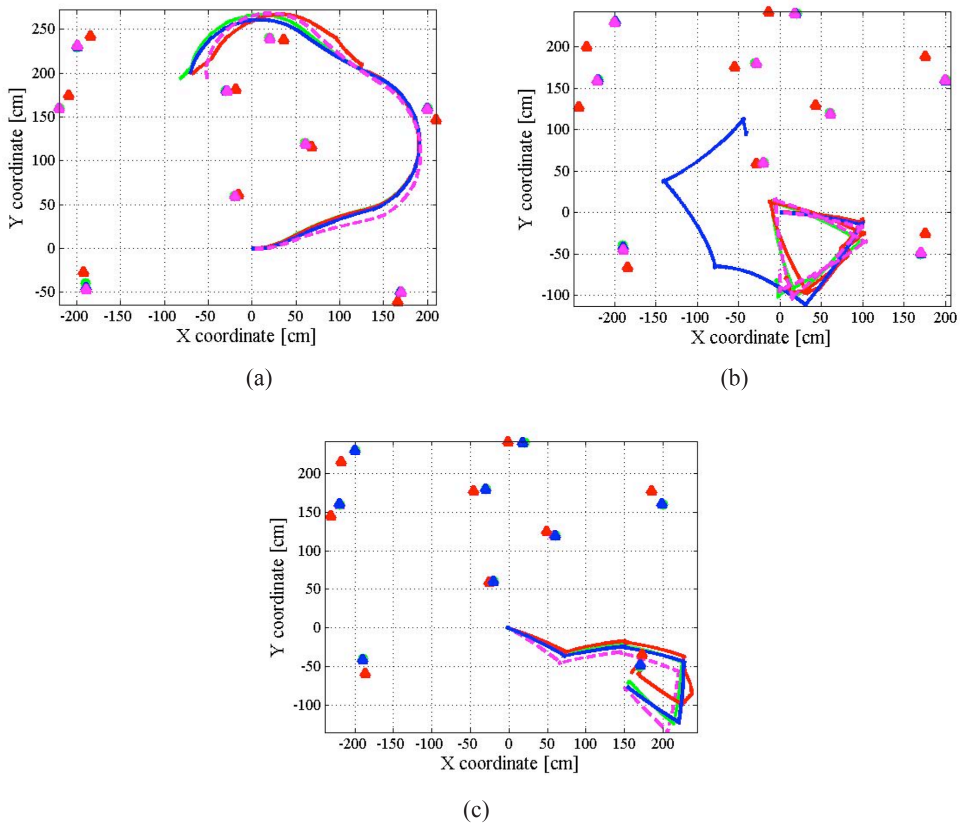

Figure 5. Comparison with different mobile robot movements; truth position (green), EKF estimation (red), Fuzzy EKF-SLAM(blue) with Gaussian membership and Fuzzy EKF-SLAM(magenta) with Triangular membership

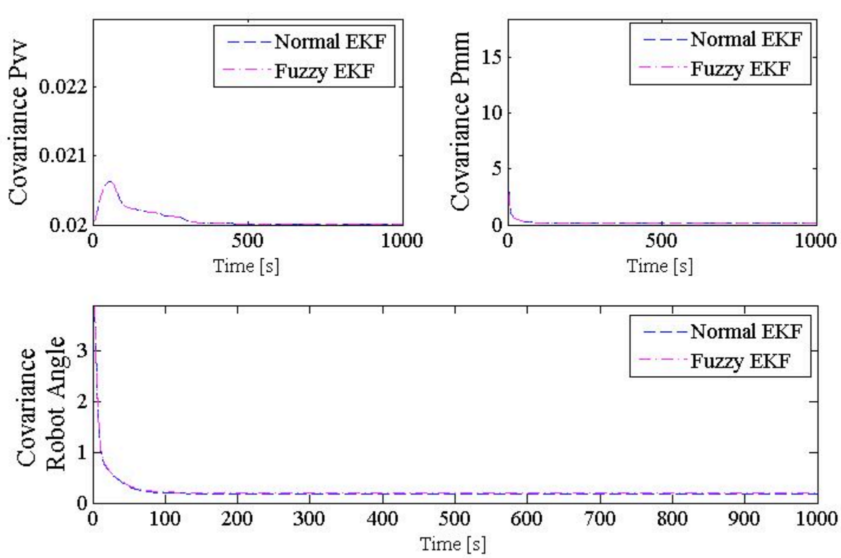

Figure 6. Comparison about the updated state covariance between normal EKF and Fuzzy EKF SLAM with Gaussian membership type

CONCLUSIONS

This paper proposed Fuzzy-EKF based mobile robot navigation problem analysis with different type of memberships. The Fuzzy Logic is applied to control the amount of information to be fed into the measurement innovation with very minimal number of rules. The number of rules cannot be increased further as it will affect the processing time for the mobile robot to perform its task. Tuning process on the Fuzzy Logic can be done on the fuzzy sets in finding the best configuration of the proposed technique. The Gaussian membership has shown a good performance in smooth mobile robot movements compared to the other two membership types; Triangular and Trapezoidal memberships.

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