Direction Estimation Error Model of Embeded Magnetometer in Indoor Navigation Environment

Guanxiong Liu, *Student Member, IEEE,* Yishuang Geng, *Student Member, IEEE*
Kaveh Pahlavan, *Fellow, IEEE,*
Center for Wireless Information Network Studies, Worcester Polytechnic Institute, Worcester, MA 01609 USA
Email: {gliu2, ygeng and kaveh}@wpi.edu

***Abstract*—With the development of the MEMS technology, it's becoming usual to embedded magnetometers, accelerometer and gyroscope inside the smart-phone. Therefore, the inertial hybrid localization technology is widely used to mitigate the inaccuracy in the standalone wireless localization results and improve the reliability in the absence of Radio Frequency Signal. One of the well known application is the WiFi localization assisted inertial navigation system, which is famous for its low cost, high availability and extraordinary accuracy. However, in the previous work, people fails to evaluate the performance of embedded magnetometers in different localization scenarios. In this paper, we build a hybrid localization platform on the Android smart-phone and conduct measurements with different indoor scenarios. From these results, we show that there are two kinds of error existed in the direction estimation. Based on the two error distributions, we simulate performance of the hybrid localization system and compare with the typical WiFi localization. The comparison gives the general idea of embedded magnetometers performance in different environment and will guide future study on algorithm design, system evaluation and application development.**

***Keywords*—wireless localization, inertial navigation system (INS), smart-phone localization, magnetometer, error model**

I. INTRODUCTION

Nowadays, the increasing needs of localization technology not only demond an accurate localization solution, but also require the reliability of localization system. With the well known received signal strength (RSS), time-of-arrival (TOA), angle-of-arrival (AOA) based approaches, location information can be obtained from open area by global positioning system (GPS) to the indoor environment where GPS signal is not available. Since wireless indoor localization requires the prior knowledge of the reference points and suffers from the multipath phenomenon caused by complicated indoor environment, the traditional pedestrian dead reckoning method maintains its priority in the absence of supporting infrastructure. To achieve the improvement of localization accuracy and reliability, research campaign proposed hybrid localization applications to combine wireless localization with traditional localization method.

One of the most commonly used platform to implement such hybrid localization system is smart-phone. The rapid development of the smart-phone has allowed it to integrate wide varieties of sensors. This advantage enables the development of a hybrid localization system based on smart-phone, which utilize data from the embedded sensors including magnetometer, accelerometer and gyroscope to build a inertial navigation system and combines it with the wireless localization. Compared with other existing indoor localization technologies, this hybrid localization approach is always under the limelight for its widely usability, higher localization accuracy and stronger reliability. Christian Lukianto et al. built the earliest prototype system that combine the inertial and wireless hybrid localization based on smart-phone and a independently developed inertial measurement unit (IMU). A step further, Wonho Kang et al. achieve to integrated the whole system by smart-phone. Instead of these works which have the assumption that the smart-phone is placed face up and head to the moving direction, Fan Li et al. build the system to handle the situation that the smart-phone is in the pocket. Note that in this paper, our measurement is based on the previous system setup.

Based on our literature search, all of the works we mentioned above generally focused on platform implementation, algorithm optimization and system integration. However, they merely have insight of the fluctuation among movement direction estimation. Wonho Kang et al. noticed the existance of unreliability of magnetometer in complex indoor environment, however, they still failed to provide detailed mathematical model of the direction estimation error. Although we can see in an intuitive way that the existence of the metal component will affect the performance of the magnetometer, it is essential and urgently to give the academic and industry a detailed model of magnetometer's error.

Among this paper, we firstly measure the magnetometer's performance based on several simple scenarios which including open space, metal doors and elevators. Based on the empirical data, the effect of the metal component to the direction estimation error is investigated. Then we take a further step to measure the direction estimation error in some real-world environments like grocery store and typical office building. To this part of measurement result, we take the previous analysis from simple scenarios and apply that to explain the magnetometer's performance. After pass through this validation process, the analysis of the magnetometer's performance can be uniformly used in general scenario which given the environment description. Therefore it may benefit future system performance analysis and algorithm design for hybrid localization system.

The remainder of this paper is organized as follows. In section II, the measurement system and measurement scenario has been introduced and necessary definitions has been provided for further analysis. In section III, the effect of metal component to the direction estimation in different scenarios has been analyzed. In section IV, the measurement has been repeated in the real-world environment and previous analysis has been applied to explain the magnetometer's performance. In section V, we summarize this paper and discuss future work.

II. SCENARIO AND SYSTEM SETUP

In this section, the measurement scenario, system setup as well as necessary parameter definitions have been discussed. We firstly conducted a series of isolated component measurements to analyze the relationship of direction estimation error and distance between metalic component and smart-phone. After that, we implement a inertial based system on the smart-phone to investigate the effect of metalic components on indoor pedestrians dead reckoning (PDR) localization. Finally, a INS/RF hybrid localization system has been developed to expand the performance analysis work towards nowadays practical localization approaches.

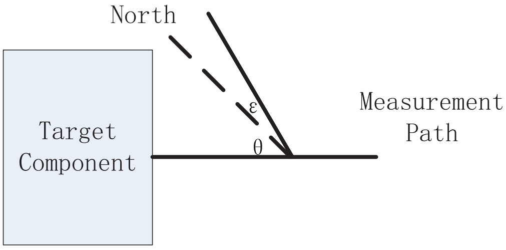


Fig. 1. Isolated Component Measurement. Measurement path is perpendicular to the metal component.

A. Isolated Component Measurement

During isolated component measurement, we choose a series of scenarios including open space, door and elevator. Both the door and elevator can be seen as regular metal component in the indoor environment while the open space measurement is used as a controlled trial. Like it shows in the Fig. 1, we locate the isolated components and get measurement path's direction through Google Earth as the ground truth.

Since all measurements are done at the Worcester, MA, USA, 1° changing in longitude is corresponding to 83Km in distance. Therefore, all of our measurements have the assumption that the reference direction (North) will not change during the process. The entire measurement process is performed using a self-designed android application on Samsung Exhibit II SGH-T679 smart phone, which runs on any android system above version 2.2 and is embedded with accelerometer and magnetometer for step detection and direction estimation respectively.

Then we do the measurements along that path at varieties of distances to the target component including 200cm, 100cm, 50cm, 40cm and 30cm. In each measurement points, we sample the data of the magnetometer with the frequency of 10Hz for 30 seconds. The defination of the direction estimation error is given as

$$\hat{\theta}_i = \theta_i + \epsilon_i \tag{1}$$

where the ϵ_i represent the i^{th} direction estimation error.

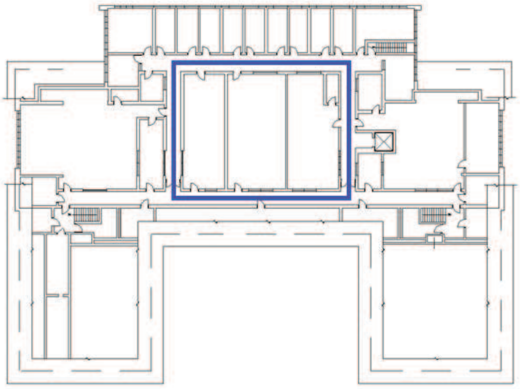


Fig. 2. 2D floor layout for Atwater Kent building, WPI.

B. Inertial Navigation

PDR navigation measurement in real-world environment is conducted in varieties of places. The open space measurement is done on the playground of the Worcester Polytechnic Institute (WPI), the grocery store environment is inside a grocery store and the typical office building is represented by 3^{nd} floor of the Atwater Kent Laboratory, the office building of ECE department at the WPI as shown in Fig. 2. In all four scenarios, rectangular trajectory has been selected for measurement and the four edges of the rectangle is defined as 1^{st} to 4^{th} sub-path in order. The objective first and foremost goes through a training process to obtain the average step length l and then walks along the main corridor on a constant speed, holding the smart phone in hand. The measurement starts from one randomly selected corner in the path and lasts for three entire cycles. Note that constant walking model is not a limitation on this work, preliminary results shows that following discussion still applied to random walking situation and it will be mentioned in future publications.

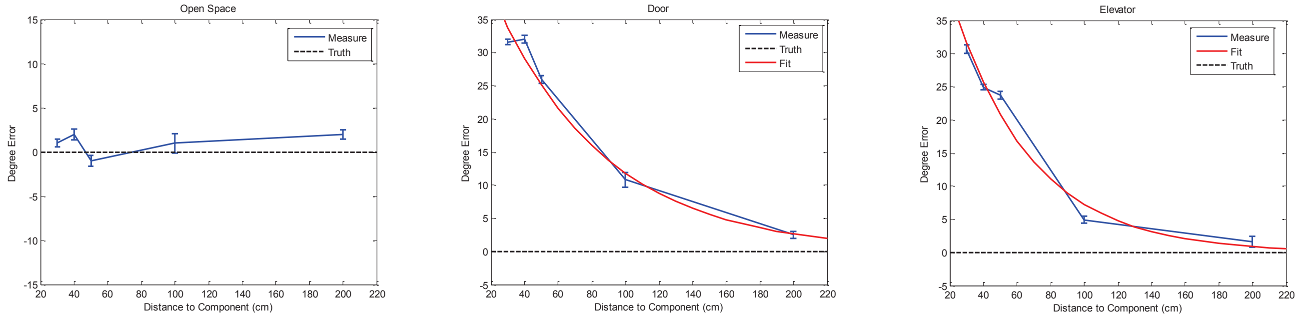
In our inertial based localization system, the pre-defined relative coordinate sets the origin position at (50, 0) and ground truth direction of the 1^{st} sub-path is relative North. The data is collected at every time a step is detected and PDR particle is recorded in the format of $(\hat{x}_i, \hat{y}_i, \hat{\theta}_i)$ where $\hat{x}_i$ and $\hat{y}_i$ is the position in relative coordinate and $\hat{\theta}_i$ is the angle between moving direction and relative North. The update process of particles is showed as below

$$\hat{x}_{i+1} = \hat{x}_i + (l + \epsilon(l)) \sin(\hat{\theta}_i) \tag{2}$$

$$\hat{y}_{i+1} = \hat{y}_i + (l + \epsilon(l)) \cos(\hat{\theta}_i) \tag{3}$$

$$\hat{\theta}_{i+1} = \hat{\theta}_i + \delta\hat{\theta} + \epsilon(\theta) \tag{4}$$

where $\delta\hat{\theta}$ denotes the the direction change, $\epsilon(l)$ and $\epsilon(\theta)$ are error terms drawn from the step length and direction estimation respectively. The iterative process indicates that the beginning state is required for this approach. Note that due to the training



(a) (b) (c)

Fig. 3. Direction Estimation Error Distribution Fitting. (a) Open Space; (b) Door; (c) Elevator

process of the step detection algorithm and the constant speed walking, the step length error is constrained at 0.2 meter. To evaluate the localization accuracy, we define the localization error for a specific PDR particle as

$$\epsilon_i = \sqrt{(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2} \tag{5}$$

where x_i, y_i are the ground truth coordinate for i^{th} PDR particle.

C. Hybrid Localization

To catch up with the latest technology and investigate the effect of direction estimation error on the performance of INS/RF hybrid localization systems, we combine the previously mentioned PDR approach with wireless localization approach, in which we use Kernel Method with the Gaussian kernel function and the reference point data is collected at the four corners at the 3^{nd} floor AK Building. The equation of the Gaussian kernel method is showed as

$$p(o|l) = \frac{1}{n}\sum_{i=1}^{n} K(o : o_i) \tag{6}$$

$K(o : o_i)$ denotes the Gaussian kernel function with observation o and the i^{th} training data o_i. $p(o|l)$ represents the probability that at location l we get the observation o which is calculated by take the equally weighted Gaussian kernel results. The detailed Gaussian kernel function is shown below

$$K_{Gauss}(o : o_i) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(o - o_i)^2}{2\sigma^2}\right) \tag{7}$$

where σ is the adjustable parameter that is used to determines the width of the kernel.

To combine the inertial navigation result with the wireless localization, we use the Kalman filter to do the off-line statistical signal processing. In the state prediction part, the Kalman filter takes the inertial navigation data and calculates the position result corresponding to the previous PDR particle update equations.

$$\bar{p}_t = f(p_{t-1}, \mu_t) = Ap_{t-1} + B\mu_t \tag{8}$$

$$\bar{p}_t = \begin{bmatrix} \bar{x}_t \\ \bar{y}_t \end{bmatrix} \quad p_{t-1} = \begin{bmatrix} x_{t-1} \\ y_{t-1} \end{bmatrix} \quad \mu_t = \begin{bmatrix} \sin\theta_t v_t \\ \cos\theta_t v_t \end{bmatrix} \tag{9}$$

$$A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad B = \begin{bmatrix} t & 0 \\ 0 & t \end{bmatrix} \tag{10}$$

where $\bar{p}_t$ is the t^{th} position prediction, p_{t-1} is the $t-1^{th}$ position and μ_t is the t^{th} inertial navigation data. Since the wireless localization also gives the position result directly, the Kalman filter's sensor prediction process is just use an unit matrix to transfer the state prediction to sensor prediction

$$\bar{z}_t = C\bar{p}_t \quad C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{11}$$

and the working process of the Kalman filter is showed as

$$\begin{cases} \bar{p}_t = Ap_{t-1} + B\mu_t \\ \bar{E}_t = AE_{t-1}A^T + E_p \\ K_t = \bar{E}_t C^T (C\bar{E}_t C^T + E_z)^{-1} \\ p_t = \bar{p}_t + K_t(z_t - C\bar{p}_t) \\ E_t = (I - K_t C)\bar{E}_t \end{cases} \tag{12}$$

where E_p is the error in the inertial navigation result, E_z is the error in the wireless localization result, E_t is the t^{th} error in the whole Kalman filter result and K_t is the so-called Kalman filter gain.

III. EFFECT OF THE VARIOUS METAL COMPONENT ON DIRECTION ESTIMATION ACCURACY

The general direction estimation result along the measurement path toward a metal door is showed in the Fig. 3(b). As for the bar figure of the direction estimation, it is very obvious that result keeps drifting away from the ground truth when the measurement position keeps forward to the metal door. Such drifting phenomenon agree with the pure inertial navigation system performance showed in other's works. When the smart-phone is at 200cm away from the metal door, there are nearly no error between the direction estimation and the ground truth. The error become 10° when the measurement is located at 100cm and it's speeding up to drift away from ground truth in the same direction when it gets close to metal door. Finally, the error reaches 30° at distance of 30cm.

We repeat the same measurement process at the open space and in front of elevator and show the bar figure of the result. As we seen from the Fig. 3(c), the direction estimation error with elevator in front also has the similar property that error may increase when the smart-phone is getting close to the elevator. Compare with the open space measurement result in the Fig. 3(a), we can see that metal component has significant effect on the direction estimation. Finally, we come up with a mathmatical model of the distance to metal component and the magnetometer's estimation error in degree.

$$\epsilon = \alpha \times e^{\beta d} \tag{13}$$

where ϵ is the direction estimation error, d is the distance to component and (α, β) is coefficient.

Component	α	β
Door	53.05	0.015
Elevator	59.41	0.021
Metal Shelf	51.63	0.015

IV. ANALYSIS OF DIRECTION ESTIMATION ERROR AMOUNG PDR LOCALIZATION

Since we have shown that the metal component can cause a significant error in direction estimation when the measurement is conducted within a range of the component, in this section we analysis the direction estimation error in PDR localization. In real-world environment the corridor in building is usually within the width of 2 to 3 meter, people who walking through the corridor can be seen as walking through the middle line of the path. When the corridor has several metal doors or elevators around, since the distance between user and these components is always less than 150cm, there will be a continues direction estimation error inside the user's inertial navigation result. Therefore, we conducted several different real-world scenarios to test the performance of the inertial navigation system and results are showed in the Fig.4 .

Generally from Fig.4 and Fig.5, we can see that inertial navigation system has the best accuracy in the open space environment. Each sub-path has similar direction with its corresponding ground truth. When we move into the grocery store, even in the wood shelf environment, the result shows bias error in some sub-paths. Such bias becomes increasingly significant in the metal shelf and typical office building environment. To look into the error inside the direction estimation in the inertial navigation system, we seperate magnetometer's data in each sub-paths at grocery store with metal shelf and typical office building environment and try to fit the direction estimation error distribution.

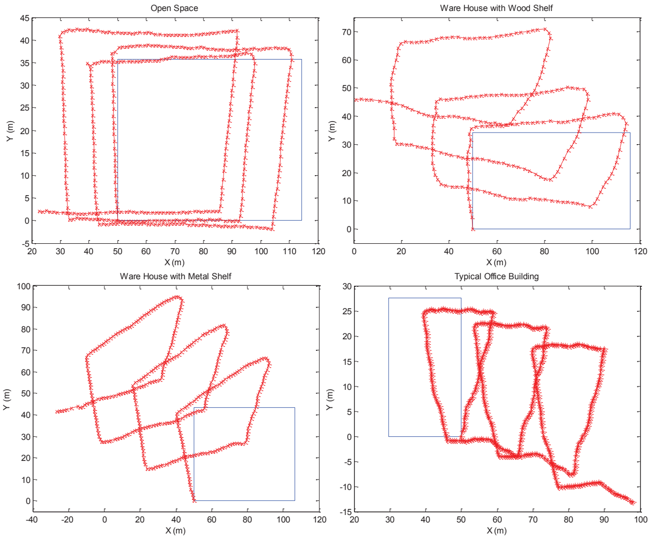
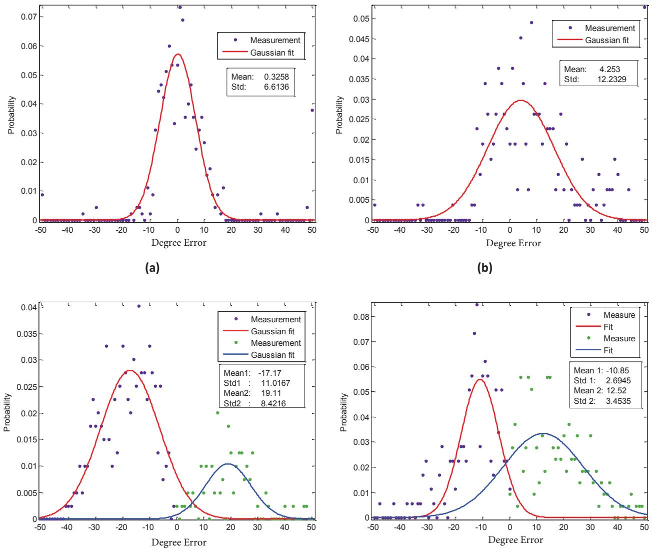
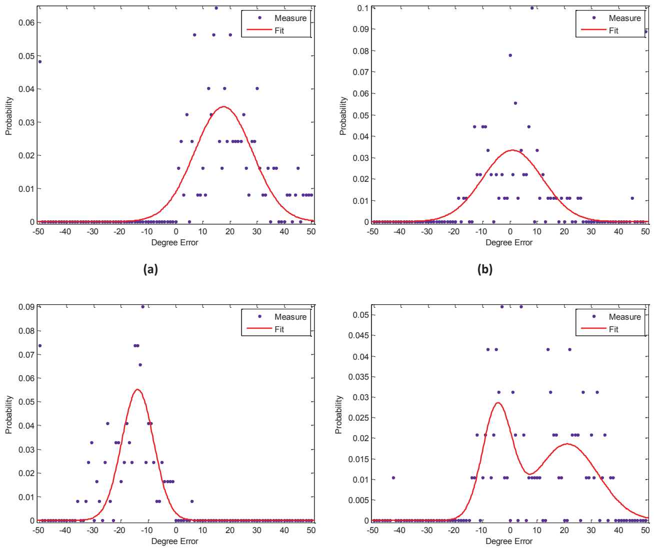


Fig. 4. Real-world Environment Measurement. (a) Open Space; (b) Grocery Store with Wood Shelf; (c) Grocery Store with Metal Shelf; (d) Typical Office Building



(a) (b) (c) (d)

Fig. 5. Direction Estimation Error Distribution. (a) Open Space; (b) Grocery Store with Wood Shelf; (c) Grocery Store with Metal Shelf; (d) Typical Office Building



(a) (b) (c) (d)

Fig. 6. Direction Estimation Error Distribution in typical office building. (a) Sub-path 1; (b) Sub-path 2; (c) Sub-path 3; (d) Sub-path 4

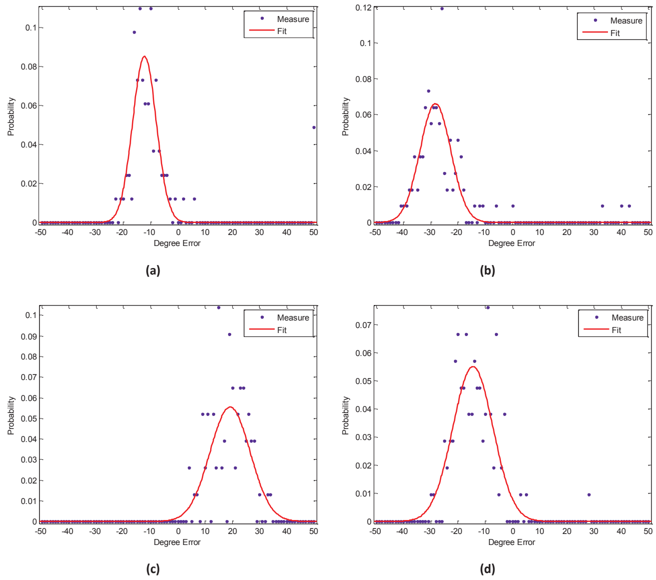


Fig. 7. Direction Estimation Error Distribution in grocery store with metal shelf. (a) Sub-path 1; (b) Sub-path 2; (c) Sub-path 3; (d) Sub-path 4

In the Fig.6, the fitting result shows that the direction estimation error in the 1^{st} and 3^{rd} sub-path forms a Gaussian Distribution with siginificant biased mean. This is highly agree with the real environment in which the corrider width is 1.8 meter and there are continues metal door along the corrider. In the 4^{th} sub-path, the error distribution is a mix of zero mean Gaussian and a bias mean Gaussian which is because of a large metal door in near middle point of the path. Along the 2^{nd} sub-path, the only metal component is the elevator and it has 1.5 meter to the right side of that sub-path. Therefore, the error distribution is nearly a pure zero mean Gaussian.

Also, we do the same analysis to the result of the grocery store with metal shelf in Fig. 7. Since this measurement is around the metal shelf, it shows the bias mean Gaussian Distributed error in each sub-path. Among four sub-paths, the bias in 2^{nd} and 4^{th} sub-path are higher which is because there two sub-paths are the narrow path through two metal shelves.

V. PERFORMANCE OF HYBRID LOCALIZATION UNDER DIFFERENT DIRECTION ESTIMATION ACCURACY

The previous section shows that in the absence of metalic component, the direction estimation error forms a zero mean Gaussian Distribution while with the existance of metalic components, it turns out to be a bias mean Gaussian Distribution. In this section, we use the direction estimation error model to simulate the performance of the overall hybrid localization system. The simulation generates inertial navigation data with zero/bias mean Gaussian Distributed Error and combines them with the wireless localization result by Kalman filter.

Performance of hybrid localization with zero mean direction estimation error has been depicted by CDF plot in Fig. 8. With 20^o direction estimation error, the distance measurement error (DME) of hybrid localization approach is 2m superior to typical RF localization. Even if the direction estimation error rise up to 50^o, the performance of hybrid approach is still comparable with RF localization. Such result shows that without the infludence of metal components, inertial based approach can adequately support the hybrid localization.

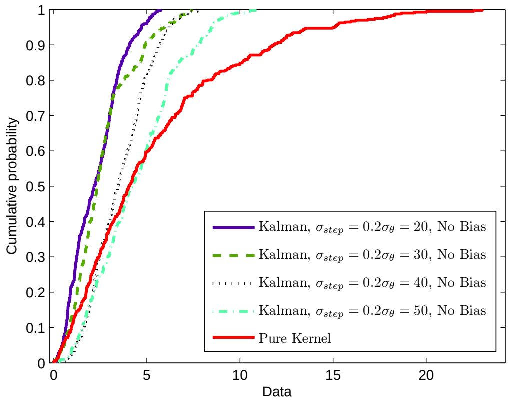


Fig. 8. Zero Mean Error Distribution Simulation Result

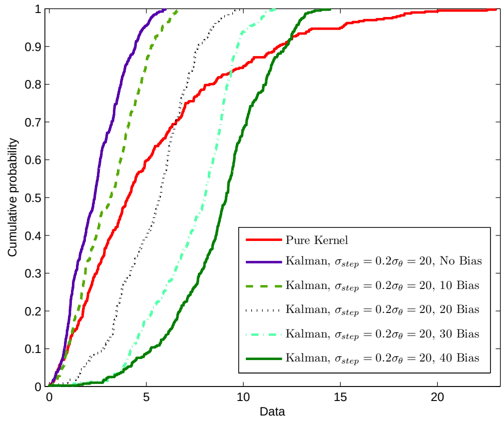


Fig. 9. Bias Mean Error Distribution Simulation Result

With bias mean direction estimation error caused by metal components, simulation results has been shown in Fig. 9. Whenever there exist the effect of metal components, inertial based approach can only provide limited support to hybrid localization. With the bias error goes beyound 20^o, the performance of hybrid localization is even worse than typical RF approach. Such understanding can be used in the future algorithm optimization, system analysis and performance evaluation.

VI. CONCLUSION AND FUTURE WORK

The major contribution of this paper is that we analyzed the effect of metal component and the distance to these components on magnetometer's direction estimation error for smartphone based inertial navigation system. A simple error model has been proposed for indoor inertial navigation performance analysis and it also facilitates the future work on algorithm design, system integration and application development.

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