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Sensor Fusion Based Discrete Kalman Filter for Outdoor Robot Navigation

Mbaitiga Zacharie

***Abstract*—**The objective of the presented work is to implement the Kalman Filter into an application that reduces the influence of the environmental changes over the robot expected to navigate over a terrain of varying friction properties. The Discrete Kalman Filter is used to estimate the robot position, project the estimated current state ahead at time through *time update* and adjust the projected estimated state by an actual measurement at that time via the *measurement update* using the data coming from the infrared sensors, ultrasonic sensors and the visual sensor respectively. The navigation test has been performed in a real world environment and has been found to be robust.

***Keywords*—**kalman filter; sensors fusion; robot navigation

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I. Introduction

ANIMALS are equipped with an astonishing variety of specialized sensors that enable them to monitor both their internal and external environment. Migrating birds are able to detect changes in their orientation with respect to the earth's magnetic field and use this information for navigation. Small bird called the bobolink spends summers in Canada and United-States and winter in South America, particularly in Brazil, Bolivia, and Argentina, a distance of some 7.000 km. So how do these birds accomplish this remarkable navigation? The answer is still not clear, and it varies depending on the species, but it is known that birds navigate using earth's magnetic field, the orientation of the sun, the orientation of stars and landmarks near their destinations, such as mountains and lacks. Although the ability of birds to use their information is known and has been verified by ingenious experiments such as raising birds in totally no magnetic environments, or in closed areas with an artificial sun that can be placed in an arbitrary location, the precise nature and the location of the sensors is not known. The navigation of feats of monarch butterflies is even more astounding than those of birds. These butterflies fly from Northern Mexico to sites throughout the Western United-States in the winter and early spring. The butterflies that return the following year are the children or grand children of those earlier migrants. The question is, where is the navigational map stored in those tiny insects? How do they pass it on to later generation? In some cases animals are able to determine the value of a particular variable by processing of sensory inputs. Such as observation of the waggle dance of the honey bee allows other bees to determine the vector direction and approximate distance to a source of pollen. Such a determination implies a form of computation, but not necessarily any associated intelligence. The bottom line of these quick examples is that animals have evolved a variety of specialized mechanisms to aid them in navigation, including the ability to sense the earth's magnetic field and the orientation of the sun and fixed stars, as well as visual sensing landmarks. Like their counterparts in the animal kingdom, robots also need sensors both to receive information from the outside world and to monitor their internal environment. Being able to operate in unstructured environment, robots will be faced with more and more difficult problems of orientation and navigation. When a robot is moving indoors on smooth surfaces over short distances, with unobstructed visibility, these problems are not severe. In such situations the robot may have a clear view of a target location and use vision for navigation. In other cases the robot can navigate to a specified target simply by using wheel encoders and converting the distance to be traveled into wheel revolution. This is Odometry or Dead Reckoning. That is, the process of determining the change in a robot's position and orientation over time by integrating its velocity with respect to time. It has a long history in navigation at sea, where it was for a long time the principal method for estimating one's map position, frequently with large errors. This method is generally not satisfactory across long distances over uneven terrain, since different wheels will experience different amount of slippage. Even on smooth floors, since its wheels are not identical, a robot actual path will gradually drift away from the desired path to the goal. The navigation task that we deal with in this research concerns the answer to the question, how do I get to the goal within the allocated time? The task involves obstacles in a terrain of varying friction properties.

Mbaitiga Zacharie is with the Department of Media Information Engineering, Okinawa National College of Technology, Nago-city, 905 Henoko Okinawa, Japan (e-mail: zacharie@okinawa-ct.ac.jp).

II. Previous work short review

With the ongoing development of the technology, the robots today are so performant that they play an important role in our everyday life in the same way the internet does because of their high workability. The robots are used for entertainment, in the factory to assemble goods, to pick up materials from one place and put them to a specified place with precision, to transport things. They are used for tasks that are difficult and dangerous for man to perform. When it comes to security, robots are used in public buildings, universities, companies and as well as for home security to mention only a few. And the most difficult problems the robots designers encounter, is when the robots are assigned to perform a task or to operate in an unknown dynamic environment due to many factors; such as the environmental

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changes that may change the robots navigation system causing them not to operate as expected. To deal with the environment al factors mentioned above the sensors fusion become necessary in order to reduce the environmental influence over the robots navigation system. Although the sensors fusion is not an easy task to deal with due to competing information provide by each sensor, many works have been proposed over the years. [1] proposed the fault tolerance sensor fusion approach for coupling multi-sensor information and robot's actions through the interaction between the robot and the environment. They formalized their process by utilizing the reinforcement learning scheme known as Q-learning proposed by [2]. And the vector quantization technique known as a Kohonen network proposed by [3] is applied to reduce the dimensionality of the sensor data during the exploration in the environment and used as states for a reinforcement learning method to obtain the target reaching behavior. Following by the local model networks (LMN) for plants modeling based on the work of [4] as they are looking for faults on wheels of the robot such as blocked wheels or servo failures. [5] discussed the mobile robot navigation using sensor fusion based only on nonlinear model predictive control scheme [6-7], which takes a finite number of Newton step in each sampling period instead of solving the complete optimal control problem and the robot localization is obtained using information from odometry ultrasonic sensors through an extended Kalman filter.

But this approximation is only valid for small deviation from the trajectory, which the system is linearized around. [8] introduced a multi-sensor fusion for mobile robot navigation in an indoor environment inspired by the work of [9]. The method deals with the general problem of concurrent localization and map building, which based on dividing the environment into two dimensional grid cells. Each cell is divided in two states: occupied or empty and to each cell there is a probability P attached, which reflects the belief of the cell being occupied by an object. The notion of occupancy grid maps were introduced in the 1980s by Moravec and Elfes are a popular probabilistic approach to represent the environment. They are an approximate technique in which one can calculate for each cell of a discrete grid the posterior probability that the corresponding area in the environment is occupied by an obstacle. But the disadvantage of this method lies in potential discretization errors and high memory requirements.

III. ROBOT TYPE IN THE EXPERIMENT

The robot used in this experiment shown in Fig.1 is a scout robot with a rugged wheeled Wi-Fi equipped with two gripping arms (5-DOF Arm ×2+1-DOF Gripper ×2) that optionally provide the robot with one wrist-mounted complementary metal-oxide semiconductor (CMOS) camera installed on it right arm. Combining mobility and a new ability to grasp and manipulate, the robot offers users broad versatility in its application. The wheels-based platform consists of 12V DC motors with integrated 800 counts per cycle optical encoder, yielding a top speed of 0.75ms^{-1}. The robot is light as its weights only 4kg with a capability to carry a maximum payload of 15 kg. Concerning the sensors types, the robot comes with ultrasonic range sensors and Infrared range sensors including two-way audio capability. These range sensors are for environment detection and collision avoidance, while the two-way audio is for communication between the robot and the user. The collision avoidance and the sensing may not be correct by information acquired from the only vision, therefore three ultrasonic sensors, with one located at the middle front bottom, one in the left front bottom hand side and one in the right front bottom hand side of the robot are integrated. The middle front sensor is used for detecting obstacle, while those at each side are used for assisting the six infrared sensors of which one is located at the middle front upper just above the middle front bottom of the ultrasonic sensor, one in the upper front left, one in the upper front right, one in the rear middle, one in the rear left and one in the rear right of the robot respectively. Two quadrature encoders are also integrated in the robot, where the left one use the channel1 and the right one use the channel 2. DC servomotor is used for steering and driving the scout robot.

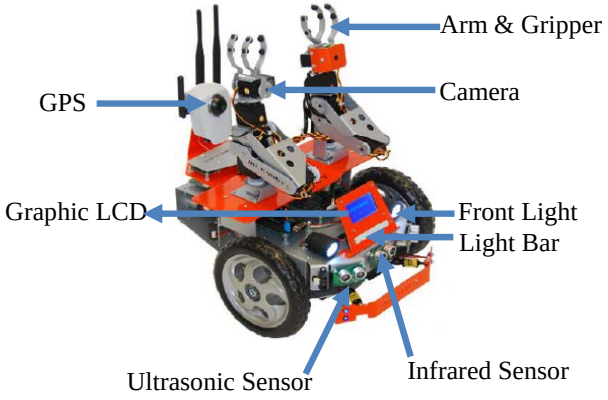


Fig. 1 Multi-DOF gripping arms robot

IV. DISCRETE KALMAN FILTER APPROACH

The Kalman filter is a set of mathematical equations that provide a computational means to estimate the state of a process being controlled by minimizing the mean of the squared error. The efficiency of the Kalman filter resides over its ability to predict with some precisions the state of a process in the past, present and future. In practice the individual state variables of a dynamic system cannot be determined exactly by direct measurements, instead we usually find that the measurements that we make are functions of the state variables and that these measurements are corrupted by noise. The system itself may also be subjected to the noise observations. To implement the Kalman Filter in our system, we consider as a condition the linearization of the system (1) about the estimate state $\hat{x}(k)$ and the control signal u_k. The linearization of the system is defined by:

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$$\dot{x} = f(x)u \tag{1}$$

Where:

$x \in \Re^n$ = column of f(x) from the null space Ω(x).

and

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ si\theta & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} v \\ \omega \end{bmatrix} = f(x)u \tag{2}$$

Where:

x_1 and x_2 = robot positions.

θ = robot orientation.

v = robot linear velocity.

ω = robot angular velocity.

The two equations that govern our proposed Kalman Filter are:

- Time update.

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k + \varepsilon_k \tag{3}$$

- Measurement update.

$$y_k = Cx_k + z_k \,. \tag{4}$$

The Kalman gain is defined by:

$$K_p = \frac{P_k H^T}{HP_k H^T + R}. \tag{5}$$

Where:

A, B, C = two dimensions matrices.

k = time index.

$\hat{x}$ = state of the system.

u = know input of the system.

Y= measurement output.

ε_k = process noise.

z_k = measurement noise.

R = measurement covariance matrix.

H = matrix.

Each of these quantities are vectors and therefore contain more than one element. In our system the measurement covariance matrix R is changed with each time step to reflect the position of the robot during its navigation. The vector x contains all of the information about the present state of the system, but we cannot measure x directly. The time update equation is used to project forward in time the current state and error covariance estimate to obtain the estimate state for the next time step. The measurement equation is used for incorporating a new measurement into the deductive estimate state to obtain an improved inductive estimate state. The first task during the measurement update is the computation of the Kalman gain k, before measuring the process to obtain the measurement noise z_k, and then to generate an inductive estimate state by incorporating the measurement using (6). And finally from (7) we obtain an inductive error covariance estimate.

$$\hat{x}_k = \hat{x}'_k + k_k(z_k - Hx_k) \tag{6}$$

$$P_k = (\alpha - K_k H)P_k^- \tag{7}$$

Where:

H represents the matrix that relates the state to the measurement z_k.

P_k^- is the robot position noise.

Here also the matrix, H changes with each time step or measurement. After each time and measurement update, the process is repeated with the previous inductive estimate state used to project or predict the new deductive estimate state. The ongoing filter cycle is represented in Fig.2.

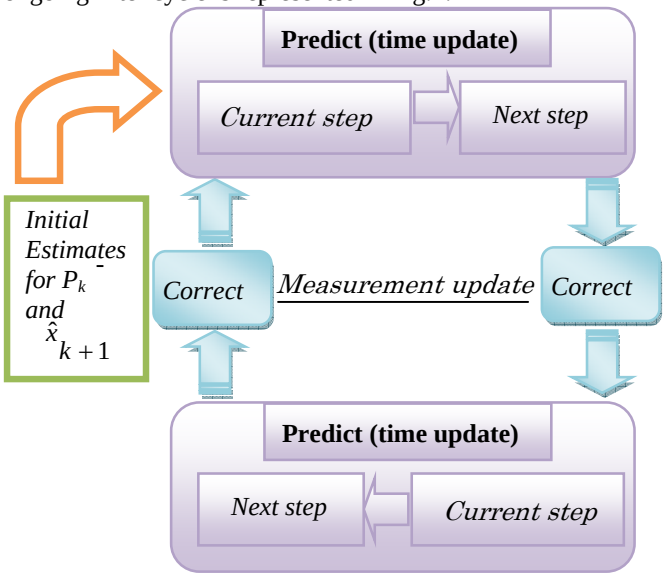


Fig. 2 The ongoing Discrete Kalman filter cycle

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V. EXPERIMENTAL RESULT IN REAL WORLD ENVIRONMENT

The experimental test is performed in a real world environmental in the college campus near the car parking, with a surface area of 100 × 100 square meters. This terrain is chosen due to its friction properties and the huge number of obstacles that can be found, which is suitable for testing the obstacle avoidance system. The program is written in C# with Visual Studio 2008 under .Net3.5. The SDK contains the facilities for memory management, system communication, user interface and utilities for audio-video input-output and sensor data acquisition. Commands and instructions send to robot are via wireless link and pass at rates exceeding 10Hz, providing real time control and access. The robot is placed for about 10 m from the first obstacle which is a rock with approximately 50 cm high and weight 3kg. All of the obstacles are arranged in such manner the robot should travel diagonally in the test area. There is no specific reason for letting the robot traveling diagonally in the test area instead due to the weight of some rocks we cannot move that forces us to decide in this way. Prior the test, three sensors: vision, infrared and ultrasonic sensors are activated for collecting the data sending in real time by the robot to the base station for future study. From the base station the robot location can be observed through the camera. The parameters involved in the test are:

- Linear velocity v = 0.70 m/s.
- Angular velocity ω = 0.2 rad/s.
- Orientation angle is to be 5° or around 0.08 rad/s.
- Maximum infrared sensor error is 0.10%.
- Maximum ultrasonic sensor error is 0.05%.

The initial value of the covariance matrix R is taken to be 80 times as R should be as large as possible. In our approach the process noise covariance matrix Q is not used. The results are shown as:

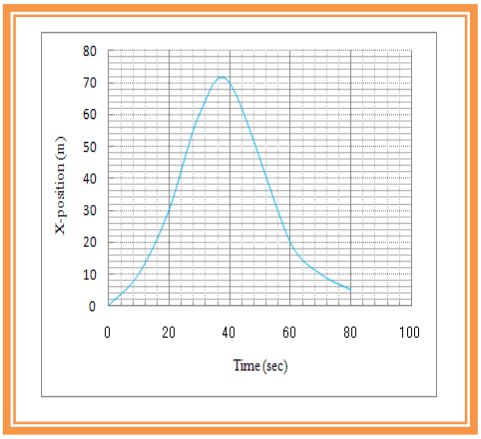


Fig. 3 Robot true x-position

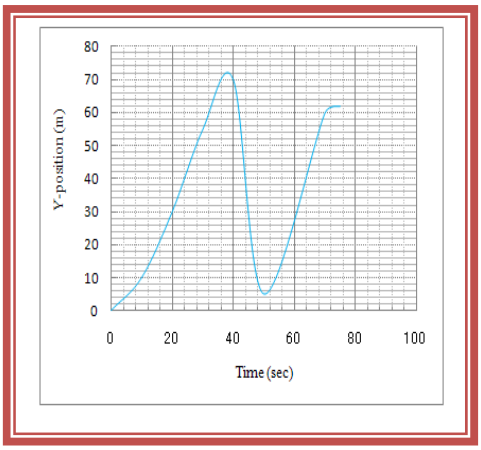


Fig. 4 Robot true y-position

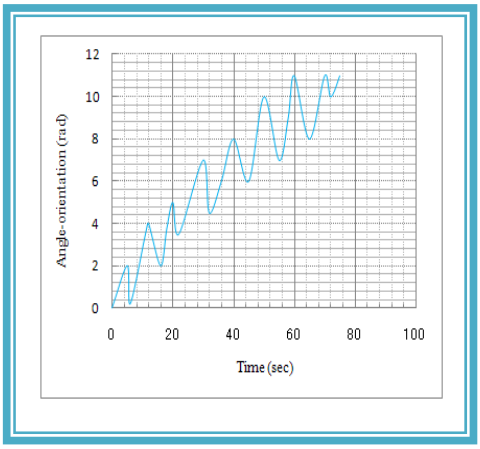


Fig. 5 Robot orirntation angle

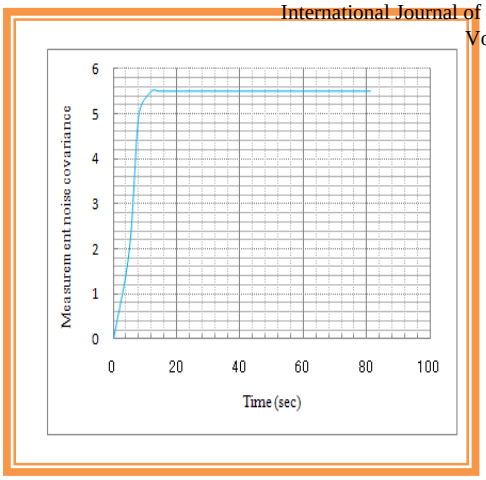


Fig. 6 Measurement noise covariance R

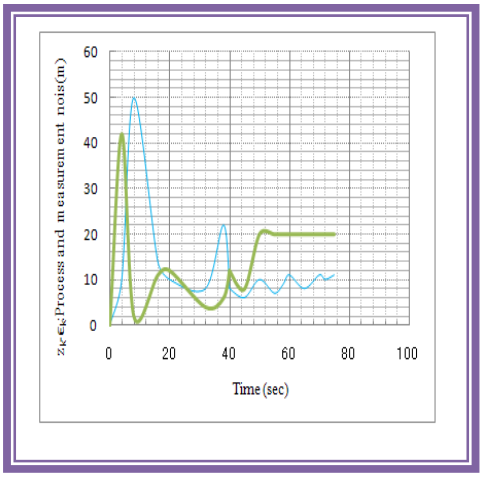


Fig. 7 Process and the measurement noise

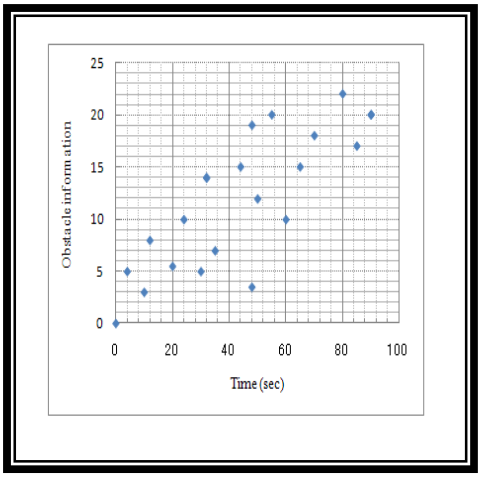


Fig. 8 Obstacles position in the test area

In many works in the open literature on Kalman filter it is difficult to see the true value of the measurement noise because it is difficult to know the true position of the robot. But in our proposed approach the true value of the robot position as well as the measurement value of the noise is known. So we can say that our filter has performed well.

VI. Conclusion

In this study we implemented the Kalman filter for reducing the environmental influence on robot navigation system when the robot is to be navigating over an uneven terrain with friction properties. The experimental test is performed in a real world environmental, where the time update is used to project forward in time the current state and error covariance estimated to obtain the estimate state for the next time step. The measurement update is used for incorporating a new measurement into the deductive estimate to obtain an improved inductive estimate. Although during the robot navigation the measurement noise can be observed the robot does get to its goal within the expected time.

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