Kalman Filter Algorithm Design for HC-SR04 Ultrasonic Sensor Data Acquisition System

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***Abstract*—In the control system application, the existence of noise measurement may impact on the performance degradation. The noise measurement of the sensor is produced due to several reasons, such as the low specification, external signal disturbances, and the complexity of measured state. Therefore, it should be avoided to achieve the good control performance. One of the solutions is by designing a signal filter. In this paper, the design of Kalman Filter (KF) algorithm for ultrasonic range sensor is presented. KF algorithm is designed to overcome the existence of noise measurement on the sensor. The type of ultrasonic range sensor used is HC-SR04 which is capable to detect the distance from 2 cm to 400 cm. The discrete KF algorithm is implemented using ATMega 328p microcontroller on Arduino Uno board. The algorithm is then tested with different three covariance values of process noise. The test result shows that the KF algorithm is able to reduce the measurement noise of the ultrasonic sensor. The analysis of variance conducted shows that the smaller value of covariance matrix of the process and measured noises, the better filtering process performed. However, this results in a longer generated response time. Thus, an optimization is required to obtain the best filtering performance.**

***Keywords*— distance sensor, signal, Kalman Filter, optimization, HC-SR04**

I. INTRODUCTION

A good sensor system is required in the design of a control system. Besides the reliability of the control method designed, good control process is also influenced by the performance of the sensor system. As it is known, one of several things that needs to be avoided in a sensor system is the presence of noise measurements. Noise on the sensor leads to consistency of measurement data becomes unstable. This, of course, will lead to a decline in the performance of the resulting control. One method that can be used to overcome this problem is to design algorithms filtering. Filtering process can be done in two forms, namely: hardware and programming algorithms. Filtering in the form of hardware can be built using electronic circuit scheme. However, it is less effective because it requires additional circuit scheme on the system. To overcome this obstacle, filtering in the form of programming algorithms into one method that can be used. Besides it does not require the electronic hardware scheme, the performance of filtering produced is even more accurate because it uses the computing process.

This paper discusses the design process of Kalman Filter algorithm (KF) to process the data acquisition system is an ultrasonic sensor. KF is an algorithmic filter which was introduced in 1960 by RE Kalman through the publication of an article about the new approach filters linear process problems and prediction [1]. The KF algorithm works by estimating the state measurable recursively. The KF algorithm is designed and implemented on type ultrasonic sensor HC-SR04. This sensor is one type of optical sensor which serves to detect the distance. Ultrasonic sensors are widely used for control systems and computer applications such as control systems, and water level monitor [2], firefighting robot [3], and the automatic vehicle braking system [4].

Studies on the application of the KF algorithm of ultrasonic sensors have been widely carried out. The implementation of the ultrasonic sensors in the system of KF Wireless Sensor Networks (WSN) for logistic purposes has been carried out [5]. Then, The KF algorithm has also been applied to monitor the water level using ultrasonic sensor [6]. Recently, the Extended Kalman Filter algorithm (EKF) has been developed for fusion ultrasonic sensor, Inertial Measurement Unit (IMU), and Magnetometer on the spacecraft [7].

In contrast to those previous studies, this paper briefly outlines the stages of the KF algorithm design for the type of the ultrasonic sensor type HC-SR04 which is widely used in computer system application. The KF algorithm design is described simply to make it easier to study. In addition, this study focuses on the analysis of the performance of the KF algorithm designed. Comparison of parameter covariance matrix of the process noise and measurement noise in the formulation of the KF algorithms are tested to determine the performance of filtering process resulted. Thus, it can be discovered the influence the election of the second parameter of the covariance matrix of the performance of filtering as well as the response time of the dynamic model sensors.

II. ULTRASONIC SENSOR

The ultrasonic sensor type HC-SR04 is used as a sensor system to detect the distance. This sensor has two transmitters that serve as transmitter and receiver. At the output, the sensor has four pins, namely Vcc, Trig, Echo, and Gnd, as shown in Fig. 1.

Fig. 1 HC-SR04 ultrasonic sensor, front (left), rear (right) (datasheet).

The sensor works by emitting ultrasonic wave through the transmitter and then reads the wave reflection using the

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receiver when there is no object detected. The ultrasonic wave is emitted by the transmitter via pin Trigger that is given the pulse signal by the microcontroller. Then, the reflected wave received by the receiver is forwarded to the microcontroller via pins Echo. From the concept, it can be seen that the ultrasonic wave is emitted when the sensor is given a pulse signal with a period of 10 μs via pin Trigger. The ultrasonic wave emitted and reflected has a frequency of 40 KHz. The resulting lag time between the transmission and reflection wave is used as a reference to calculate the distance of the sensor to the object. Based on the datasheet sensor type HC-SR04, the amount of distance can be calculated using (1).

$$s = 1kT \quad (1)$$

with s is the distance, T is the wave period in units of microseconds, and k is a constant. The k value is adjusted by the unit of the measured distance. For the unit of cm the value of $k = 58$, while for the inch unit, the value of $k = 148$. HC-SR04 ultrasonic sensor has the following specifications: working voltage of 5 VDC, 15 mA of operating current, operating frequency of 40 kHz, a maximum distance of 400 cm, a minimum distance of 2 cm, angle measurement of 15°, the dimension C 45 mm L 26/20 mm T 18 mm, and weight of 20 grams.

III. KF Algorithm Design

A. Discrete Kalman Filter Formulation

KF is an algorithm that can perform recursive estimation of the state of the dynamic behavior of a system. It is also able to estimate the state when models of dynamic systems are not well known [8]. This KF algorithm formulation is designed in the form of discrete time to estimate the state and measurement of the dynamic model presented as follows.

$$x_k = Fx_{k-1} + Bu_{k-1} + w_{k-1} \quad (2)$$

$$z_k = Hx_k + v_k \quad (3)$$

with $x_k \in \mathbb{R}^n$, $u_k \in \mathbb{R}^l$, $z_k \in \mathbb{R}^m$ are, respectively, the state vector, feedback, and measurement. $F \in \mathbb{R}^{nxn}$, $B \in \mathbb{R}^{nxl}$, $H \in \mathbb{R}^{mxn}$ is a constant matrix state, feedback, and measurement. w_k and z_k is a vector of noise and noise measurement process.

The KF Algorithm consists of two main processing stages, namely: stage prediction and correction phase. At the stage of the prediction, the algorithm used meets the following equation.

$$\hat{x}_k^{(-)} = F\hat{x}_{k-1} + Bu_{k-1} \quad (4)$$

$$P_k^{(-)} = FP_{k-1}F^T + Q \quad (5)$$

with $\hat{x}_k^{(-)}$ is a priori state estimated for a posteriori state $\hat{x}_k$ and $P_k^{(-)}$ is the covariance matrix a priori of the error estimated, while Q is the process noise covariance matrix. In the correction phase, the algorithm used meets the following equation.

$$K_k = P_k^{(-)}H^T\left(HP_k^{(-)}H^T + R\right)^{-1} \quad (6)$$

$$\hat{x}_k = \hat{x}_k^{(-)} + K_k\left(z_k - H\hat{x}_k^{(-)}\right) \quad (7)$$

$$P_k = (I - K_kH)P_k^{(-)} \quad (8)$$

with K_k is strengthening Kalman which serves to minimize the a posteriori error covariance matrix error P_k and R is the covariance matrix of the measurement noise. The second stage of the KF design process can be formed in a diagram as presented in Fig. 2. From this diagram, it can be seen that the process of prediction and correction occurs continuously to generate the estimated value of the measurement. Thus, the measurement noise that appears in the sensor system can be eliminated.

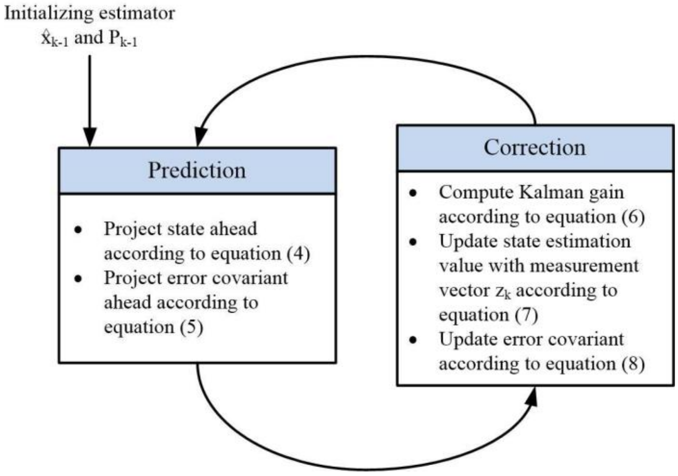

Fig. 2 Diagram of Kalman Filter algorithm.

B. Design of KF for Ultrasonic Sensor

The KF algorithm for ultrasonic sensor is designed according to (4) through (8). The model assumes sensor system dynamics equations with order system one with the following parameters.

$$F = [1] \quad (9)$$

$$B = [0] \quad (10)$$

$$H = [1] \quad (11)$$

Thus, it is obtained that state x_k is scalable and meets the distance $z_k = x_k$. Then, it is determined the noise covariance of matrix process Q and covariance measurement R as follows.

$$Q = [1e - 5] \quad (12)$$

$$R = [2{,}92e - 3] \quad (13)$$

The matrix Q can be determined arbitrary, whereas the matrix R is determined based on variance of the raw data measurement distance can be calculated using Microsoft Excel. Furthermore, using the parameters that have been determined, it can be substituted into (4) through (8) as follows.

$$\hat{x}_k^{(-)} = \hat{x}_{k-1} \quad (14)$$

$$P_k^{(-)} = P_{k-1} + [1e - 5] \quad (15)$$

$$K_k = P_k^{(-)}\left(P_k^{(-)} + [2{,}92e-4]\right)^{-1} \quad (16)$$

$$\hat{x}_k = \hat{x}_k^{(-)} + K_k\left(z_k - \hat{x}_k^{(-)}\right) \quad (17)$$

$$P_k = (1-K_k)P_k^{(-)} \quad (18)$$

Equations of (14) to (18) are further applied in the form of software programming language on the Arduino IDE. More specifically, the flowchart of programming designed is shown in Fig. 3.

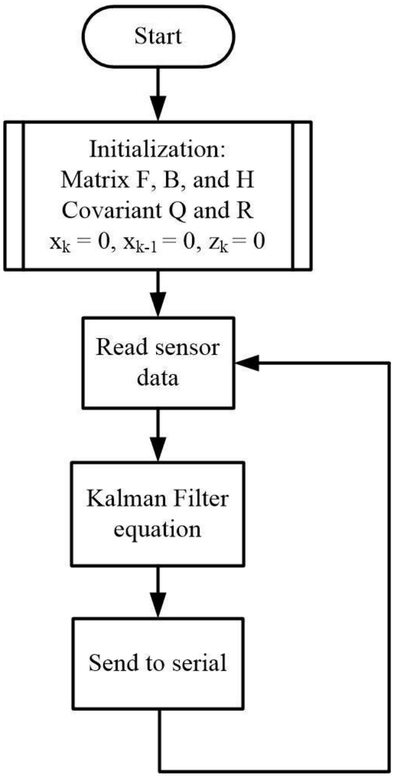

Fig. 3 The flowchart of programming.

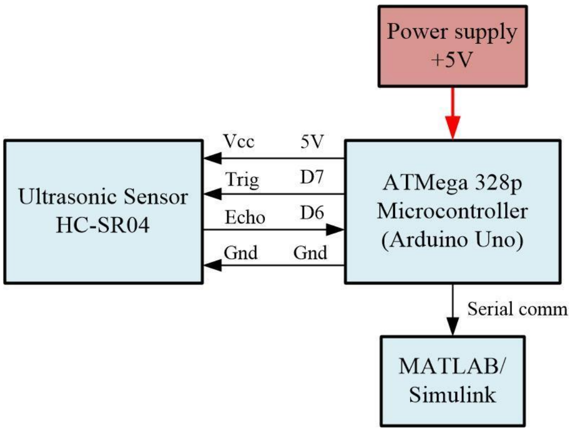

Fig. 4 Design block diagram of the system.

C. Hardware Design

Hardware used consists of the ultrasonic sensor type HC-SR04, microcontroller module Arduino Uno, and a PC. The ultrasonic sensor was used as the sensor system being tested by implementing the KF algorithm on Arduino Uno microcontroller module in accordance with the flowchart in Fig. 3. The PC was used to display and analyze the measurement data in graphical form by using MATLAB Simulink 2013a. The designed block diagram is shown in Fig. 4, while the data acquisition scheme in MATLAB Simulink is presented in Fig. 5. The data acquisition system parameters set are presented in Table I.

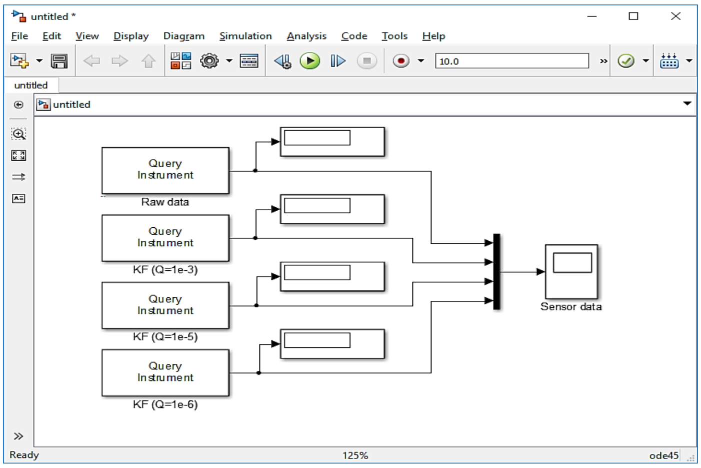

Fig. 5 Scheme of data acquisition system in MATLAB Simulink.

TABLE I
PARAMETER DATA ACQUISITION SYSTEM

Parameter	**Value**
Baudrate serial	115200
Data format	ASCII
data type	Float (% f)
Buffer size	512
Port	COM2
Sampling time	0.01 s

IV. TEST RESULTS

The KF algorithm that has been designed for the ultrasonic sensors was tested using two test scenarios. The first test was done with setpoint of constant distance, while the second scenario involved assigning set-point of distance change. Both scenarios were also tested using the process noise covariance matrix Q presented as follows.

$$Q = \begin{bmatrix} 1e-3 & 0 & 0 \\ 0 & 1e-5 & 0 \\ 0 & 0 & 1e-6 \end{bmatrix} \quad (19)$$

The three constants in the matrix Q are determined to find out the performance of filtering resulted using $Q = 1e\text{-}5$ as the nominal value in accordance with (12).

A. The First Scenario Testing

In the first scenario, the test was done to investigate the filtering performance at steady state condition. Testing was done by placing the sensor in front of a flat object with a distance of 10 cm. The third noise covariance value in (19) was used to determine differences in the performance of filtering resulting from. The test results are shown in Fig. 6 with the bigger results presented in Fig. 7. Based on the test results, it was obtained that the KF algorithm was able to reduce noise measurement with different performance in accordance with the value of the process noise covariance. Fig. 6 and Fig. 7 show the nominal value of the process noise covariance Q = 1e-5set is able to reduce noise, although it produces a transient response for 1 second. Value covariance Q = 1e-3 that is lower than the nominal value is also able to reduce measurement noise, but the resulting performance is not better than the nominal value despite producing transient response faster. Value covariance Q = 1e-6 that is greater than the nominal value appears to have a better performance. However, the second scenario testing needs to be done to ensure these conditions.

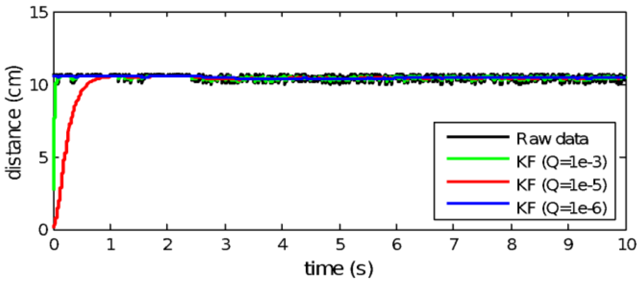

Fig. 6 Filtering performance with a setpoint of constant distance.

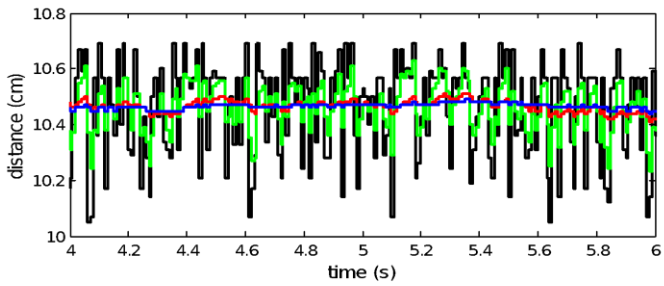

Fig. 7 Magnification filtering performance with a setpoint of constant distance at a steady state.

B. *The Second Scenario Testing*

The second test was performed to determine the response time of the sensor when it was given changing distance. Changes of distance tested were from 10 cm to 7 cm and then to 13 cm. In addition, testing was also done by providing the changing distance at random with a nominal spacing of 10 cm. Similar to the first scenario, the third value in the process noise covariance (19) was also used in this test. The test results obtained are presented in Fig. 8 and Fig. 9. From the test results for the changing distance value, both for determined and random distance found that the response time of the performance of filtering resulting different for each value of the process noise covariance tested. Value covariance Q = 1e-3 produces the fastest response time, while the covariance Q = 1e-6 produces a slower response time. Thus, it can be concluded that the value of the process noise covariance Q is getting smaller producing a slower response time. Conversely, if it is selected bigger Q value noise process, it produces faster response time.

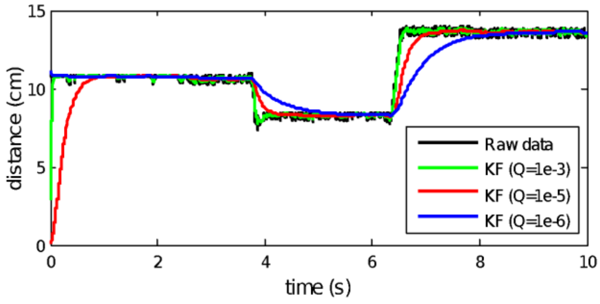

Fig. 8 Response time filtering performance by setpoint of changing distance specified.

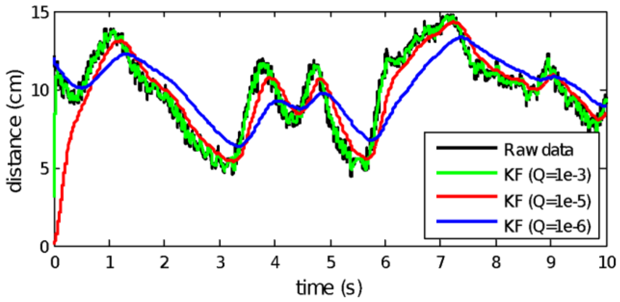

Fig. 9 Response time filtering performance by the setpoint of random changing distance.

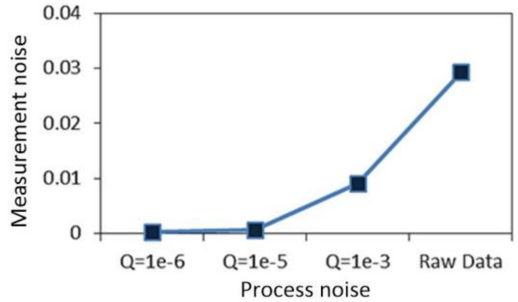

Fig. 10 Comparison of the measurement noise variance to noise variance process.

C. *Variance Analysis*

The variance analysis calculation was done to determine the quantitative data measurements resulting from the testing process. The analysis of variance was done by calculating the variance of the data obtained for all three grades noise covariance of the Q process defined The results of the analysis with the help of Microsoft Excel indicates that the magnitude of the measurement noise variance exponentially proportional to the magnitude of the noise variance process value specified. The value measurements resulted for the noise variance process are Q = 1e-3, Q = 1e-5, and Q = 1e-6 in a row is R = 9.06e-4, R = 6.43e-5, and R = 2.07e-5. These results are displayed in Fig. 10.

V. Conclusion

The KF Algorithm has been successfully designed and tested for data acquisition systems on the ultrasonic sensor type HC-SR04. The test results show that the KF algorithm is able to reduce measurement noise generated by the sensor system. The analysis of the variance done generates noise variance value measurement that is proportional to the noise variance process specified. However, it is inversely proportional to the time response generated. The smaller the measurement of the noise variance value, the resulting response time is slower. Thus, it is required an optimization parameter of selection matrix of noise covariance process and noise measurements in order to produce filtering process and the best time response.

Acknowledgments

Special thanks go to the Laboratory of Electrical Computer Engineering Program Polytechnic Sukabumi on facilities and equipment that have been provided in this study.

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