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Liquid Level Estimation in Dynamic Condition using Kalman Filter

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ABSTRACT
The aim of this paper is to estimate true liquid level of tank from noisy measurements due to dynamic conditions using kalman filter algorithm. We proposed kalman filter based approach to reduce noise in liquid level measurement system due to effect like sloshing. The function of kalman filter is to reduce error in liquid level measurement that produced from sensor resulting from effect like sloshing in dynamic environment. A prototype model was constructed and placed in dynamic condition, level data was acquired using ultrasonic sensor to verify the effectiveness of kalman filter. The tabulated data are shown for comparison of accuracy and error analysis between both measurements with Kalman filter and statistical averaging filter. After several test with different liquid levels and analysis of the recorded data, the technique shows the usefulness in liquid level measurement application in dynamic condition.
Keywords: Estimation, Kalman filter, Dynamic, LabVIEW, Sloshing.

I. INTRODUCTION

Modern automotive vehicle in today world are equipped with digital meters and gauges as well as extra functionality that inform driver for different conditions of vehicle. One of important function is inform driver about fuel consummation of vehicle and how distance vehicle can travel without refilling fuel. However these additional functions and high precision digital display need to rely on the accuracy of level sensor. The performance of liquid level measurement system in dynamic environment, which mainly depends on level sensor, is becoming concern for automotive vehicle industry and every day vehicle user. The importance and need of level sensor reliability in dynamic environment over long period of time has led to the introduction of different form of level sensors like motionless and contactless level sensors. Different filtration techniques were used for noise reduction in sensor due to different environmental condition.

II. LITERATURE SURVEY

There are different methods for sensing the liquid level. Gauge is one of the simplest methods for liquid level measurement, in this method there is a gauge floating on liquid surface and the position of gauge generally measured using angular transducer or LVDT [1]. In a basic capacitive level sensing system, capacitive sensors have two conducting terminals that establish a capacitor. If the gap between the two rods is fixed, the fluid level can be determined by measuring the capacitance between the conductors immersed in the liquid. Since the capacitance is proportional to the dielectric constant, fluids rising between the two parallel rods will increase the net capacitance of the measuring cell as a function of fluid height [3].Another contactless method for liquid level measurement by using ultrasonic sensor. An ultrasonic sensor sends a package of ultrasonic signals. There is a reflection of ultrasonic signal on the edge of liquid or tender material. The controller measures the time in which the emitted ultrasonic signal gets back to receiver due to the refection from liquid level. By using the acoustic velocity and the time measured from emission to reception, the device determines the container's filled-up state [4].

In dynamic environment like automotive fuel tank or fuel tank of ship, whatever the method used apart from level sensor accuracy, liquid level measurements also get influenced by the sloshing effect by the motion or acceleration of vehicle. In case of automotive vehicle acceleration effect produce the sloshing in fuel tank, this sloshing wave have frequency proportional to the magnitude of acceleration and other parameter like geometry of tank and fluid level etc. [6].

To reduce the effect of sloshing on liquid level measurement systems, varies mechanical dampening methods consisting of baffles, statistical averaging methods and electrical dampening techniques have been introduced in past. However most of these methods have higher cost of production. The accuracy of these measurements of liquid level in dynamic conditions is also not up to the mark. The approaches like electrical dampening and statistical averaging preliminarily perform averaging on sensor acquired data (row data) over some time frame. Averaging of row data over variable time frame also used in past [8].To increase accuracy of level sensing in dynamic conditions vehicle speed from speed meter has been used to determine the variable length of time frame for averaging. When vehicle is moving with low speed (static condition) averaging is done on small time frame and at higher speed (dynamic condition) averaging is done on large time frame. Despite using a speed as reference for time frame averaging method still have significant error in its measurements.

Shiratsuchi [9] described approach using a capacitive type fuel level sensing system that uses three capacitors to determine the fuel surface plane angle, and a fourth capacitor is used as reference capacitor to reduce the variations in the dielectric constant. The high cost associated with having many capacitors makes this approach infeasible. Some researchers also try reduce the effect sloshing using neural network approach and support vector machine [2][5],these approaches have complex structure and hard to implement in controllers.

In this paper, kalman filter based approach has been described that able to reduce effect of dynamic environment on liquid level measurement system. The approach described is applicable to any type of level sensor. The main focus of described approach is to eliminate effect of sloshing on liquid level measurement system and parameter like temperature and contamination which also effect measurement system accuracy are not investigated. Some sloshing compensation methods are compared with results obtains by kalman fitter approach to show its effectiveness over other.

III. MEASUREMENT SYSTEM

Kalman filter have been used in verity of application in field of engineering, rocket tracking, robot tracking, control system and Business. Kalman filter is an effective mathematical tool to estimate the future state of system using physical system model and related measurement and process error variance parameter. Here in described approach uses a simple 1D kalman filter for the sloshing compensation. Figure 1 show an overview diagram of proposed measurement system.

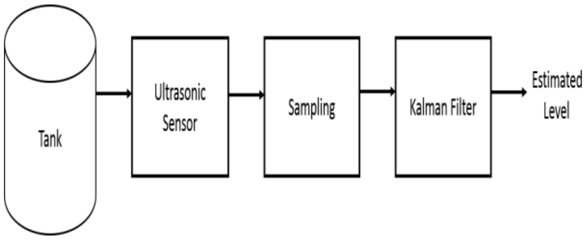

Fig1: Block diagram overview of proposed system

A. Ultrasonic Sensor

Ultrasonic sensors are low cost and characterized to operate in different environmental condition. Ultrasonic sensors can be used in containers with pressure up to 2 mega Pascal; temperature rang up to 100°C and depth up to 3 meter. Ultrasonic sensors also have high accuracy with only 2% error in measurement [4]. The ultrasonic sensor determines the liquid level by transmitting echo pulses and measuring the return time of the echoes reflected from surface of liquid. If the velocity of sound in the medium is known then the fluid level can be calculated using the following equation

$$level = level_{ref} - \frac{1}{2} v.t \qquad (1)$$

Where $level_{ref}$ is the height of the tank, v is the speed of the sound and t is the time-of-flight of the ultrasonic echo. Working of ultrasonic sensor is shown in Figure 2.

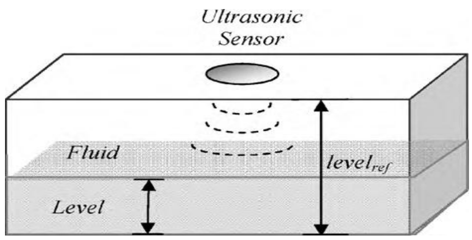

Fig.2: liquid level measurement using ultrasonic transducer

B. Kalman filter

Rudolf kalman published his paper describing idea of kalman filter in 1960.kalman filter equation can be solved numerically using recursive structure type that output depends only on current state of input and output earlier . Kalman filter need some initial values to start estimation process, filter predict and adjust the parameter of system model with each new iteration and new measurement. Filter tries to reduce the estimation error by adjusting parameters. Kalman filter is set of mathematical equation that provides an efficient computational tool to estimate the state of process, in way that minimizes the mean square error. Kalman filter able to supports estimation of past, present and even future states of system. Kalman filter is one of best optimal estimator for class of system with uncertainty. It also famous tool for finding true estimation from the noisy sensor measurement data [10].

Kalman filter estimate a process state at given time by comparing mathematical model and sensor acquired measurement data. Optimal estimation done by weighting according to model, measurement and process noise. State space model for system represented as shown in equation 2 and equation 3.

$$x_k = A.x_{k-1} + B.u_k + w_k \quad (2)$$

x_k is called an state vector consisting an state variable at time step k. A is the state matrix, B is the control matrix.

$$z_k = H.x_k + v_k \quad (3)$$

z_k is called the observation vector at time step k. It concern with data which is known through measurement.

w_k and v_k represent the state and measurement white noise with known covariance matrices Q and R. H is the matrix which relates the actual state with the measurement Kalman filter is made up of two set of equations

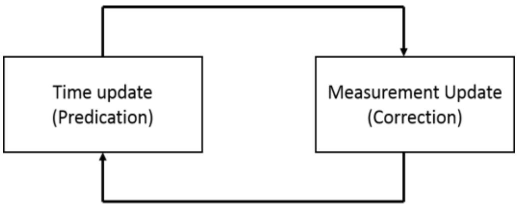

Fig.3: kalman filter iteration process

Predication (time update) equations

$$\hat{x}^-_k = A.\hat{x}_{k-1} + B.u_k \quad \text{Project state ahead} \quad (3)$$

$$P^-_k = A.P_{k-1}A^T + Q_k \quad \text{Error covariance ahead} \quad (4)$$

Correction (measurement update) equations

$$K_k = P^-_k.H^T.(H.P^-_k.H^T + R)^{-1} \quad (5)$$

$$\hat{x}_k = \hat{x}^-_k + k_k(z_k - H.\hat{x}^-_k) \quad (6)$$

$$P_k = (I - k_k.H).P^-_k \quad (7)$$

$\hat{x}^-_k$ is priori estimation of state.

P^-_k is error covariance matrix

K_k is kalman gain

To implement the filter, the measurement noise covariance R is usually measured prior to operation of the filter. To determine variance of the measurement noise of the filter, several offline samples of noise covariance, R must be tested and analyzed. Another constant that needs to be set is process covariance Q, which is difficult to be estimated because of the lack of ability in observing the process that we are estimating [10].

C. Real problem modeling

Analog value by the ultrasonic sensor is numerical and scalar value. In this research single ultrasonic sensor is used for level sensing therefore single dimensional kalman filter is introduced. There no control signal U_k involved. As we know the sensor output is numerical constant the present value does not change due to change in past value. Other constant used, which H was set to 1 because it is known that the measurement is composed of the state value and noise.

U_k =0; A = 1; B = 1; H = 1

After knowing all the constant in kalman filtering technique predication and correction equations are simplified as shown in Figure 3. Initial value for parameters in kalman filter

z_k = sensor value, $\hat{x}^-_k$ = 0, P^-_k =100

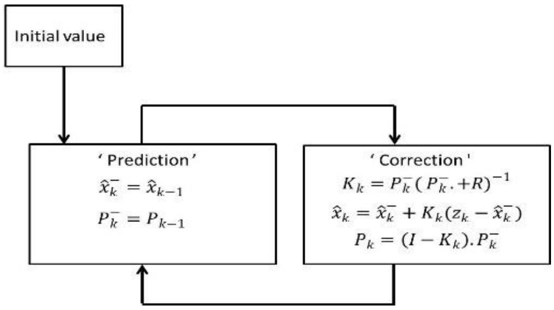

Fig.4: 1D kalman filter iteration process

IV. EXPERIMENTAL SETUP

For experiment circular shape tank was used with approximate height 27 cm and diameter is 20 cm. Ultrasonic sensor fitted at the center at top cover of tank. Tank was filled with liquid above half portion. Measurement system is investigated for different level of liquid in tank. For sloshing effect vibrations are artificially generated using moving platform. Figure 5 shows overview of experimental setup.

The level signal from the ultrasonic sensor was acquired using the LabVIEW software and arduino uno, which was connected to the ultrasonic sensor on tank. LabVIEW (short for Laboratory Virtual Instrumentation Engineering Workbench) is a platform and development environment for a visual programming language from National Instruments. LabVIEW is mostly use for design instrumentation and control system, here labVIEW is use to visualize and filter data by designing kalman filter.

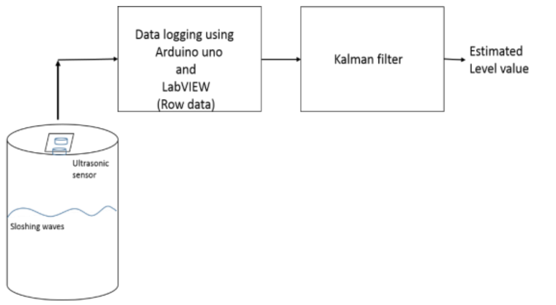

Fig.5: Experimental setup for level measurement system

Arduino uno controller kit is used as data acquisition card. The liquid level signal indicated by the ultrasonic sensor output was sampled and recorded at 10 Hz.

V. RESULTS

Three type of filter mean, median and kalman is investigated for filtration separately. Moving mean and moving median filter slide across the row data provided by sensor and calculate mean/median values in adjacent sample points [2]. If x is the sampled raw signal of length N from sensor, and w is size of the sliding window of the filter, then the filtered output y using mean and median can be obtained using Equation (1) and (2), respectively

$y[i] = \text{mean}(x[i-1], x[i-2], \ldots, x[i-w])$, for $w \le i \le N$ (8)

$y[i] = \text{mean}(x[1], x[2], \ldots, x[i])$, for $1 \le i < w$ (9)

$y[i] = \text{median}(x[i-1], x[i-2], \ldots, x[i-w])$, $w \le i \le N$ (10)

$y[i] = \text{median}(x[1], x[2], \ldots, x[i])$, for $1 \le i < w$ (11)

The measurement noise variance R and process noise variance Q has been set to a specific value for output analysis of Kalman filter. Initial values for the Kalman filter parameter are set as shown in table.

Table 1: Filter Parameter

Sr.No.	Kalman Filter Parameter	Value
1	Pk	100
2	Xk	0

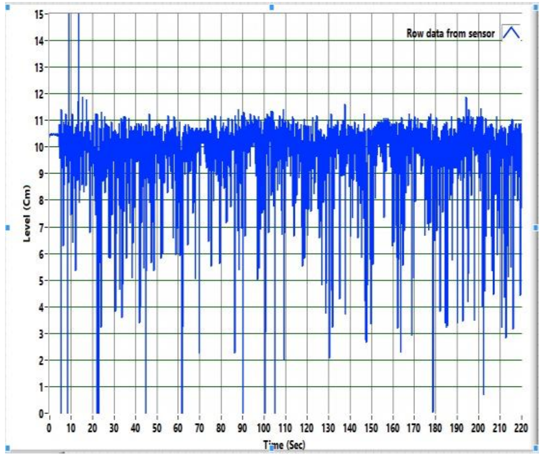

Fig6: Noisy data from ultrasonic sensor

Figure 6 shows a graph for noisy data acquired using labVIEW. Data is sampled at rate 10 Hz. Data acquired in dynamic environment contain large variation. Ultrasonic sensor reading for sloshing liquid level contains large deviation from actual value of liquid level even if ultrasonic sensor has high accuracy.

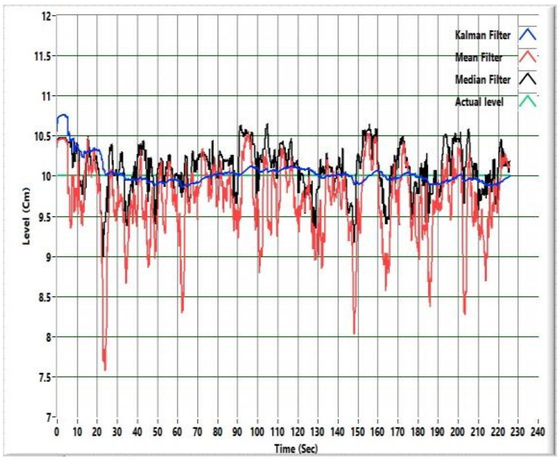

Fig7: Response of Different Filter methods

Figure 7 shows output results obtained by separately running filters on row data from ultrasonic sensor in dynamic condition when actual tank liquid level is 10 cm. Mean and maiden filter are used with moving window of 20 samples. Kalman filter is tune setting values of an Q and R. Different values of Q and R were used and best results obtained at Q=0.0001 and R=2, response is shown in graph. The approach was also tested for different liquid level in tank with some initial parameters for kalman filter. Table 2 and Table 3 shows comparison with other two approaches in terms of error in output of filter compare to actual level of liquid.

Table 2: Filtered values different methods

S.N.	Atual Tank Level (cm)	Moving Mean (cm)	Moving Median (cm)	Kalman Filter (cm)
1	10	8.9	10.5	9.9
2	12	12.3	12.4	12.15
3	18	17.4	18.5	17.8
4	19.5	19.9	20.1	19.4

Table 3: Error in filter output

Sr.no.	Error in applied filter output		
	Mean	Median	Kalman
1	1.1	0.5	0.1
2	0.3	0.4	0.15
3	0.6	0.5	0.2
4	0.4	0.6	0.1

Compared to methods like statistical avering method (mean/median), the proposed method provides much less error in estimation also variation in final output are also very low. It is possible to get smoother values in statistical averaging method by varying window size over more samples but it need to store values equal to number of samples in window, which required more space in memory. While kalman filter only utilize current sample for estimation due to which past values does not need to store, which makes kalman filter more suitable for controller application with lower memory space. Kalman filter required initial 20-30 samples to converge for correct estimation. It uses difference between expected value and sensor value to converge to optimum estimation of state .After Filter converges to optimum value, error in estimation reduced to approximately 20% compare to error in other filtration technique.

VI. CONCLUSION

It has been seen that The Kalman Filter is a quite appropriate, feasible, mathematical device for level measurement in dynamic environment. In particular, it proved very useful to get highly stabilized results in measuring levels of liquids carried in tanks of mobile vehicles As it can obtain quite simple equation forms when reduced to one-dimensional matrix vector, it can be preferred in micro-controller applications. The application is independent and portable because mathematical model or case equations belonging to the measurement system are not used. That is to say, A Kalman Filter optimized for level measurement functions the same in the tanks of different dimensions and levels.

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