Simulation design of piezoelectric ultrasonic IoT-sensor (PMUT)

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Piezoelectric Micromachined Ultrasonic Transducer (PMUT) is a microelectromechanical system (MEMS). Unlike bulk piezoelectric transducers which use the thickness mode motion of a plate of piezoelectric ceramic, PMUT are based on the flexural motion of a thin membrane coupled with a thin piezoelectric film. The paper offers algorithm for simulation design of PMUT sensor with high level of detail. It is intended for students, professors and designers. The design of experiment (DoE) includes application of theory for: PMUT, Amplifier, Schmitt-trigger, SR-trigger, sample-and-hold scheme, analog-to-digital converter, controller and RF-transmitter. The methodology belongs to edge computing. With the chosen detail level, the algorithm is a good base for design of network element in IoI-environment.

Keywords: DoE, edge computing, IoT, MEMS, PMUT

Симулация на пиезоелектричен ултразвуков IoT-сензор (Мила Илиева-Обретенова). *Пиезоелектричният ултразвуков микродатчик (PMUT) е микроелектромеханична система(MEMS). За разлика от големите пиезоелектрични сензори, които използват движението от дебелината на пластинка от пиезоелектрична керамика, PMUT се основава на вълнообразното движение на тънка мембрана, свързана с тънък пиезоелектричен филм. Настоящата статия предлага алгоритъм за проектиране на симулация на PMUT-сензор с висока степен на детайлизация и представя функции за програмиране на контролер от високо ниво. Предназначена е за студенти, преподаватели и проектанти. Дизайнът на експеримента включва прилагане на теориите за: PMUT, усилвател, Шмит-тригер, SR-тригер, схема „следене-запомняне“, аналогово-цифрово преобразуване, контролер и радиочестотно предаване. Методологията принадлежи към edge computing. С избраната степен на детайлизация алгоритъмът е добра основа за проектиране на мрежов елемент в среда на IoT.*

Ключови думи: дизайн на експеримент, микроелектромеханична система, edge computing, IoT, PMUT

Introduction

Piezoelectric Micromachined Ultrasonic Transducer (PMUT) [1] is a microelectromechanical system (MEMS). Unlike bulk piezoelectric transducers which use the thickness mode motion of a plate of piezoelectric ceramic, PMUT are based on the flexural motion of a thin membrane coupled with a thin piezoelectric film. In comparison with bulk piezoelectric ultrasonic transducers, PMUT can offer advantages such as increased bandwidth, flexible geometries, natural acoustic impedance match with water, reduced voltage requirements, mixing of different resonant frequencies and potential for integration with supporting electronic circuits especially for miniaturized high frequency applications. There are no PMUT simulations in recent research, e.g. [2] and [3], or simulations are with low level of detail [4]. The paper offers algorithm for simulation design of PMUT sensor with high level of detail. It is intended for students, professors and designers.

Methodology

Methodology for simulation design is defined from the working of sensor. Fig.1 shows the working of PMUT. Pulses with resonant frequency of sensor cause oscillation and ultrasonic wave, which travels to the object and back. Returning to the sensor the ultrasonic wave causes electro pulse, which is processed and gives information for the distance to the object, e.g. liquid.

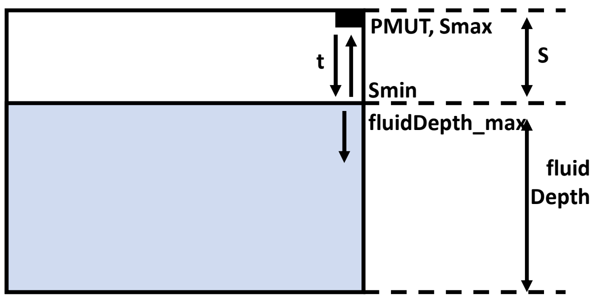

Fig.1. Working of PMUT.

The design of experiment (DoE) includes application of theory for: PMUT, Amplifier, Schmitt-trigger, SR-trigger, sample-and-hold scheme, analog-to-digital converter, controller and RF-transmitter [4]. The methodology belongs to edge computing. Fig.2 shows test bench for simulation research.

The time-of-flight t begins when the microcontroller sets the SR-trigger, which begins accumulating charge on a sample-and-hold integrator. At the same time the microcontroller produces a series of pulses at the resonant frequency of the PMUT (122 kHz) and voltage 2.5 V. The pulse is amplified to 32 V. The transducer receives these pulses, creating a pressure wave in the tank that is reflected at the liquid interface. The reflected wave is received by the PMUT, creating a voltage signal on the membrane with a peak amplitude of 500µV. The PMUT signal is amplified with a gain of 70 dB and feeds a Schmitt-trigger. The Schmitt-trigger, with built-in hysteresis, resets the SR-trigger when the reflected amplified signal rises above the threshold voltage (Vref) of 1.25 V. The trigger reset the sample-and-hold integrator, which has accumulated charge on its output capacitor. An ADC before the microcontroller converts the output voltage of the integrator Vout to a digital value (number of counts), that is a linear measure of the time-of-flight. By subtraction, the number of counts is a linear measure of the fluid depth inside the tank. Then the liquid depth is transmitted to server by RF-transmitter.

Results

The results include calculating of simulation.

1. Defining the parameters of test bench:

- Maximum tank high: $S_{max} = 2.1\ [m]$,
- Minimum distance to liquid: $S_{min} = 0.21\ [m]$,
- Sound velocity in air: $V = 343\ [^{m}/_{s}]$,
- ADC bits: $ADC_{bits} = 8$,
- ADC range: $ADC_{range} = 2.2\ [V]$,
- Sample-and-hold offset: $V_{offset} = 2x10^{-3}\ [V]$.

2. Calculating the slope of sound velocity V_S in seconds per meter:

(1) $$V_s = \frac{1}{343} = 2.915x10^{-3}\ [^{s}/_{m}]$$

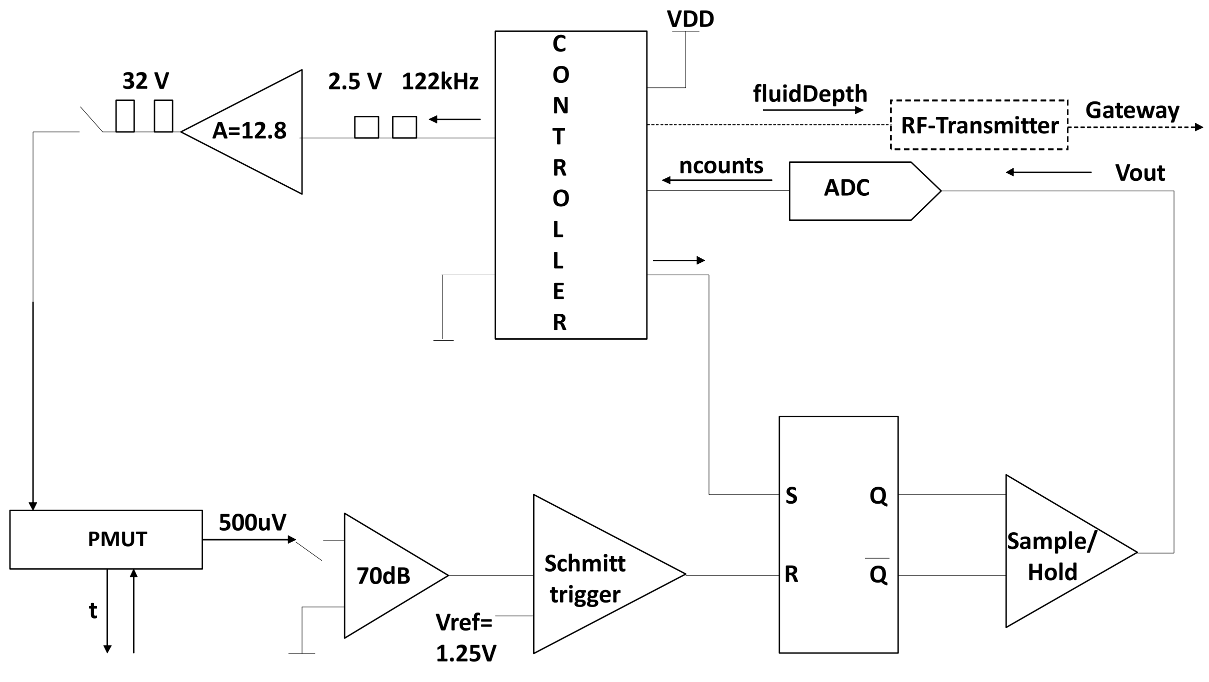

Fig.2. Test bench for simulation research.

3. Calculating the maximum time for travel to liquid and backwards:

(2) $\grave{t}_{max} = 12.243x10^{-3}\ [s]$

4. Calculating the minimum time for travel to liquid and backwards:

(3) $\grave{t}_{min} = 1.2243x10^{-3}\ [s]$

5. Calculating the ADC counts:

(4) $ADC_{counts} = 2^8 = 256\ [counts]$

6. Calculating the active ADC counts:

(5) $ADC_{activ} = 255\ [counts]$

7. Calculating the counts of flight:

(6) $Fly_{counts} = ADC_{activ} - 1 = 254\ [counts]$

One count for pulses with frequency 122 kHz is foreseen.

8. Calculating the factor of time T_f in seconds per count:

(7) $T_f = \frac{\grave{t}_{max}}{Fly_{counts}} = \sim 50x10^{-6}\ [{}^{s}/_{count}]$

9. Calculating the time offset: 1 count

(8) $t_{offset} = 1xT_f = 50x10^{-6}\ [s]$

10. Defining the function Time of flight $t = f(S)$

Time of flight is linear function of the kind $y = ax + b$, where
y is the Time of flight in seconds,
a is the slope V_S in seconds per meter,
x is the distance S form sensor to liquid in meter and
b is the time for pulse feed with frequency 122 kHz t_{offset}.

Therefore

(9) $t = V_S x 2xS + t_{offset}$.

The sonic wave travels the distance from sensor to liquid and backwards: $x = 2xS$. Function Time of flight has the following analytical form:

(10) $t = 5.83x10^{-3}xS + 50x10^{-6}\ [s]$

11. Calculating the maximum time of flight:

(11) $t_{max} = 12.293x10^{-3}\ [s]$

12. Calculating the minimum time of flight:

(12) $t_{min} = 1.2743x10^{-3}\ [s]$

Fig.3. shows the function $t = f(S)$.

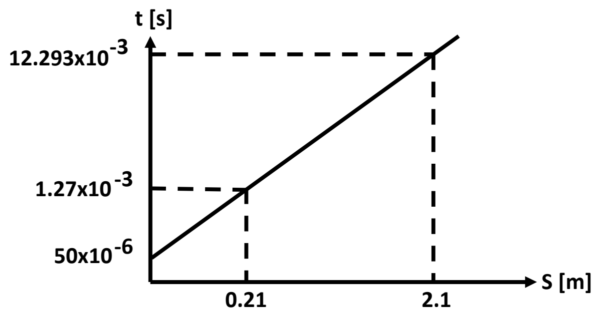

Fig.3. The function t=f(S).

13. Calculating the ADC factor in volts per count:

(13) $ADC_{factor} = \frac{ADC_{range}}{ADC_{counts}} =$

$$= 8.59375x10^{-3}\ [{}^{V}/_{count}]$$

14. Calculating of ADC scale in counts per volt:

(14) $ADC_{scale} = \frac{ADC_{counts}}{ADC_{range}} = \sim 117\ [{}^{counts}/_{V}]$

15. Calculating the voltage slope in volts per second:

(15) $VoltageSlope = \frac{ADC_{factor}}{T_f} =$

$$= 171.875\ [V/_s]$$

16. Calculating the output voltage:

The output voltage is a linear function of Time of flight $y = ax + b$,

where

y is the output voltage V_{out},

a is the voltage slope in volts per second,

x is Time of flight in seconds,

b is the intercept voltage in sample-and-hold scheme V_{offset}.

The output voltage V_{out} has the following analytical form in volts:

(16) $V_{out} = VoltageSlope\ x\ t - V_{offset}\ [V]$

17. Calculating the maximum output voltage $V_{out,max}$:

(17) $V_{out,max} = 2.11\ [V]$

18. Calculating the minimum output voltage $V_{out,min}$:

(18) $V_{out,min} = 0.217\ [V]$

Fig.4 shows the function $V_{out} = f(t)$ with minimum and maximum output voltage.

19. Calculating the ADC counts, responsible for output voltage:

(19) $ncounts = V_{out} x ADC_{scale}\ [counts]$

20. Calculating the maximum ADC counts:

(20) $ncounts_{max} = \sim 247\ [counts]$

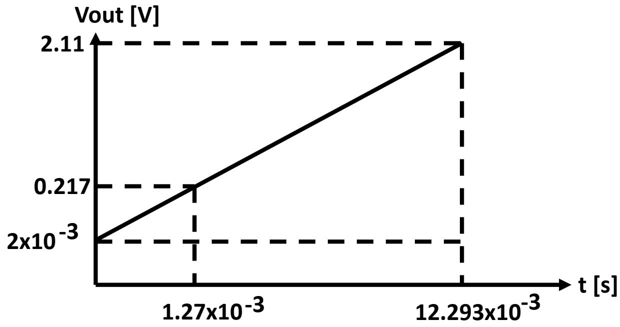

Fig.4. The function $V_{out} = f(t)$ with minimum and maximum output voltage.

21. Calculating the minimum ADC counts:

(21) $ncounts_{min} = \sim 26\ [counts]$

Fig.5 shows the function $ncounts = f(t)$ with minimum and maximum ADC counts.

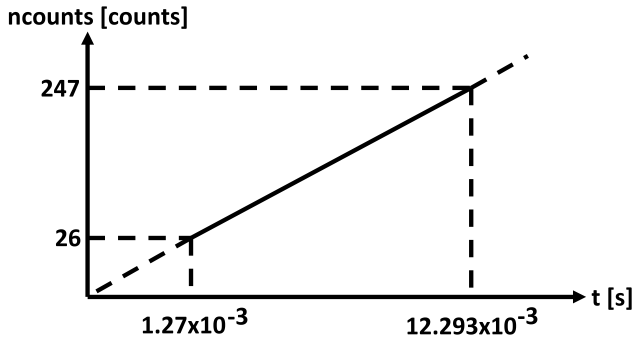

Fig.5. Function ncounts=f(t) with minimum and maximum ADC counts

22. Calculating the distance factor in meters per count:

(22) $factor = \frac{S_{max}}{ncounts_{max}} =$

$$= 8.5x10^{-3} [m/_{count}]$$

Fig.6 shows the function $ncounts = f(S)$.

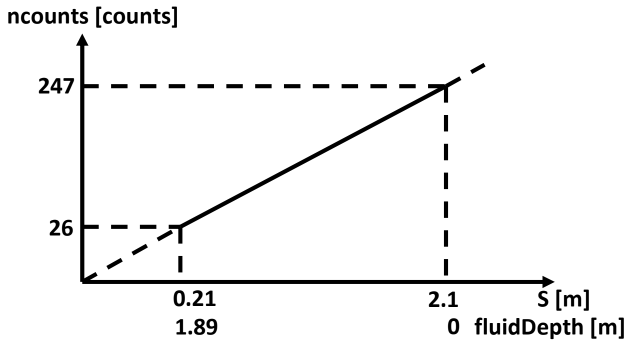

Fig.6. The function ncounts=f(S).

23. Calculating the fluid depth in meters:

(23) $$fluidDepth =$$

$$= S_{max} - ncounts\ x\ factor =$$

$$= S_{max} - ncounts\ x\ \frac{S_{max}}{ncounts_{max}} =$$

$$= S_{max}\left(1 - \frac{ncounts}{ncounts_{max}}\right)[m]$$

Fig.7 shows the function $fluidDepth = f(ncounts)$.

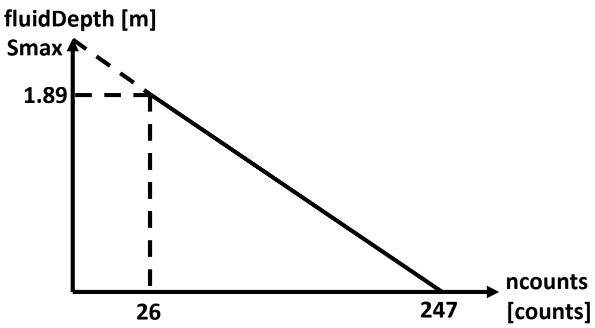

Fig.7. The function fluidDepth=f(ncounts).

24. Calculating the $fluidDepth$ in percent:

(24) $$fluidDepth = S_{max}(100\% - S\%)\ [\%]$$

Fig.8 shows the function $fluidDepth = f(S\%)$.

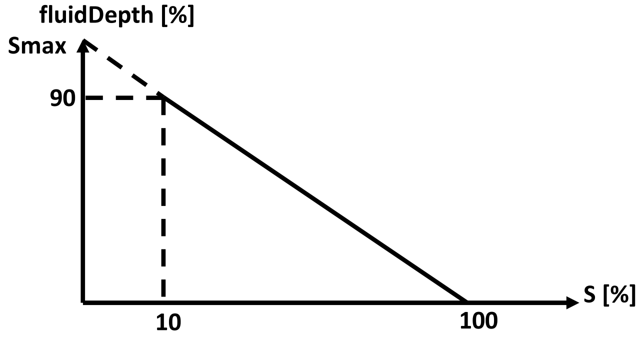

Fig.8. The function fluidDepth=f(S%)

25. Controller programming

The controller programming must match exactly the simulation design and include periodically conversion of output voltage (ncounts) in fluid Depth, monitoring of fluid level and reporting of any significant changes. For the periodically calculation of fluid depth the following program is represented:

```
real fluidDepth (int ncounts) {
            real Smax;
            real Smin;
            int SoundVelocity;
            int ADCbits;
            real ADCrange;
            real Voffset;
         /* model for piezoelectric pressure sensor:
            VelositySlope = 1/SoundVelocity
            TimeMax = VelocitySlope*2*Smax
            TimeMin = VelocitySlope*2*Smin
            ADCcounts = 2^ADCbit
            ADCactiv=ADCcounts - 1
            FlyCounts = ADCactiv – 1
            Tf = TimeMax / FlyCounts
            toffset = 1* Tf
            Tflight = VelocitySlope*2*S + toffset
            TflightMax = VelocitySlope*2*Smax +
toffset
            TflightMin = VelocitySlope*2*Smin +
toffset
            ADCfactor = ADCrange / ADCcounts
            ADCscale = ADCcounts / ADCrange
            VoltageSlope = ADCfactor / Tf
            Vout = VoltageSlope*Tflight – Voffset
            VoutMax = VoltageSlope*TflightMax –
Voffset
```

```
            VoutMin = VoltageSlope*TflightMin -
Voffset
            ncounts = Vout*ADCscale
            ncountsMax = VoutMax*ADCscale
            ncountsMin = VoutMin*ADCscale
            factor = Smax / ncountsMax
        */
        return Smax – ncounts*factor;
}
```

Conclusions

The paper represents an algorithm for simulation design of piezoelectric ultrasonic IoT-sensor (PMUT). Requirements of designers and service developers are considered. The paper contributions are the following:

1. Steps of algorithm for simulation design of piezoelectric ultrasonic sensor (PMUT) are defined with high level of detail.
2. With the aim of verification, the algorithm is illustrated with sensor for liquid level measurement.
3. Integration of both areas is demonstrated – simulation design and controller programming – by interaction of steps of both levels.
4. Reusable steps are developed – on the same level – for simulation of different kinds of sensors (e.g. parking sensors) or for management of different functional elements (PMUT, sample-and-hold scheme, ADC); between both levels – for simulation calculating and for controller programming.

Future work could be considered in following aspects:

1. Sensor adaptation for working with different aim: e.g. sensor for parking;
2. Controller programming in other functional areas (security, maintenance, performance, accounting);
3. Modeling of sensor communications and tis consideration as network element.

Acknowledgements

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