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Development of Hardware Dual Modality Tomography System

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Abstract: The paper describes the hardware development and performance of the Dual Modality Tomography (DMT) system. DMT consists of optical and capacitance sensors. The optical sensors consist of 16 LEDs and 16 photodiodes. The Electrical Capacitance Tomography (ECT) electrode design use eight electrode plates as the detecting sensor. The digital timing and the control unit have been developing in order to control the light projection of optical emitters, switching the capacitance electrodes and to synchronize the operation of data acquisition. As a result, the developed system is able to provide a maximum 529 set data per second received from the signal conditioning circuit to the computer. *Copyright © 2009 IFSA.*

Keywords: electrical capacitance tomography; optical tomography; dual mode tomography (DMT); forward modelling; signal conditioning circuit.

1. Introduction

In recent years, numerous types of tomography sensors have been designed and developed in monitoring and investigating the industrial solid/gas flow. Researches were carried out in order to obtain a good flow meter for process control. The tomography development is also focusing on producing high quality image to suit the demand from industrial sectors. Several sensing principles of tomography sensor in one modality were approaches to produce image reconstruction on solid/gas flow, such as the electrical capacitance, gamma, and optical tomography. In previous researches, the utilization of only one tomography modality is not capable to gain a high-resolution image in full range concentration distribution, and also not sufficient to explore all important flow characteristics [1]. Currently, the new trend in sensor development of solid/gas flow is either through dual or triple modality in one sensor plane. This technique enables to overcome the constraints found when one tomography modality is applied.

Considering the limitations of one sensing modality, a new idea of dual modality is developed by combining an electrical capacitance and optical sensor in one sensor plane. The main purpose of this project is to obtain a high resolution image fusion in full range concentration distribution. The dual modality tomography DMT project is aimed to obtain information about the contents of pipe line which is based on the intensity measuring and dielectric properties of the solid/gas inside the pipeline. Here, both optical sensors and electrical capacitance sensors are used for developing Dual Modality Tomography (DMT) primary sensor. The electrical capacitance sensor consists of eight electrodes in circumference of pipe line. Meanwhile, the optical sensor consists of 16 pair's transmitters and receivers in the same pipe line. All the detailed development of primary sensor and hardware were elaborate in this paper.

2. Primary Sensor Design of Optical

When producing and determining the sensor output for optical sensor, sensor modeling is very crucial. As usual the types of application are taken into consideration when developing sensor modeling. Abdul Rahim in his research [2] on solid/gas flow measurement developed the optical path length model. The model was designed and applied to make estimation on the sensor output voltage amplitude. Results show that the particle flow rate is proportional relation with output voltage amplitude. Meanwhile Ibrahim [3] used optical attenuation model in his research about the liquid/gas system. Results show that the model is useful and suitable for the liquid/gas application system because different optical attenuation coefficient with different material. Chan [4] developed an optical path width model in solid/gas measurement. For the research he generated the sensor output that is based on the width of sensing beam within the pipeline projection. In this project research the researcher has adopted the modeling type developed by Chan [4]. Similarly, the sensor output used is dependant on the blockage effect when solid materials intercept the light beams transmitting in a straight line to the receiver. Generally, the basic principle of the sensor modeling in this project is the light beams transmitting in a straight line to the receivers.

The optical tomography applied of 16 pairs of optical sensors, which consist of 16 LEDs and 16 photodiodes. The LEDs allow 140^{o} of wide emission angle and the photodiodes have a 100^{o} reception angle. The sensors located around the peripheral side of an acrylic flow pipe with 100mm inner diameter. The LED transmitters are labeled as Tx0 to Tx15 while Rx0 to Rx15 for the photodiode receivers. The diameter of the sensor's fixture which mounts the Tx and Rx is 100 mm and its circumference can be obtained by using the Equation in 1.

$$C = \pi \times d \tag{1}$$

Whereby: C = Circumference of sensor's fixture (mm), π = 3.142 and d = diameter of fixture (mm). As the optical sensor (transmitter and receiver) is distributed around the circumference of the fixture as shown in Fig. 1, the angle between each emitter and its adjacent receiver viewed from the centre of the circle is 8.02 degree.

3. Primary Sensor Design of Electrical Capacitance Tomography (ECT)

The ECT electrode design is made out of a pipeline sensor which uses electrode plates as the detecting sensor. These plates are mounted symmetrically on the periphery of an insulating pipe as shown in

Fig. 2. The pipe uses solid and gas as its medium. The solid particles will yield standing capacitance output that is useful for image reconstruction.

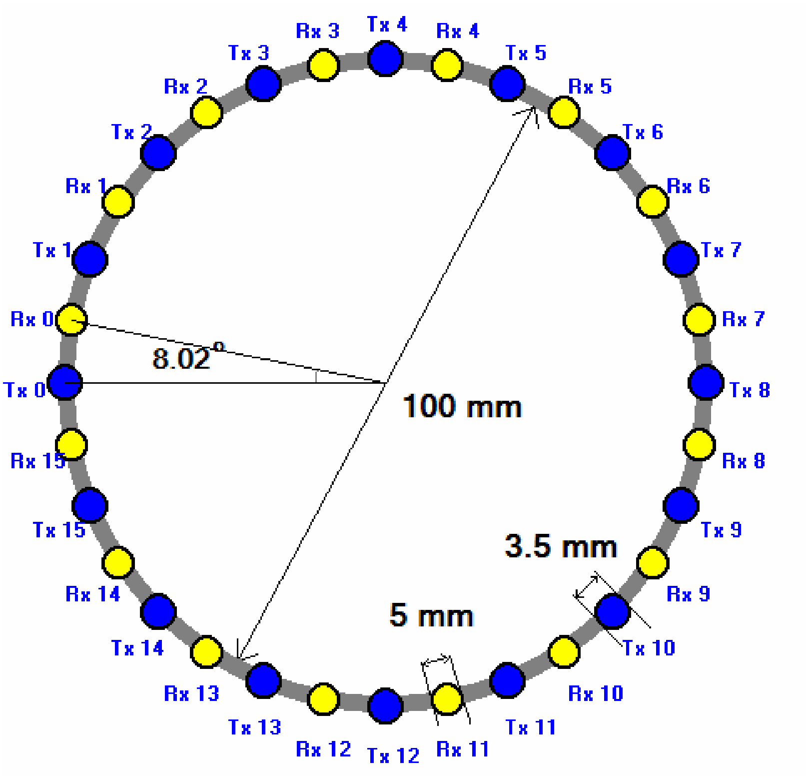


Fig. 1. Layout of optical primary sensor.

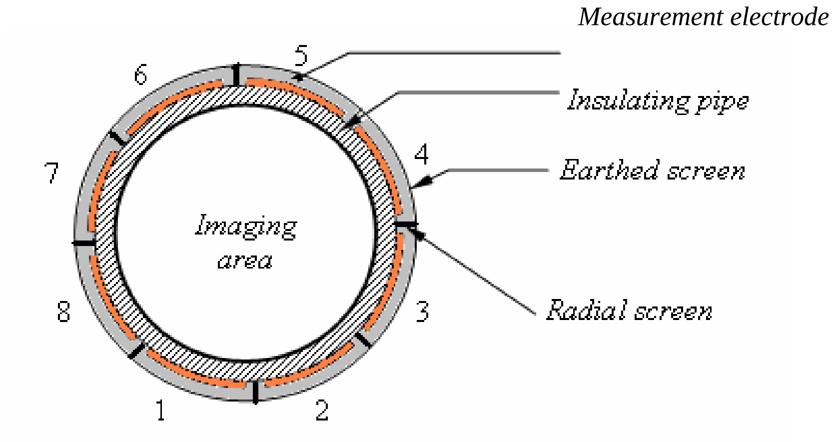


Fig. 2. Cross-sectional view of the ECT sensor.

4. Optical Hardware

Basically there are three parts in the developed circuits which are the light projection unit, received signals conditioning unit and digital timing and control unit. The light projection unit contains a series of LED drivers that provide a high and adjustable dynamic current to each LED individually. The received lights' intensity is measured in signals conditioning unit. It contains a series of signal transformation circuits that convert the received signal from photodiodes to a proportional voltage. To perform the transformation operation parallel processing technique uses 16 sets of such circuit. The digital timing and control unit, on the contrary, uses a master clock. This is to control the sequence of light projection and synchronize the operation of data acquisition system (DAS) when capturing the output voltage from signals conditioning unit. An important aspect during the circuit development is the considerations of the highest data rate that may be achieved and the stability of signals in each part of circuits.

To drive each LED individually this circuit is developed with 16 similar emitter driver circuits. The emitter is designed to use pulse mode so that it can handle a larger current and therefore generate a greater intensity of radiation. The circuit is shown in Fig. 3. The 2N3904 NPN transistor was chosen to obtain the high speed switching and high current driver. With this also the number of components can be minimized. This transistor has similar characteristic of Darlington transistor and is able to provide the collector with constant current up to 4.5 Amp or pulse current up to 9.5 Amp and support the switching frequency up to 1 MHz. This transistor directly replaces the commonly used LED driver which is formed by a switching transistor and a high current transistor [5].

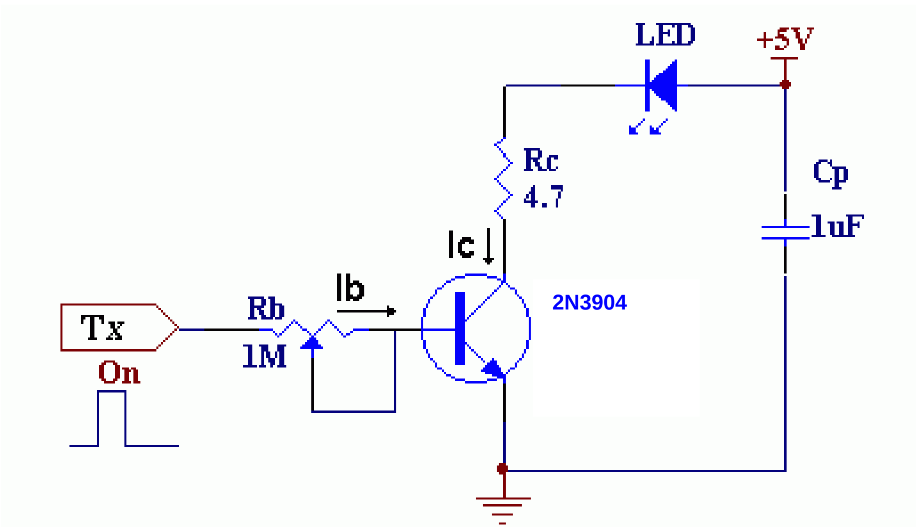


Fig. 3. The emitter driver circuit.

In transforming the received signals from photodiodes to voltage a signal conditioning circuit is designed. The input of the sensor is a physical signal represented by light, while the output sensor is electrical signals that are proportional to the intensity of received light. The TLE2084 is selected as the converter's operational amplifier (op-amp) in the circuit as it has a high input impedance (10^{12} Ω, J-FET input stage), double bandwidth (3 MHz of unity bandwidth) and triple slew rate (13 v/us of positive slew rate at 25^{o}C) fast setting time (0.05 us) and low noise voltage (4 µV) at 10 kHz. Fig. 4 shows the improved photovoltaic mode converter. Through the modification, a second resistor with a value equal to feedback resistor is added in series with the non-inverting input of the op-amp. This new arrangements of parts changes a differential-input current to voltage converter. The new innovation provides a better solution to noise sensitivity and DC offset error [6]. Besides that, the presence of C_1 as the cumulative parasitic capacitance of R_1 results in the high frequency noise generated by photodiode that is being filtered. The combination of R_1 and C_1 provides a single low-pass frequency-selective circuit that have a roll of -20 dB/dec above the critical frequency, f_L. The cut-off frequency formed by R_1 and C_1 selection is based on the maximum frequency to drive the emitters. It is expected to be equal to 16 kHz.

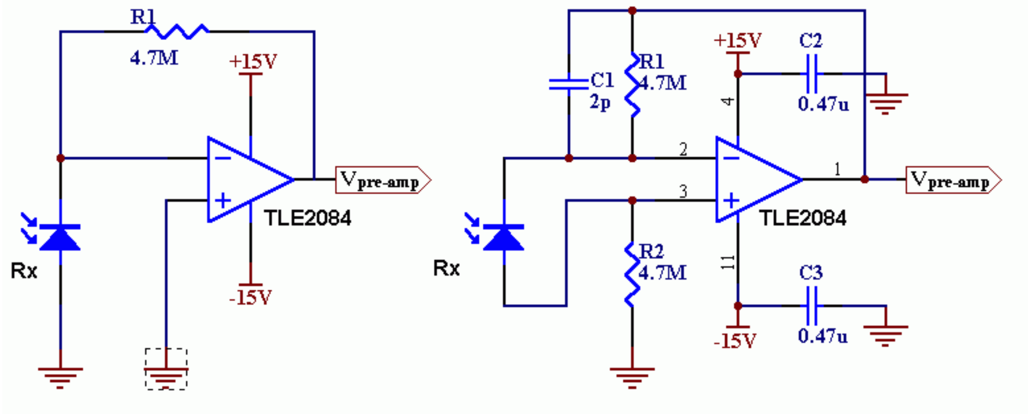


Fig. 4. Current to voltage converter circuit.

5. Electrical Capacitance Hardware

An ECT sensor comprised of a set of measurement electrodes mounted symmetrically inside or more typically outside an insulation pipe [7]. These measurement electrodes are connected to the electronic devices, or commonly known as signal conditioning system. Capacitance measurement circuit, amplifying circuit, AC to DC converter circuit and filter circuit are the items that make up the signal conditioning system. Other than that, a sine wave generator is also required as the excitation source for the system. The electronic devices outputs are then sent to the data acquisition system to be changed from analog to digital conversion. The digital data will be sent to computer for analysis and image reconstruction.

For the research, the signal conditioning circuit is designed to be plugged directly onto the PCB sockets of the electrodes. Conventionally, all the signal conditioning circuits are placed in one bulky signal conditioning board. However, here, eight identical circuits are separated into eight different PCB. Each PCB is plugged onto every electrode for this research. During the operation, should only one signal conditioning board is not working; users can simply change it by plugging out the board and replace it with a new board. Fig. 5 is an example of one of the set of signal conditioning circuit. For this electrical capacitance tomography a stray immune AC based capacitance measuring circuit has been developed. AC based capacitance measuring circuit is highly sensitive, has good linearity, good stability and high resolution AC [8]. It uses an operational amplifier (op-amp) with resistor feedback which directly measures the AC admittance of an unknown capacitance. This type of circuit has found extensive applications owing to their low drift and good SNR. Fig. 6 shows a typical hardware of electrical capacitance sensor including the AC based capacitance measuring circuit.

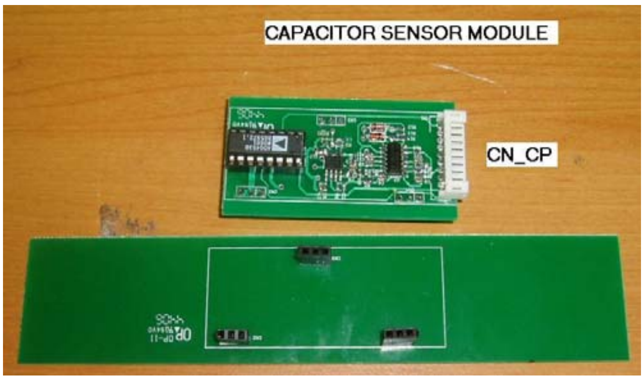


Fig. 5. ECT signal conditioning board.

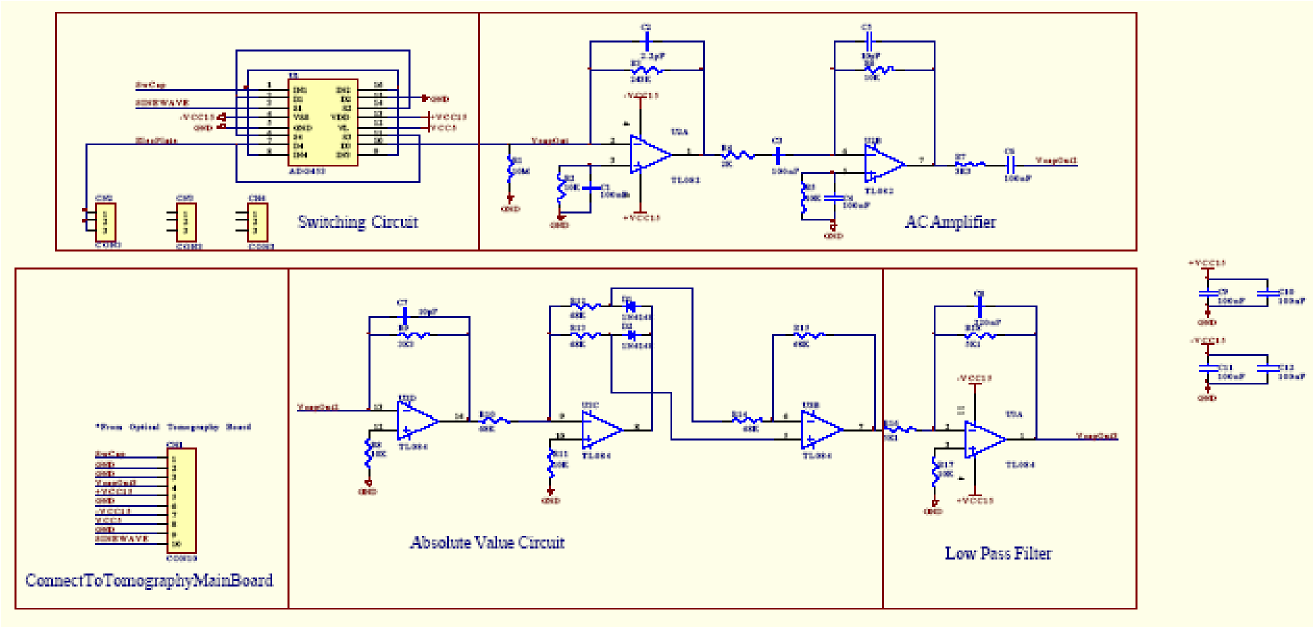
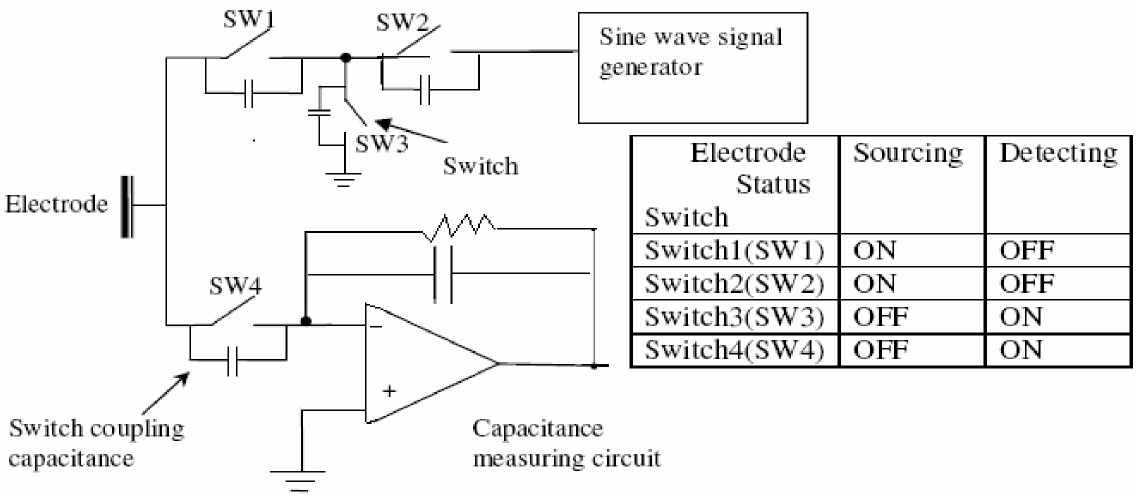


Fig. 6. Typical electrical capacitance hardware.

Usually, switching circuit is formed by CMOS analog switches which mainly functions to control the status of the electrodes. From here researcher can choose the electrode as either being the source or detecting electrode. Each set of signal conditioning circuit needs a switching circuit. Normally, the configuration of the switching circuit in an ECT system is represented as shown in Fig. 7.



Electrode Status / Switch	Sourcing	Detecting
Switch1(SW1)	ON	OFF
Switch2(SW2)	ON	OFF
Switch3(SW3)	OFF	ON
Switch4(SW4)	OFF	ON

Fig. 7. Basic switch arrangement of electrode selection.

6. DMT Digital Timing and Control Unit

The digital timing and control unit is designed for three reasons. First is to control the optical projection. The controlled parameters include the frequency of projection, sequence of projection and duration of light emission. Second is to control the switching the electrode of ECT. The third function is to control the timing to perform data sampling so as to synchronize (data from optical and ECT) the operation of data acquisition. It is crucial to do synchronization due to the dynamic change of the output signals from both signals conditioning unit. An accurate sampling timing is required to obtain the measurement of output signal optical and ECT in steady-state. Fig. 8 shows the configuration of DMT CLK and logic interface circuit.

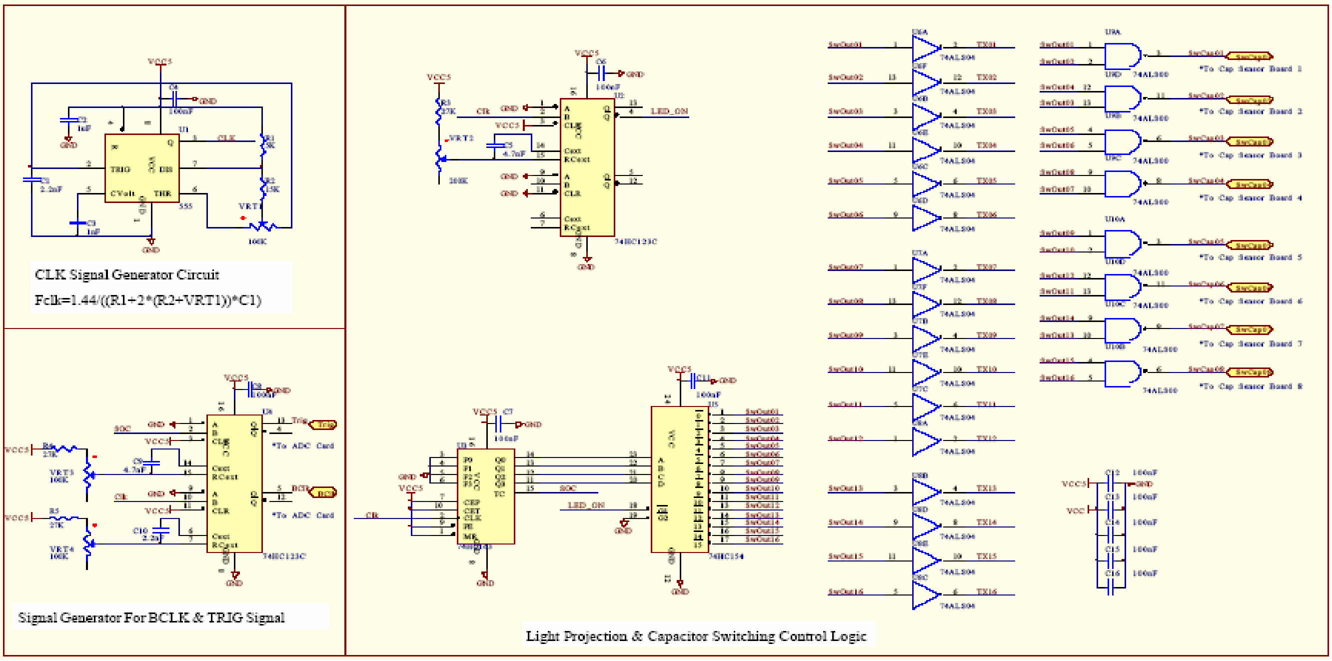


Fig. 8. DMT CLK and logic interface circuit.

In this project, the projection frequency is fixed at 4.8 kHz instead of maximum rate due to the sufficient data for real-time image processing. A 555 timer has been configured in a stable mode which is sufficient to generate the *Clk* signal with frequency of 4.8 kHz. The *Clk* signal's generator schematic is shown in Fig. 2 where the output signal's frequency is given by the following equation (Fairchild, 2001).

$$f_{Clk} = \frac{1.44}{(R_A + 2(R_B + VR_T)) \times C_T} \tag{2}$$

Based on Equation 2 and selected value of R_A and C_T in schematic, the value of R_B+VR_T must be 65.68 kΩ in order to obtain the decided output signal's frequency. The unequal value of resistor of 65.68 kΩ has been replaced with a fix resistor, R_B and a variable resistor, VR_T. In the developed circuit, the VR_T variable resistor has been replaced with a 25 turn cermets trimmer to adjust and fix the frequency of *Clk* at 4.8 kHz. Zetex (1994) notifies that, using multi-turn cermets trimmer provide an accurate trimming resistor and stability over a large range of temperature.

7. Result and Discussion

Based on the experiment, the optical sensor and signal conditioning unit used required an approximately 70 us of setting time. So, the output signal can achieve steady state. The dynamic signal captured from receivers Rx10 (red in color) and Rx11 (blue in color) for projection Tx1 to Tx5 in experiment are shown in Fig. 9. The green positive edge signals the start of each projection. The condition in which the signal achieved the steady state for corresponding projection is when the negative edge occurred.

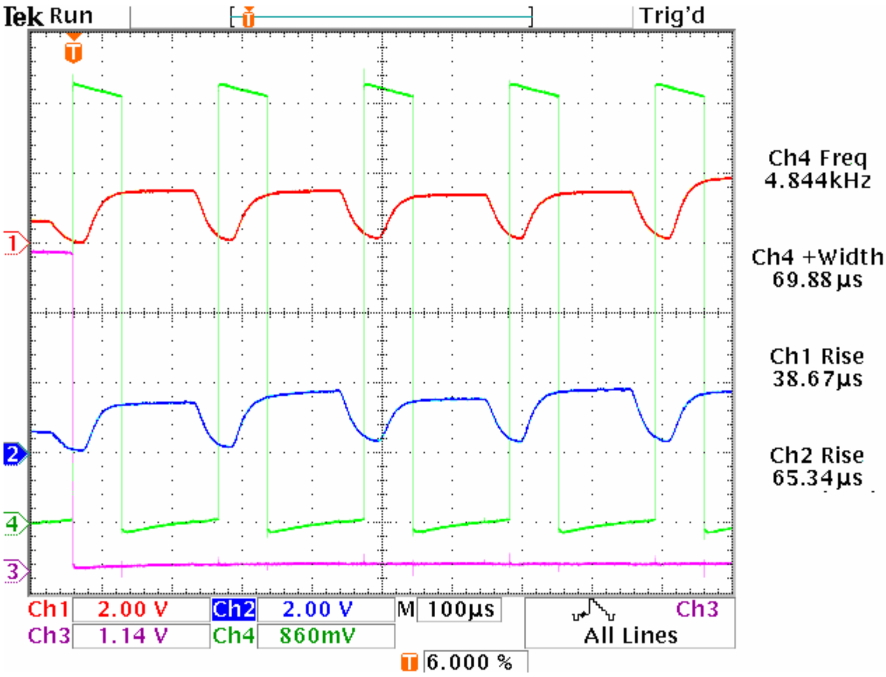


Fig. 9. Approximately 70 µs is required by signals to achieve steady state.

From the data collected, a maximum data sampling rate at 333 k samples per second is achieved. This indicates that a conversion of single sample required 3 µs. A single projection will provide 16 output signals because 16 sensors are used. Therefore, 48us of data sampling time is required to complete the conversion of those analog signals including capacitance signals. Hence, the minimum interval between the projections is more or less equal to 118us (70us + 48us) and the allowed maximum projection frequency is equal to 8474 Hz (1/118us). 16 projections are required in order to complete a cycle of projection as 16 emitters are in used. 256 optical signals and two set of ECT signals (28 signals x 2 cycles = 56 signals) are obtained from each signal conditioning circuit. As a result, the developed system is able to provide a maximum 529 set data per second (8474/16) received from the signal conditioning circuit to the computer.

The projection frequency in this study is fixed at 4.8 kHz instead of maximum rate due to the sufficient data for real-time image processing (where 300 set data per second is produced to computer to perform image reconstruction). The designed timing diagram for projection and operation of data acquisition can be referred to Fig. 10.

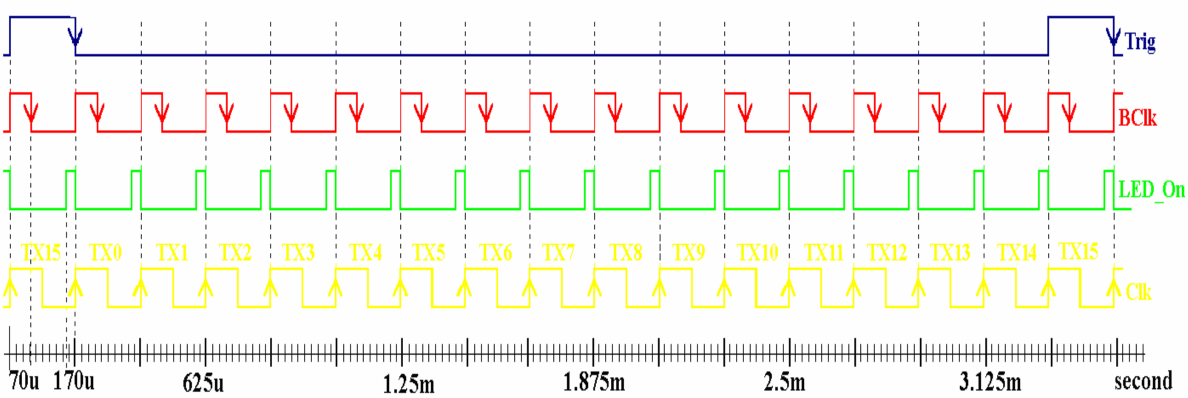


Fig. 10. Digital timing and control signals.

8. Conclusions

A new development of DMT hardware has been discussed. The actual photograph for the hardware system is shown in Fig. 11.

Fig. 11. DMT Hardware.

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