

Portable Sensing Field Device: Noncontact Ranging and Temperature Tool

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Abstract — The portable sensing field device is intended to be a lightweight, portable, multifunction sensing device for a wide array of consumers. The objective is to create a non-contact device that can sense the distance to a target as well as its exterior temperature. The ranging system utilities a “time of flight” approach in determining target distance. Using an infrared laser, the analog receiver circuit is able to detect the bounce back off a target. This bounce back is then translated to a time difference, which can be turned into a distance. The combination of these two different functions can prove to be a very useful tool in the field. The project was chosen out of genuine interest in the subject of optical engineering.

Index Terms — Infrared, non-contact, ATmega328, low noise amplifier, TDC, GP21, time of flight, Avalanche Photo Diode, laser rangefinder.

I. INTRODUCTION

Measuring the distance you are from an object is a practice humans have been using since the beginning of time. For any kind of symmetry, one must be able to find a distance, and then use basic mathematics to divide that distance into something more useful. For our purpose, we decided to build a non-contact range finder. This is to say, instead of using a tape measure or any other primitive form of distance measuring, we will be able to dynamically measure the distance to an object within range by measuring the time it took for a mounted laser beam to reach the target and return home. Though it is not a new concept, laser rangefinders are traditionally expensive, so we were motivated to create our own and find out why it was so expensive, or prove that it could be done cheaper.

In addition to being able to find the range, we thought adding a functionality that will be able to sense the temperature an object is emitting would make be a very useful addition. In keeping with the non-contact theme, we

constructed a non-contact thermometry device to be implemented along with the range finder. Though both functions are non-contact, they do not employ the same technology. The thermometry aspect does not use any kind of concentrated laser to perform its function, instead it uses a sensor that can detect the blackbody radiation produced by a body, and convert it to a voltage that can be converted to an actual temperature reading after being programmed into the microcontroller unit.

II. SYSTEM COMPONENTS

The sensing device is best analyzed and described as separate sub-modules consisting of the IR temperature circuit, power system, laser receiver module, central microprocessor, and TDC processing. A generalized block diagram is shown in Fig. 1.

A. Microcontroller

The microcontroller chosen for our design is the Atmel ATmega328. This processor is part of the Arduino Uno development board which has great community support and a user friendly development environment. There 20 I/O pins which more than satisfies the needed amount in are design.

B. APD Module

The APD module is responsible for absorbing incident light of the proper wavelength and outputting a voltage with minimal distortion. The main components of this module are the high voltage supply, the APD sensor, and the transimpedance amplifier. The sensitivity and operation of the APD module is essential in achieving our range goal.

C. Time to Digital Converter

ACAM is a German silicon manufacturer that specializes in time to digital converts (TDC), and our design uses the most recent addition to the ACAM TDC line, the GP21. The GP21 is a third generation part with many useful functions that include integrated Fire Pulse Generator (FPG) that can be used to activate the laser and begin a TOF measurement. The GP21 waits for a START channel to go logic high, and then begins a time measuring process based upon interior propagation delays and redundant circuitry. The actual TDC unit inside of the GP21 can then interpret those time values into digital values that can be used, which are placed by the GP21 into its result registers.

D. IR Temperature Module

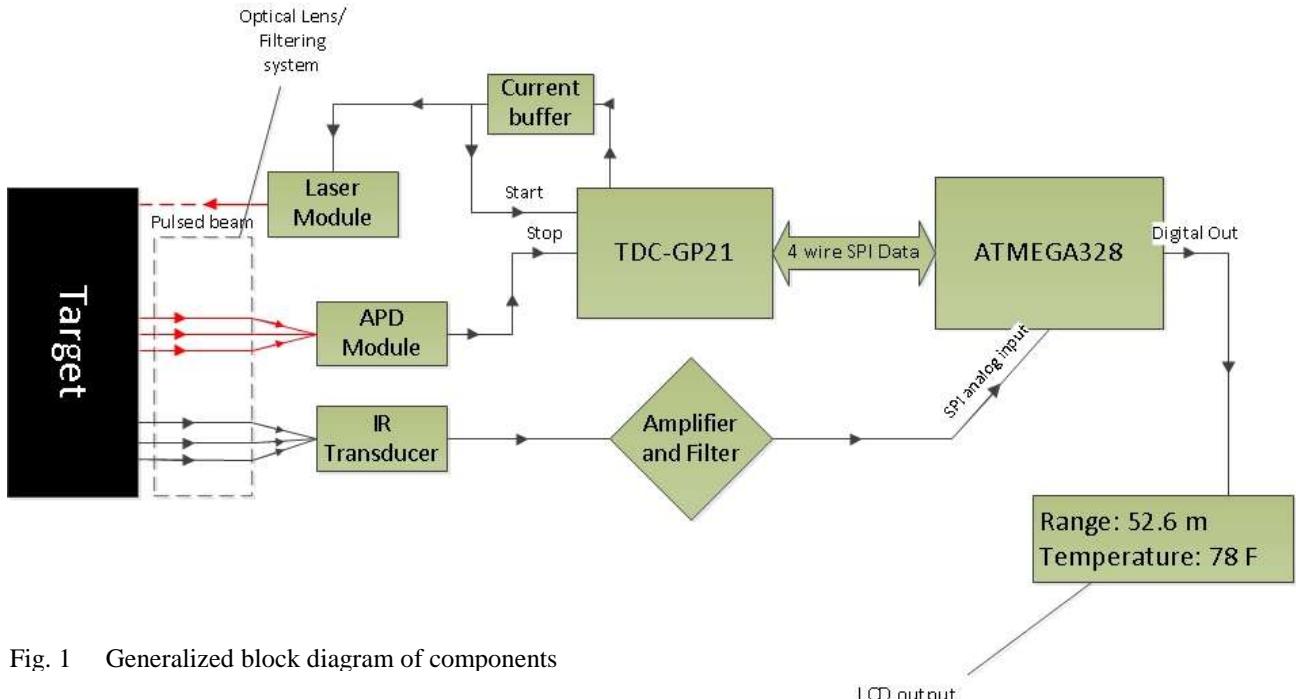


Fig. 1 Generalized block diagram of components

The IR temperature module is based on the Melexis MLX90614. This is a digital output sensor equipped with a MLX81101 thermistor, which is sensitive to infrared wavelengths, and an ASSP MLX90302, which is designed to process the output of the thermistor. To achieve respectable accuracy, there is also a low noise amplifier and 17-bit analog to digital converter built in.

E. Power System

The devices used within the project operate at either ± 5 VDC or +3.3 VDC. To obtain these voltages we have selected to use a LM7905 for the -5 VDC, LM7805 for the +5 VDC and a LD1117V33 for the +3.3 VDC. Our sources will be two 9V batteries, one to operate the LM7805 and LD1117V33, and one to operate the LM7905.

III. AVALANCHE PHOTODIODE RECEIVER MODULE

The APD receiver module is responsible for detecting the minuet levels of infrared modulated light that bounces off the target of interest. In being a purely analog device, noise elimination was a major consideration during the design of the module. Other design considerations included quantum sensitivity, high voltage biasing and transimpedance amplifier bandwidth considerations.

The design of the APD module can be further broken down into the APD sensor, the transimpedance current to voltage amplifier and the high voltage biasing supply. The

module will utilize a 5 volt dual rail power supply. The +/- 5V rails will be used by the op-amp for its main power.

Further details discussing the APD module will be discussed in the following sections.

A. Avalanche Photodiode Sensor

Due to the high voltage biasing requirements of an APD, it is an ideal sensor to use for detecting very low levels of light and makes an ideal range finding device. When a photon is absorbed by the junction and an electron breaks free, an electron-hole pair is generated. This electron moves through the substrate colliding with neighboring electrons which creates an “avalanche” of electrons and a large current. This avalanche effect creates a built in gain stage before the current even leaves the APD.

The Hamamatsu S2381 APD has a peak wavelength pass-band at 800 nm. This is well within the range for our output laser which operates at 780 nm. By biasing our APD sensor at about 160 volts we can effectively achieve a gain of over 1000 times the original incident light that hits the sensor. Shown in Fig. 2 is a graph of how the gain changes with respect to an increasing high voltage bias on the APD.

B. DC High Voltage Converter

Like mentioned previously, the DC high voltage converter is required to bias the avalanche photodiode. Since the S2381 APD has a breakdown voltage of 200 V, we should bias the sensor close to that. Since the project is

meant to be portable, we chose to purchase a prebuilt high voltage converter for the sake of its small size rather than built it ourselves. The high voltage supply chosen was the Emco Q04. It consists of an oscillator, transformer, and rectifier. The Q04 is capable to output up to 400 volts, but we only require 160. So we will operate the device with an input of 5 volts. Since we will input 160 volts into the APD, it is essential that the output of the HV supply be current limited using a high resistance value. This will limit the current through the APD sensor to around 160 μ A.

C. Trans-impedance Amplifier

In order for the output of the avalanche photodiode to be useful, it must be converted into a voltage and fed into the microcontroller. The APD will output a very small photocurrent that is proportional to the amount of infrared light that is incident on the surface. The generalized transimpedance amplifier output is given in equation 1:

$$V_o = -I_p * R_G \quad (1)$$

The transimpedance amplifier is also responsible for adding gain to the signal. This is due to the input signal being multiplied by the gain resistor value. Since we are trying to detect light signals from a distance away, we chose a 1 M Ω resistor value.

Since the output of the transimpedance amplifier turns negative, our waveform will be flipped. A unity gain inverting buffer is necessary to invert the waveform so it is representative of the original pulse. Shown in Fig. 2 is the output of the inverting gain stage for a distance of 10 feet from the optical assembly.

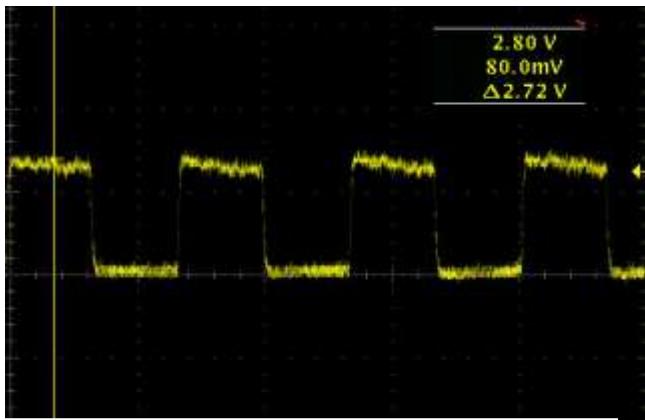


Fig. 2 Pulsed output of transimpedance amplifier

D. Comparator Pulse Adjustment

For the purpose of finding the range to the target, we are not concerned with the amplitude of the received

waveform. All that matters is if we are able to “see” the incoming signal. So to make it more consistent have not have to process very low amplitude signals, we chose to use a high speed comparator with a low reference voltage level to go high whenever it is able to pick up on the signal bounced off the target. In using this method, we can also choose what we want the high voltage to be. Since this signal will go into the TDC for digital processing, we want the signal to go high at 3.3 volts. By inputting this as our input to our digital computation circuit, we can find the time difference of the two signals. Shown on Fig. 3 is the completed APD module circuit.

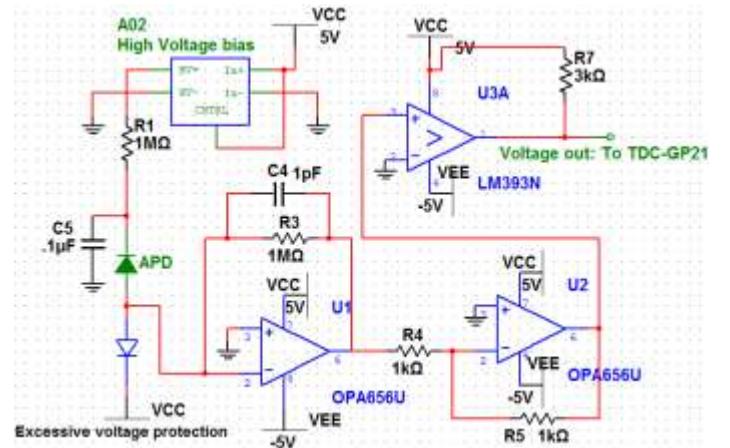


Fig. 3 APD module circuit

IV. LASER AND OPTICS

The light that is diffused off the target surface will diverge in all directions and in order for us to use it with our photodiode sensor; we must use optics and filtering to focus it. Without the use of optics, the receiver would be limited to a range of less than a few feet.

A. Laser Module

The power of the laser is directly related to how much light will come back to the source. We used an infrared laser module of bandwidth 780nm. Since this laser is in the near infrared bandwidth, it is barely visible to the human eye, but visible enough to be useful in the development stages of our project. Our APD has the highest quantum efficiency in at the 800nm range, so 780nm is acceptable for our application. The output power of the laser is 100mW. It is necessary to use such a high-powered laser because after the beam travels through the air and hits the target, a large amount of its original power will be absorbed by the target or lost due to spectral reflections, as well as a significant loss due to filtering.

The laser module used has a built in focusing lens to keep the outgoing beam as narrow as possible. As the laser

travels to a target, it will diverge, causing additional power loss to the returning signal. Additional optics may be introduced to the lasers output in future versions of the device.

B. Optical Assembly

In order to use the returning light, it must be precisely focused onto the die of the avalanche photodiode. This is done through the use of a plano-convex lens produced by Edmund Optics (EO). The lens has a special V-Coating designed by EO that ensures minimal reflectance at our desired wavelength to allow maximum transmittance of our laser. A rather large focal length of 125mm ensures the maximum power from the returning light will be focused on to the APD. The placement of the APD is also essential in capturing the returning signal; even the slightest error in placement significantly reduces the amount of light hitting the APD and therefore diminishes the quality of the returning signal.

In addition to using a lens, it is also essential to use an optical filter. Though the APD is most sensitive in the 800nm range, it is still capable of capturing other wavelengths of light, especially in the 600-1000nm range. The filter is responsible for only allowing light in the 780nm range to pass. It will reject all ambient light so the sensor does not react to light of its surroundings. The filter is very precise and only has a variance of +/- 10nm, however its peak transmittance is only roughly 60%.

V. TDC-GP21

The TDC-GP21 produced by ACAM is a very complex device that can be broken down into the following sub-modules:

- 1) Serial Peripheral Interface
- 2) Control Unit
- 3) Clock Control Unit
- 4) Fire Pulse Generator
- 5) TDC Unit
- 6) ALU Unit

A. Serial Peripheral Interface

The GP21 uses a standard 4-wire Serial Peripheral Interface (SPI) bus for communication with the master microcontroller. The GP21 follows an active-low chip-select protocol and cannot be used as a 3 wire SPI device. The Serial Select Not (SSN) line is also used in a reset style function. Individual read and write cycles must be punctuated by tying the SSN line to logic high in order for the device to function properly. Not allowing the SSN line to go high for a minimum time period of 50 ns will cause the GP21 to be unable to complete further read or write

cycles. The transfer of data is timed by the 16 MHz oscillator signal from the microcontroller circuit which has been pre-divided by software to be effectively running at 8 MHz. All data sent and received by the GP21 follows the MSB first protocol and the GP21 only supports the SPI mode 1 (Clock Polarity Bit = 0, Clock Phase Bit = 1).

The instruction set of the GP21 is limited to a series of operational codes (op-codes) that the microcontroller can use. The op-codes relevant to our design are listed here:

- 1) 0x8X – Write to address X.
- 2) 0xBX – Read from address X.
- 3) 0xC0 – Write configuration registers to EEPROM.
- 4) 0xF0 – Transfer EEPROM to configuration registers.
- 5) 0xC6 – Compare EEPROM to configuration registers.
- 6) 0x70 – Init function.
- 7) 0x50 – Power-On Reset function.
- 8) 0x01 – Start time of flight measurement.

B. Control Unit

The Control Unit of the GP21 consists of 7 control registers, 7x32 bits of EEPROM, a status register, and a test register. Each control register is 32 bits long, with the upper 24 bits containing that actual data that control the operation of the GP21, and the lower 8 bits containing identification information designated by the programmer. The data in the control registers can be loaded to, or restored from the EEPROM by sending the appropriate operational codes to the GP21. The status register can be read to inform the programmer of any errors that may have occurred during operation, including those related to EEPROM, TDC timeout, expected hits, as well as inform the programmer which result register the next result will appear in. Using the op-codes available, our design called for the heavy modification of the control registers and their factory default settings.

Configuration Register 0 is responsible for controlling some of the most important parameters of the GP21. By writing 0xFFCC2001 to the register, we configured the FPG to generate 127 pulses (the maximum allowed), as well as determine the reference clock divider, the number of periods required to calibrate the high speed oscillator, and its settling time. This register also configures the GP21 into Measurement Mode 1, sets auto-calibration active, enables ALU calibrated output, and sets all channels (START and STOP1) to be triggered by the rising edge.

Configuration Register 1 must have the value of 0x01C10001 written to it. This value configures the GP21 to expect only 1 hit on the STOP1 channel, calculate STOP1-START, enables fast initialization, and activates the low current driver for the 32.768 kHz oscillator. This value also configures the register to allow for traditional

GP2 operation of the EN_START pin, which we will be using as the input from our modified FPG output.

The remaining registers (2-6) are less important in our design; however their values that they must contain are 0x00000001, 0x21000001, 0x20000001, 0x80000001, and 0x00101701 respectively. Register 3 is used to enable the timeout ALU function which allowed for easier debugging. Register 5 and 6 are used in conjunction with register 0 to set the output of the FPG and double the output voltage, as well as define the settling time of the high speed oscillator and activate double resolution mode.

C. Clock Control Unit

The clock control unit is responsible for starting and calibrating the dual clock signals required for successful operation of the GP21. The GP21 uses a very accurate 32.768 kHz crystal oscillator, as well as a 4 MHz resonator or crystal. The 32.768 kHz crystal is used constantly while the chip is functioning, and is used to activate the 4 MHz oscillator to be used in the measuring process. When set into automatic calibration mode, periods of the reference clock are used by the GP21 to generate more accurate and consistent results from measurement to measurement. The 4 MHz oscillator is not necessary when using a microcontroller, as they can share a clock signal; however this introduces more noise into the circuit and can alter the measurement process.

D. Fire Pulse Generator

The fire pulse generator on the GP21 is configured to send the maximum number of pulses (127) to ensure the signal is received and a measurement can be made regardless of the rudimentary optics assembly in our design. The FPG has a maximum current output of roughly 48 mA and an output voltage equal to the core voltage (3.3V). While the voltage is enough to power the laser in our design, the current must almost be doubled. For this reason we included a current buffer in the form of a comparator in between the FPG and the laser module/START channel. We used the comparator to increase the output current to a more stable 80+ mA to ensure our laser operates at its full power.

E. TDC Unit

Not to be confused with the device itself (TDC-GP21), the TDC unit onboard the GP21 is the section of the device actually in charge of the measurement process. The START channel begins the measuring process and the TDC waits until the STOP1 channel goes high for the expected number of hits, which is only 1 for our case, to end the measuring process. The measurement process uses redundant circuitry that, when triggered by the

START channel, begins counting the number of gates passed by the signal using a coarse counter and ring oscillator. When the STOP1 channel is high, the measurement process ends, and the TDC unit can convert the number of gates passed into a usable value representing the time between the START and STOP1 channel activations. These time values are placed into a raw data register that can be retrieved by the ALU for calculating desired outputs. Fig. 4 shows the time measurement process for Measurement Mode 1.

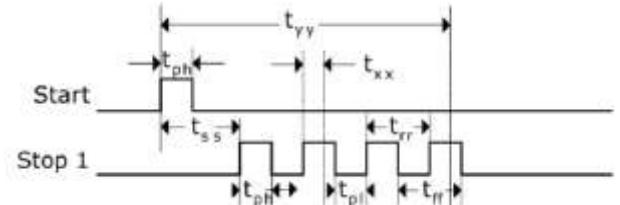


Fig. 4 Timing diagram in Measurement Mode 1

F. ALU Unit

The TDC unit is capable of measuring up to 4 hits on each STOP channel in reference to the START channel; however the ALU can be programmed to find the time differences with reference to any hit on any channel. The ALU retrieves the information from the raw data of the TDC and then, based on the values in the control registers, performs the desired calculations. Our design uses the double resolution feature of Measurement Mode 1, so we only have the STOP1 channel and the START channel to use in our calculations. The value that we desire to know is simply the difference between the first hit on STOP1 and the first hit on START. The ALU will calculate this information and then place the value into the result register designated by the Pointer Result Register. As noted by the Control Unit section, our design calls for the use of the GP21's automatic calibration mode, which is recommended by the manufacturer. When this feature is activated using Measurement Mode 1, the value in the result register will be a 32-bit, fixed-point number containing 16 integer bits and 16 fractional bits. The MSB represents a value of 2^{15} and the LSB represents a value of 2^{-16} .

G. Post Processing

Though the ALU onboard the GP21 is used to calculate digital values representing time differences between signals, these values do not represent a time we can use. The real time between the signals is calculated by

$$\text{Time} = T_{\text{ref}} * \text{RES_X} * N \quad (2)$$

In (1), the value in the result register is multiplied by the reference clock T_{ref} (0.00000025 for 4 MHz) and then multiplied by N , which is the pre-divider for the high speed oscillator (DIV_CLKHS = 1 in our design). The result of this calculation is now the true time difference between the START and STOP1 channels. This time difference must now be converted into a usable distance using the equation

$$Distance = (c*t)/2 \quad (3)$$

This value resulting from executing (2) is a usable distance value ready to be displayed on the output LCD. The whole measurement process is summarized in figure 5.

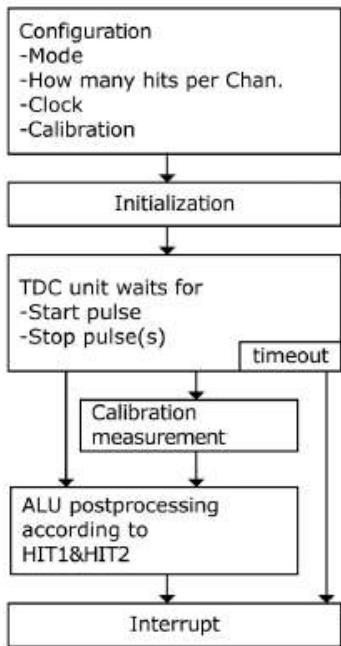


Fig. 5 Summary of GP21 TOF process

VI. INFRARED TEMPERATURE MODULE

The infrared temperature module is responsible for detecting the level of ambient IR radiation, converting that to a voltage and then to temperature values. The device integrates an RGB LED that produces different colors based upon a preset reference temperature. The external lens concentrates the LED into a spotlight visible on the target.

The design of the infrared temperature module can be further broken down into the thermopile detector, signal conditioning ASSP (Application Specific Standard Product), microcontroller, and triple output RGB LED.

A. MLX90614

Due to the lack of support on the analog sensors which require look-up tables and precise values to calculate and calibrate, we decided to go with the digital sensor. The Melexis branded sensor, MLX90614, is used for our non-contact infrared temperature module. It is built from 2 chips which are developed and manufactured by Melexis:

- 1) The infrared thermopile detector MLX81101
- 2) The signal conditioning ASSP MLX90302, specially designed to process the output of IR sensor.

Both the IR sensitive thermopile detector chip and the signal conditioning ASSP are integrated in the same industrial standard TO-39 package can. The MLX90614 is factory calibrated in wide temperature ranges from -40 to 125°C for the ambient temperature and -70 to 382.19°C for object temperature. The field of view (FOV) of 35° offers an accuracy of $\pm 0.2^\circ\text{C}$; however, this accuracy is only rated for a range of 2 feet. Therefore, we extend the range of detection by using a Fresnel lens and changing the EEPROM from SMBus.

B. MLX81101

The MLX81101 is one of the components that comprise the MLX90614. It is a solid state thermopile sensor which has on-chip thermistor for ambient temperature compensation on the silicon edge of the sensor. Using a thermistor is the device that will give the closest possible reading for ambient temperature for thermopile. The MLX81101 is well known for high reliability, long-term stability, low cost, and small size. Moreover it is fully CMOS compatible process.

C. MLX90302

The signal conditioning ASSP MLX90302 combines a low noise programmable amplifier, a high resolution 17-bit ADC, and a powerful DSP unit. Therefore, the MLX90614 can be used in applications as a high accuracy and high resolution thermometer. The principle operation of the signal conditioning MLX90302 is controlled by an internal state machine which controls the measurements and calculations of the object and ambient temperatures. The output of the MLX81101 sensor is amplified by a low noise, low offset, and programmable gain amplifier. Then it will be converted by a high resolution 17-bit ADC to a single stream and fed to a powerful DSP for further processing. In order to achieve the desired noise performance and refresh rate, the signal later is treated by programmable Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) low pass filters for further reduction of unwanted bandwidth of the input signal. The measurement result from the IIR filter is then available in

the internal RAM. There are 2 different cells available, one of which is an on-board temperature sensor, and one for the MLX81101 sensor. The onboard temperature cell is the corresponding ambient temperature T_a , and the MLX81101 thermopile cell is the corresponding object temperature T_o . These both temperature measurements have a resolution of 0.02°C. We could later read these two data either by reading RAM cells using the SMBus 2-wire interface, or we could read through the PWM digital output. For the purpose of design, power, and portable we use the first method which we read the values from SMBus compatible 2-wire interface that later will discuss in microcontroller section.

D. Microcontroller

The microcontroller is used to display temperature of object, adjust emissivity, and adjust filter for Fresnel lens. The MLX90614 has two SMBus compatible communication pins, Serial Data (SDA) and Serial Clock (SCL). SDA pin is a digital input and output which used for both the external PWM module output of the measured object temperature and the digital input and output for the SMBus. On the other hand, the SCL is only a digital input which is used as the clock for SMBus compatible communications. Moreover, this pin has an auxiliary function for building an external voltage regulator. The connection between the MLX90614 sensor and ATmega328 is really straight forward; both the SCL and SDA are connected to any two of the five analog pins, and a calculated resistor needs to be connected between 3.3V and the SDA.

While the wiring is straight forward, the software interface the wiring between the MLX90614 and microcontroller is not. The standard wiring library doesn't work for the MLX90614 because it involve with SMBus compatible 2-wire interface, so we implemented the i2cmaster library. To complicate things even more, the i2cmaster library doesn't work out of the box with our ATmega328 microcontroller. We needed to rename, change, and add some files to get it working.

In coding part, we basically read the data from internal RAM where ambient temperature T_a is stored at 0x006 and object temperature stored at 0x007. With the resolution of 0.02°C per LSB we use these formulas as part of the code to calculate the temperature:

```
tempData = (double)((data_high & 0x007F) << 8) +
           data_low; (x)
```

Where tempData is data of at RAM address 0x007 of the object temperature T_o

```
tempData = (tempData * tempFactor)-0.01; (x)
```

Where tempFactor is resolution of MLX90614, 0.02 °C

$$\begin{aligned} \text{Celsius} &= \text{tempData} - 273.15; & (x) \\ \text{Fahrenheit} &= (\text{Celsius} * 1.8) + 32; & (x) \end{aligned}$$

Where celsius is the object temperature in C, and Fahrenheit is the object temperature in F.

E. Calibration

The result from the MLX90614 is accurate compared to commercial thermometers. However, the accuracy is limited only 2 feet of range due to the large field of view of 35°. Therefore, we decided to implement a Fresnel lens in order to increase range of detecting. The task itself involves with precise temperature measurements and emissivity calibration. First we heat up an object which has assumed emissivity of 1 to a temperature of 66°C (as long it is larger than 60 °C). After that we implemented a Fresnel sensor in front of the MLX90614 which we isolate in a black tube, then calculate the new object temperature with the Fresnel lens in front of it. We got a new temperature measurement of 53°C. We then measured an ambient temperature around 25°C for both with and without the Fresnel lens. Finally, we use the equation 4 below to find out the new emissivity

$$E = \frac{T_{o_NEW}^4 - T_{A_NEW}^4}{T_{o_REAL}^4 - T_{A_REAL}^4} \quad (4)$$

From this equation we found the new emissivity to be 0.64062. Using this value, we then calculated the new EEPROM values for the MLX90614. The corresponding 0.64062 value is calculated to be A3FF. After calculating the value in hex of new emissivity for the EEPROM address 0x04, we do the same with 0x0F where the new value is calculated to be 0EFD.

These two values of the new emissivity constants are addressed at 0x04 and 0x0F, and replace the old ones by using the microcontroller and SMBus interface. First we access the address, then erase them by writing them with zero, and finally write the new values to the address 0x04 and 0x0F with the right corresponding PEC.

F. Color Preference

In order to create more functionality for the infrared thermometer, we implemented the color preference to it. We are using triple output RGB LED which is connected to the ATmega328 microcontroller. The green color of RGB is set to the ambient temperature, the red color is set to anything larger than ambient temperature 10°C, and the blue color is set to anything smaller than ambient

temperature 10°C. Moreover, in order to have the RGB LED brighter and more focus, we use the biconvex lens.

VII. CONCLUSION

The portable sensing field device, in being handheld and battery powered, represents a significant investment of both time and research in the fields of electrical engineering and optics. Integrating both contactless infrared temperature measurement and laser range finding, the field device has infinite possibilities in everyday use.

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GROUP MEMBERS



Robert Pribyl is graduating from the University of Central Florida BSEE program in the summer of 2011. He is enrolled in graduate courses for the MSEE in the fall and plans to pursue research at UCF and a career in nano-electronics and optics.



Joel Yello is graduating from University of Central Florida with a BS in electrical engineering in the summer of 2011. Upon graduation, he intends to pursue his master's in electrical engineering at UCF. Topics of interest include analog signal processing,



William Brown is graduating from The University of Central Florida with his bachelors in Electrical Engineering. Upon graduation, he intends to pursue a career in the US defense industry.



Khoa Nguyen is graduating from University of Central Florida with a BS in electrical engineering. Upon his graduation, he intends to pursue a job in instrumentation system engineering or other relevant fields.