Optical Line Smoke Detector

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Abstract—**Fiber optic sensors are used in a variety of applications, including smoke detection. Smoke is a dangerous household combustion product that may result in smoke inhalation injuries. Smoke is also an indirect indicator of a fire. Smoke particles interact with light to change the optical power output from a light source. The air gap, otherwise known as the field that is exposed to smoke, may be designed using mirrors and lenses to increase the optical line path length, thus enhancing the sensitivity of the smoke detector. A Motorola microcontroller is used to perform data-logging, analog-to-digital conversion of the optical power signal, and the triggering of an audible alarm. The smoke alarm system was successfully demonstrated, and the optical line extended path length was demonstrated to work separately. The final product was assessed in terms of its operating range and repeatability in comparison with a commercial ionization smoke detector. Suggestions are made to help improve the design and development of the next generation of optical line smoke detectors.**

Index Terms—**smoke sensors, smoke detectors, fiber optic sensors, fire detection**

I. Introduction

SMOKE is a household contaminant that takes the form of airborne solid/liquid particulates and gases often released from the combustion of materials. Although it may sometimes be used in constructive applications such as pest control and military defense (e.g. smoke-screening), it predominantly manifests itself as the unwanted by-product of a fire. The composition of smoke will depend on the nature of the burnt sources as well as the conditions of combustion. Although visible particles in smoke are commonly composed of carbon, many compounds of smoke from a fire are highly toxic and/or irritant such as carbon monoxide, aldehydes, and organic acids. These and other by-products will result in breathing complications referred to as smoke inhalation injuries. A smoke inhalation injury is due to inhalation or exposure to hot gaseous products of combustion, causing severe respiratory complications. The death rate of patients with both severe burns and smoke inhalation can be in excess of 50% [1].

Early detection of smoke serves to prevent fire or smoke related injuries or fatalities. Smoke detectors have been developed to sound an alarm when smoke concentrations exceed a predetermined threshold level of safety. These detectors commonly implement two designs: ionization detectors and optical detectors. Ionization detectors use radioactive material to produce alpha radiation in combination with an ionization chamber that produces an operating current. When the radiation is absorbed by smoke, a drop in operating current is detected [2]. Although these detectors are inexpensive and sufficiently effective, fiber optic sensors provide other advantages.

Compared to early fire detection systems, fiber optic sensors are absolutely explosion-safe since they query photons and not electricity, and may be used in most access-difficult places such as pipelines or fuel tanks. Their application extends into facilities with increased radiation levels and chemically aggressive substances. Optical smoke detectors have the added advantage of being less sensitive to false alarming from cooking or bathroom steam than ionization detectors [3]. Fiber optic sensors also resist humidity, vibration, and, within their range, they also resist heat. They also have the ability to continue monitoring the development of a fire during the crisis itself [4].

Fiber optic smoke detectors vary in design, but they usually

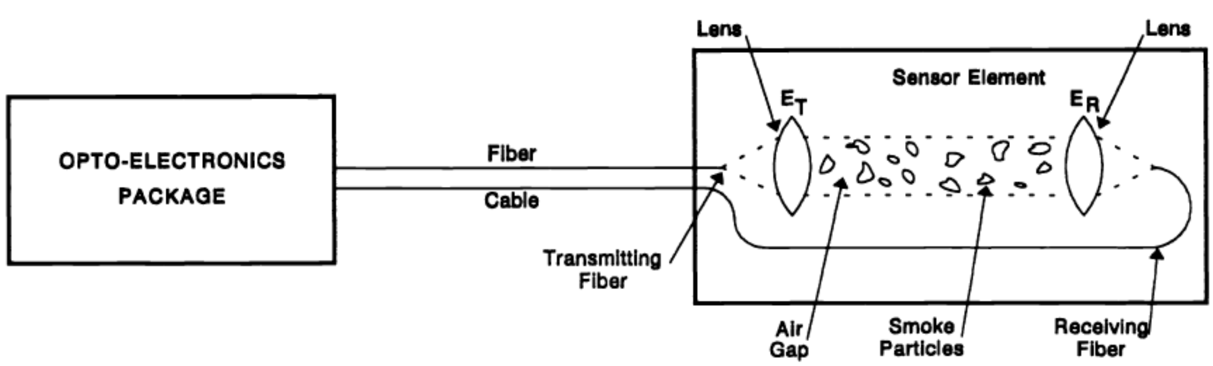

Fig. 1. Schematic of a fiber optic smoke sensor using single-light beam transmission and reception for measuring the loss of optical power due to signal degradation by smoke.

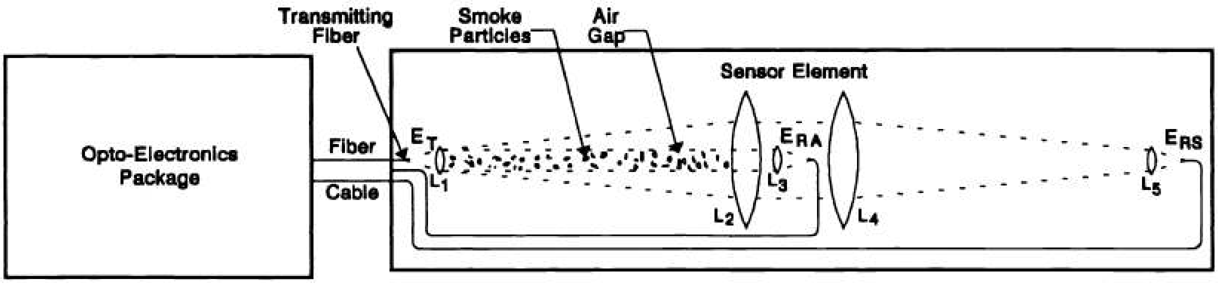

Fig. 2. Schematic of a fiber optic smoke sensor using single-light beam transmission and dual reception for measuring the optical power scattered by smoke with lens L3, and the optical absorption power with lens L5.

will depend on the measurement of optical power absorption and scattering across an air gap that is to be exposed by smoke. Fig. 1 illustrates a simple design of a fiber optic smoke detector that measures the optical power loss due to signal degradation from smoke particulates in the air. The light beam is enlarged using convex lens to increase the cross-sectional area of the air gap, thus increasing the sensitivity of the detector. The optical power will be proportional to the smoke density. Another better method of sensing smoke is illustrated in Fig. 4, whereby two measurements are made to increase the sensitivity. Lens L5 is used to measure the absorbed optical power from the smoke particles, and lens L3 (located a few degrees off the optical path) is used to measure the scattered light that is received as a result of smoke particles interacting with the light source [5]. The methods described are typical smoke detection schemes that are employed.

the main problem and describes the scope of the project; provides all necessary background information about the application; description of the basic engineering principles involved in generating the fiber optic sensor system.

II. Proposed Design

The goal of this project is to design an innovative smoke detector capable of continuous data-logging and producing high sensitivity to smoke by means of fiber optic sensing. There are several parameters that one may choose to change in order to vary the sensitivity. The physical parameters may include changing the transmission wavelength, the size of the air gap, the specific lenses to be used to collimate light, and so forth. The wavelength at which an optical signal is transmitted is best to be selected between the near-infrared and near-ultraviolet range. The parameter of interest for this project is to increase the area of the air gap using a highly concentrated beam of light that will be used to measure the optical power between the direct path of the source and receiver.

Smoke detectors have a tendency to be small in size and compact in design. Therefore it is imperative that the size of the detector be small so as it may also compete with the existing smoke detectors. A simple method of increasing the length of an air gap is by using a series of mirrors to increase the path length of the optical signal while having it confined to a small area.

Due to resource and time constraints, the proposed design could not be completely and functionally implemented, however, key concepts and principle designs were constructed for proof of concept.

TABLE I
Design Requirements

Requirement	Details
accurate detection	Smoke detector must be sensitive enough to detect smoke, but not sensitive to the point that non-smoke ambient particles are detected.
continuous monitoring	Optical power must be logged in memory periodically. Logging rate is increased upon smoke detection. Optical power is to be continuously monitored.
simple to operate	Stand-alone operation with no maintenance necessary (plug and go).
simple to install	Easily mountable near the ceiling of a standard home and initiate monitoring.
low product cost	Component and manufacturing costs must not exceed the price of current smoke detectors available.
low power consumption	Smoke detector should not waste electrical resources and only use the minimum power that is required.
product robustness	Ability to withstand abuse from the user and its operating environment.

III. Design Implementation

A. Product Design Requirements

A complete list of the key design requirements and corresponding details is outlined in Table I. Although it is not mentioned in the table, the fundamental goal is to develop an innovative optical smoke detector that would address all of the key requirements.

The key specification of the design is to use a microcontroller capable of outputting a voltage signal for triggering an alarm, analog-to-digital (ATD) conversion, data-logging (sufficient memory storage), and data retrieval from an off-line computer. A visible light range should be used as the optical wavelength, as it is more susceptible to interference from solid particulates than the extremes of low-frequency radiowaves and high-frequency gamma-rays. A visible light range optical light-emitting diode (LED) is also a safer alternative free from electromagnetic interferences (EMI) unlike radiowaves, for example. Upon exceeding the safe threshold of optical power obstruction, an alarm must be triggered. The alarm must produce a noise in the audible range (20 Hz – 20 kHz). Since the smoke detector must adhere to stand-alone operation (i.e. independent of external power sources in case their failure), it should be explicitly specified that the power supplied to the device must be a DC source that may be powered by commercially available batteries. Although it is not important in the implementation of a prototype design, the end-user product should be enclosed so that the exposure of the electrical components to the outside environment is reduced. The enclosure of the device also serves for aesthetic purposes.

B. Conceptual Design Development/Evaluation

Initially, several working design concepts were analyzed to draw ideas of the existing smoke detection schemes. Some of the detection schemes involve single-light beam transmission and reception with air gap optical power interference, and single-light beam transmission and dual reception with combined optical power interference and optical scattering, as well as spectrometric fiber optic smoke detectors [5]. A spectrometric fiber optic smoke detector works by using a single fiber as both the source and detector. Light is reflected from a mirror across an air gap (where smoke is introduced) causing a decrease in optical power and a shift in the reflectance spectrum [5]. Although this is a sensitive sensing method, spectrum power analysis would be difficult to do with the components and expertise made available.

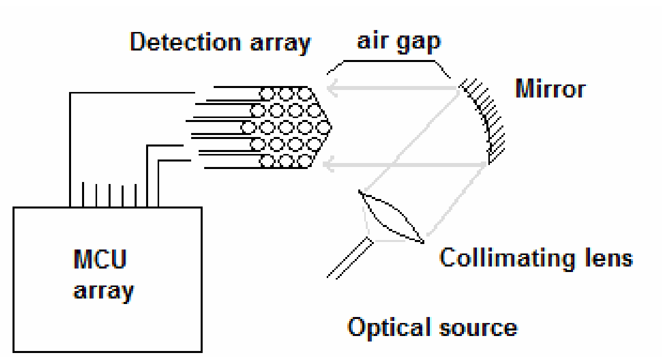

Fig. 3. A single optical transmission point is expanded and reflected to a detection array of fibers. Analysis of the optical power is performed by the MCU array.

Several concepts were brainstormed and evaluated based on feasibility, innovation of design, and whether the design would increase sensitivity. Two prominent concepts that emerged are based on light beam-expansion combined with fiber optic reception, and an optical line design.

Fig. 3 shows a concept that involves an array of packed single-mode fibers that would process a fraction of the expanded light beam. Having the input of each fiber connected to a microcontroller unit (MCU) for processing would allow for heightened sensitivity since a small cross-section of light may be analyzed more accurately. The problem with this concept is that it is CPU intensive and more power would be consumed. Also, an array of MCUs would be required to complement the number of detection fibers. This design would be more effective if the detection scheme was substituted with a charged coupled device (CCD) array instead, however such a device is not available.

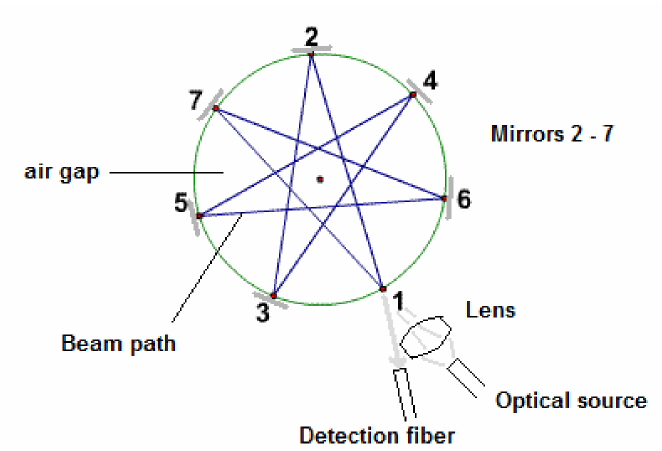

Fig. 4. A single optical transmission point is concentrated and reflected several times to increase the path length. The concentrated beam enters a detection fiber and the optical power proceeds to be analyzed by an MCU.

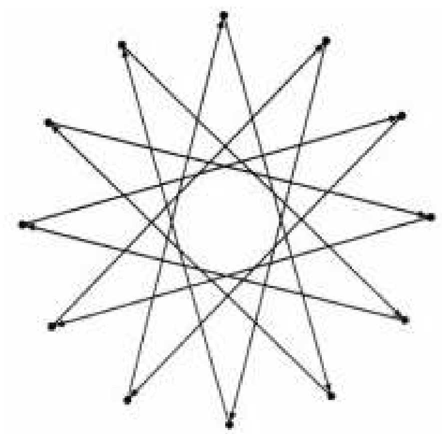

Fig. 5. 12-pointed star offers an increased path length and increased detection area.

Another more feasible approach involves using a concentrated light source with an extended path length that would be used as the air gap as shown in Fig. 4. This method is effective since a single light beam produces a mesh in a small area using mirrors. The smoke particles will be large in comparison to the concentrated light beam. Thus, when a smoke particle interacts with the concentrated light beam, a significant drop in optical power may be detected. The strategy employed in designing the beam mesh involves the reflection of the light source at small angles between mirrors. The concept may be expanded to use thousands of mirrors micro-fabricated in a confined space.

As an example, Fig. 5 shows an expansion of the beam path length with a 12-pointed star. An infinitely-pointed star would cover the entire area of the air gap. It should be noted that the optical path begins and ends at the same point. The total path length of the optical line should not exceed the maximum distance at which the optical power may be transmitted in air. In order to reduce aberration of the beam, a lens is used to concentrate the light source to the first mirror.

One MCU will be sufficient for analysis and data-logging. This provides improved and reduced power consumption compared to the other considered alternative.

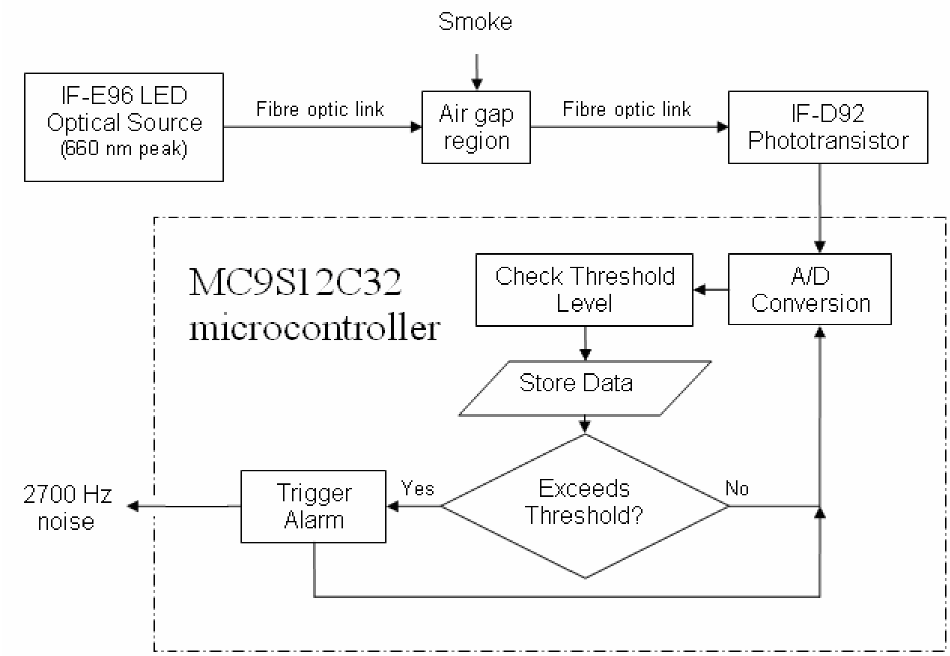

Fig. 6. Block diagram of the smoke detector with an expanded view of the MC9S12C32 programming flowchart.

Increasing the path length of a light source to create many optical lines that the lightwave follows has been previously described, up to a generation of a 3 km long optical path producing a 10 μs delay [6]. A delay of such magnitude would not affect the overall performance of the smoke detector.

C. *Product Generation*

The components that were available for the project include those materials and items from the ES691a course, including the appropriate LEDs, phototransistors, resistors, and fiber optic cables. The key component that was provided full functionality for the project was the MC9S12C32 microcontroller unit. The MCU is capable of performing analog-to-digital conversion, and also has 2 kilobytes of random access memory available for data logging. The alarm is triggered by a piezo-electric buzzer purchased at *The Source* (3-20 VDC, 10 mA at 12 V, 2700 Hz buzzer tone.)

The block diagram of the interaction between the physical components is shown in Fig. 6. Also included in the figure is a flowchart of the algorithm that was used to sense fluctuations in the optical power from the physical layer. Data storage of the ATD value was stored continuously in memory location $0900 of its memory map (prior to any smoke detection.) Upon detection of smoke, the values were continuously logged starting at $0901, up to $0F00. This would ensure 1535 loggings of the ATD conversion values, each reading occurring at an interval of 1.5 sec. This allows for over 38 min of continuous logging during an entire period while smoke is detected. The code that performs the tasks labeled in the flowchart can be found in the appendix. Since the MCU is powered using a constant 5 V power source and that it does not benefit to power components separately, the same power is

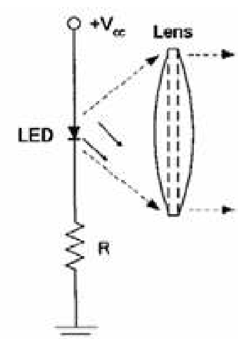

Fig. 7. Schematic diagram of the optical receiver circuit for R = 1 kΩ and using an IF-E96 plastic fiber red LED. The lens is used to focus the light onto the first incident mirror. (Vcc = 5V)

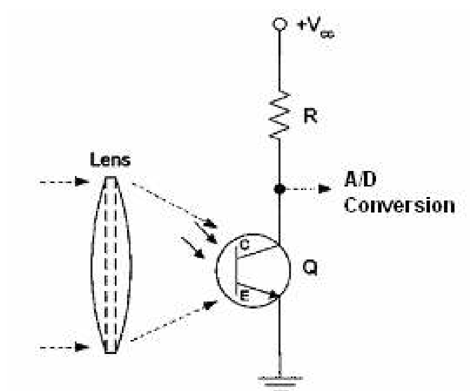

Fig. 8. Schematic diagram of the optical receiver circuit for R = 20 kΩ and Q is the IF-D92 plastic fiber optic phototransistor. The lens collects all the light from the reflected light source. (Vcc = 5V)

used for all components (i.e. 5V.)

The initial phase of implementation involved producing a means of sensing the optical power output from a constant red LED light source. This was achieved using an IF-E96 plastic fiber red LED and wiring it as a constant transmitting source shown in Fig. 7. This red LED transmits at peak optical power output at 660 nm. The resistor serves only to limit the current between power and ground. The receiver was wired using an IF-D92 plastic fiber optic transistor that responds between 400 nm and 1100 nm, with peak response at 870 nm. The receiver

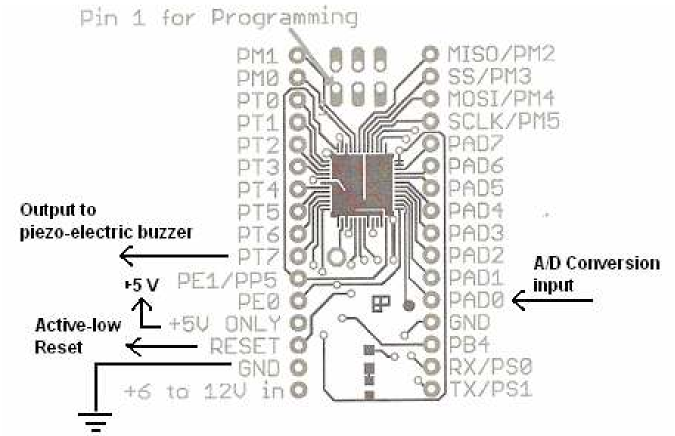

Fig. 9. MC9S12C32 16-bit microcontroller target board

circuit is shown in Fig. 8. Although the point of maximum photosensitivity does not correspond to the peak output wavelength of the transmitter, the loss in sensitivity is considered to be negligible for prototyping purposes.

The MCU was wired together with the transmitter, receiver, and the piezo-electric buzzer according to Fig. 9. The MC9S12C32 microcontroller came ready on a target board that has an 6-pin interface to allow for programming using a PE Micro USB Multilink Interface. Programming was performed in assembly using CodeWarrior IDE version 5.7.0. The output of port PT7 of the MCU may be activated to provide 5V, which is sufficient for triggering the 2700 Hz tone of the piezo-electric buzzer.

During the next phase of implementation of the design, the air gap structure was constructed. It was built on a wooden platform, with mirrors used to direct the beam of the optical source. The mirrors used contained glass and did not have directly reflective surfaces. This refracted the optical signal and was more difficult to create a specified optical line path. Although Fig. 7 and Fig. 8 both show lenses that would concentrate the light beams, lenses were not implemented in the prototype since lenses of appropriate size and focal lengths are difficult to acquire. A 5-pointed star optical path air gap was successfully constructed and is demonstrated in Fig. 10.

At this point during the implementation phase, problems were encountered in trying to combine the original optical source and phototransistor detector pair with the air gap. Calibrating and directing the beam precisely at the phototransistor was too difficult to do without lenses; however, the concept of redirecting the optical source many times to increase the path length was demonstrated successfully. The demonstrated path length shown in Fig. 10 was measured to be 19.0 cm. This concept may be extended to include thousands of micro-mirrors to significantly increase the path length and consequently the sensitivity area covered by the air gap.

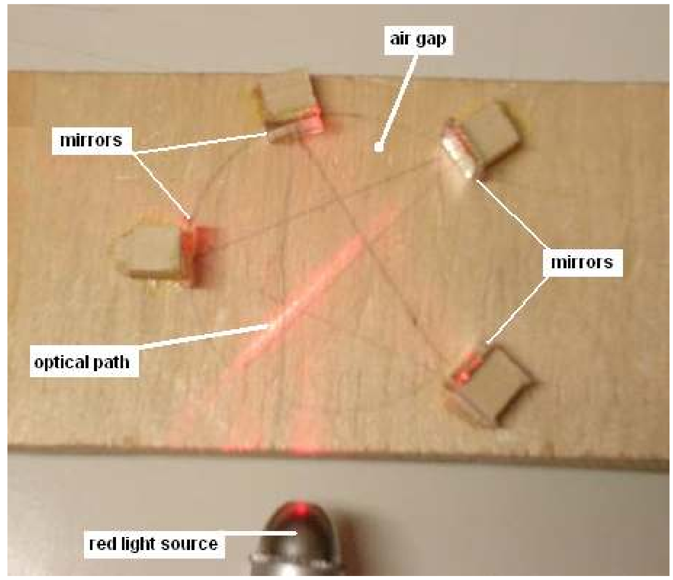

Fig. 10. Top view of a 5-pointed star optical path demonstration of concept. Phototransistor detector is not shown. The optical path length inside the air gap was measured to be 19.0 cm.

Since it was difficult to direct the optical source precisely at the phototransistor, an alternative air gap was constructed whereby no mirrors and no lenses were used. The purpose of this design was to demonstrate that an optical smoke detector may be crudely implemented and sufficiently sensitive despite having a very small air gap. The short-distance air gap integrated with the working components (MCU, transmitter, receiver, buzzer) was measured to have a distance of 2 mm, 95 times shorter than the mirror-based air gap. The final product

TABLE II
FINAL PRODUCT PERFORMANCE WITH RESPECT TO ORIGINAL DESIGN REQUIREMENTS

Requirement	Evaluation
accurate detection	The product was successful in distinguishing ambient air from smoke-filled air.* Smoke density detection limits remain unknown.
continuous monitoring	Optical power was logged in memory continuously, not periodically. Logging rate is constant upon smoke detection; however, more data readings were made.
simple to operate	Stand-alone operation with no maintenance necessary (plug and go) was easily achieved. User only needs to provide power to device.
simple to install	The device is small and occupies very little space, therefore it can be easily mountable near the ceiling of a standard home.
low product cost	Component and manufacturing costs are difficult to assess. Prototype was manually constructed using cheap and available components.
low power consumption	Smoke detector does not waste electrical resources and uses 5V to power all components.
product robustness	Although the overall prototype remains robust, the LED and phototransistor components are fragile. In a final product design, the device would be enclosed to protect fragile components.

*based on experiments conducted in a 14x14x17 cm^3 controlled container of smoke.

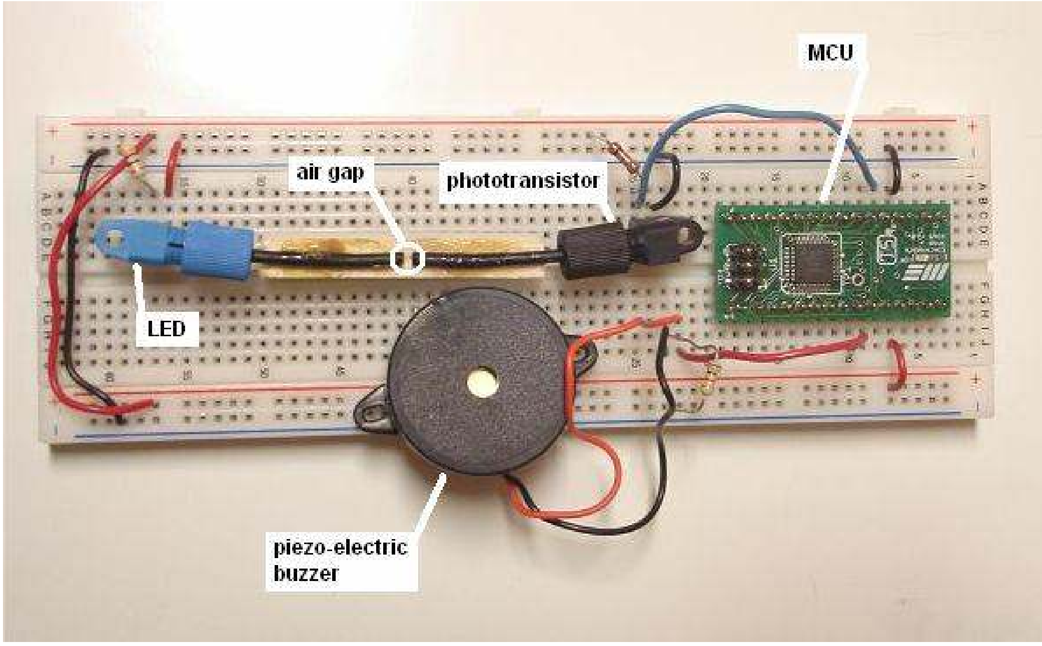

Fig. 11. Prototype of the short-distance air gap smoke detector (air gap distance = 2 mm.)

was constructed and calibrated for the short-distance air gap. The prototype is shown in Fig. 11. The fiber optic cables were 3.0 cm in length and cut using a 90° cutting tool. The ends were polished delicately for 5 min using a polishing cloth (although not special for fiber optic purposes). The fiber optic cables were secured to a 0.7 x 0.7 x 4.5 cm piece of wood with Pres-tite contact cement. All electrical wiring was done on a breadboard.

In order to calibrate the smoke detector, a test program was run in order to evaluate the optical power level for ambient air conditions. This value was found to be $3FB_{16}$, with the largest value being $3FF_{16}$. Since the analog-to-digital conversion measures values between 0 V and 5 V, $3FB_{16}$ may be calculated to equal 4.98 V. The sensitivity of the product corresponds to $(1 / 3FF_{16}) * 5$ V = 4.9 mV / hex-value (i.e. the product may detect changes as low as 4.9 mV.) Surprisingly, this was found to be an adequate level of sensitivity.

D. Product Evaluaion

The final product is a simple implementation of an optical smoke detector. The components used in the design are accurate devices capable of reproducing readings and results, which implies that the overall design may be easily reproduced to provide at least near-identical performance. The only component which may not function identically is the phototransistor (since it works in the analog domain.) That is why each unit may have to be calibrated in ambient air conditions individually in order to reproduce performance.

Comparisons of the final product with respect to the original engineering requirements (Table I) are made in Table II. Note that these comparisons are done using the short-distance air gap solution.

The original specifications required that the product be based on an air gap with an extended path length for the optical power source in order to increase its sensitivity. Although this was not implemented in the work prototype, the proof-of-concept of an extended path-length has been demonstrated. Commercially available optical smoke detectors utilize special lenses and professionally assembled products. If the tools and expertise of manufacturing were at my disposal, I am quite confident that the final product would have been integrated with the extended path-length air gap as part of the design.

Other specifications that were originally discussed included using an MCU capable of data-logging, ATD conversion, and external triggering of an alarm. This specification was addressed in the design using a MC9S12C32 microcontroller that has the ability to perform all the desired tasks. The design was also implemented using a DC power source, an audible alarm system (2700 Hz) by means of a piezo-electric buzzer, and a visible light range that may be easily obstructed by smoke (660 nm wavelength). To paraphrase, the data acquisition and warning systems have been successfully embedded into the final product. This has been discussed in detail in the previous section. All of the previously discussed specifications have been integrated into the design of the product, except for the enclosure (although it may be easily manufactured, and it does not contribute to performance, rather it enhances the robustness of the product.)

A failure analysis of the product was not performed because it has been previously discussed that fiber optic sensors are inherently robust in nature, and are resistant to humidity, vibration, and with in their operating range, heat [4]. The only failure point worth mentioning is that if the smoke levels of the environment become so high, the device may become exposed to fire that consequently heats and deforms the physical and electrical components of the device, producing damage.

In order to evaluate the quality of the performance of the product, a few experiments were conducted in order to assess the final solution for its operating range, repeatability, and sensitivity. It must first be noted however, that the operating range of a smoke detector will be inherently dependent on its

TABLE III
EXPERIMENTAL ANALYSIS

Performance factor	Experiment
Operating range	This is related to the sensitivity of the product. The operating range of the smoke detector from the smoke source was found to be 20 cm. At this point, the smoke detector struggled to detect the combustion particles.
Repeatability	The smoke detector was able to continuously provide detection of smoke up to a detection range of 10 cm from the smoke container. However, results would vary upon further increase of operating range.

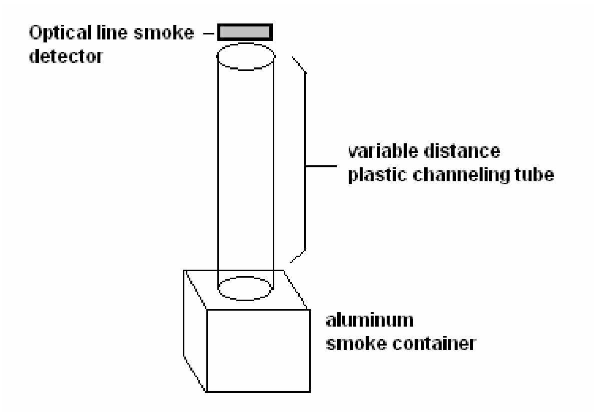

Fig. 12. General experimental setup for producing interaction between combustion particles (smoke) and the optical smoke detector. The plastic channeling tube was varied in length between 0 cm, 10 cm, and 20 cm in order to determine the operating range of the smoke detector.

sensitivity. Therefore, only an experiment to test the operating range of the smoke detector was performed. The sensitivity of the smoke detector will require having a fixed range of the smoke detector from a smoke source with variable smoke density. Since the initial smoke density cannot be determined (let alone reproducible generation of specific smoke densities), the sensitivity according to smoke density is substituted to be a test of the operating range of the smoke detector under constant smoke density conditions. A constant smoke density condition is defined to be the amount of smoke generated from the complete combustion of a single tissue ply in a 14x14x17 cm^3 aluminum container. The aluminum container trapped smoke that was produced by a single match igniting the ply of tissue paper. Upon complete combustion the tissue paper, the aluminum container was now filled with smoke. There was no practical way of measuring the density of the smoke, so the performance of the final product was simply compared against a commercial smoke detector. The commercial smoke detector is an ionization detector with unspecified sensitivity limits. Table III outlines the means of analyzing the generated optical smoke detection product with respect to the operating range and repeatability. The ionization detector was able to successfully detect smoke for all experiments, whereas the optical smoke detector failed to detect smoke upon increasing operating ranges. Increasing the operating range means to decrease the smoke density, since an addition of clean air is mixed with the combustion particles. The plastic channeling tube was developed using acetate sheets of clear plastic. The tubes were 12 cm in diameter, and varied between 10 cm and 20 cm in length. It was very difficult to produce controlled experimental results, especially when the generation of smoke varied between each experimental iteration, and that the smoke density is not quantifiable with the resources at hand. Fig. 12 shows the setup of the experimental apparatus. The plastic acetate sheets were sealed to the aluminum container. Table III overviews the experimental analysis that was involved in determining the operating range and the repeatability of the optical line smoke detector. The results are relatively qualitative, however, it is difficult to quantify smoke safely in a controlled environment.

IV. CONCLUSION

Concise statement of the outcome; evidence that the design objectives (ie. Product Design Requirements) have been met.

Fiber optic smoke detectors have been discussed and analyzed to be robust solutions in the area of smoke detection. A proof of concept has been demonstrated for extending the path length of a concentrated light beam in an n-pointed star, where n corresponds to the number of vertices situated by mirrors including a vertex for the optical source and detector. Although the optical path demonstration was not implemented in the design due to other limiting design factors (such as availability of proper lenses), a fiber optic smoke detector was nonetheless implemented and demonstrated successfully using a microcontroller as the functional core. The microcontroller was programmed in assembly to perform ATD conversion, data logging, and to trigger an external piezo-electric alarm when the optical power level exceeds a calibrated threshold limit. The overall product was analyzed with a series of operating range experiments to determine the range and alternatively, the sensitivity, of the device. Measurements have concluded that although the product is able to detect smoke at short operating ranges, the quality of performance greatly diminishes as longer ranges are introduced. The product is primarily limited by the short-distance air gap that was implemented. A first generation working prototype product has been designed and developed. The success of the project was surprisingly great considering the only problem encountered occurred with the implementation of the extended path length air gap into a refined, working product.

V. RECOMMENDATIONS

Discuss the limitations of current solution, and suggestions about improving the design.

There are a number of things that could have been done to improve the design. In order to be able to implement the extended path-length air gap, calibration of the light source so that the beam is directed precisely along the mirrored path would result in a detectable light source at the phototransistor, and consequently would improve the sensitivity of the smoke detector. The light beam would have to be concentrated with lenses of appropriate size and focal lengths.

Instead of having data-logging occurring in the memory of the microcontroller itself, it would be useful to have the microcontroller programmed to provide data-logging directly to a built-in USB port. This would improve data accessibility, especially if the data is formatted in a readable manner.

An enclosure for the entire device along with a mounting mechanism to position the smoke detector in a high location (since smoke is known to rise) would be of benefit to the end-user.

Physically polishing the ends of the fiber optic cables using finer polishing clothes may yield better results as the optical signal would be minimized from any physical obstructions.

A useful improvement to the design would be program automatic calibration. This would occur during the reset state of the microcontroller in which the signal level is measured and calibrated to be the base point. This would allow for flexibility of the smoke detector to be used for other specialized purposes, such as smoke detection in kitchens where smoke levels are allowed to increase slightly more than in other rooms of a house.

Using an LED transmitter that works with a peak optical power output that complements the peak response of the phototransistor may help improve the sensitivity as well.

Finally, the best way of optimizing the sensitivity of the smoke detector would be to change the reference voltages (high and low) to be in the operating range of the fluctuating voltage level at the emitter of the phototransistor. This would significantly increase the sensitivity of the detector since the resolution (or minimum detectable voltage change) would be in the order of fractions of millivolts.

APPENDIX

The assembly code for the optical line smoke detector is appended at the end of the report.

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Assembly code of the Optical Line Smoke Detector

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;************************************************************
; ES 691a: Optical smoke detector
;************************************************************
; The following code was made for an optical smoke detector.
; This code performs Analog-to-Digital (ATD) conversion of a signal
; that has been sent via fibreoptic channel.  When the voltage
; level of the input signal goes below a certain threshold, 5 V
; is outputted at port PT0 in order to sound an alarm.
;************************************************************

; export symbols
        XDEF Entry          ; export 'Entry' symbol
        ABSENTRY Entry  ; for absolute assembly: mark this as
;application entry point

; include derivative specific macros
        INCLUDE 'mc9s12c32.inc'

ROMStart    EQU  $4000  ; absolute address to place my code/constant
;data


        ORG   ROMStart
;************************************************************
; CODE SECTION: MAIN PROGRAM
;************************************************************
        FDB   $03FB     ; ATD THRESHOLD VALUE (4.98V)

Entry:
        LDS   #RAMEnd+1  ; initialize the stack pointer
        LDX   #$0000          ; initialize X register to 0.

        JSR   INIT
DONE:
        STD   $0900     ; Store ACCD in the continuous memory location
        JSR   CONVERT
        JSR   COMPARE

        BRA   DONE
        RTS

;************************************************************
; Subroutine INIT: Intialize ATD
;************************************************************
INIT:
        LDAA  #$10
        STAA  DDRT        ; Output 0 V when no ALARM initially.
        LDAA  #$00
        STAA  PTT

        LDAA  #$80         ;config word to turn on ADPU
        STAA  ATDCTL2 ; ADPU - ATD Power Down
                          ; Flags clr normal, disable interrupts.
        JSR   DELAY        ; Allow 100us for ATD to power up.

        LDAA  #$00          ; Select continue conversions in
        STAA  ATDCTL3  ; active background mode.
                    ; 1 conversion = 1 sequence
                    ; Conversion results placed in corresponding
                    ; result register up to sequence length.

        LDAA  #$00             ; Select final sample time = 2 ATD clocks,
        STAA  ATDCTL4     ; prescalar = 2
;(PRS4:0 = 00000) ((PRS4:0)+1)*2

        RTS

;************************************************************
; Subroutine CONVERT:
;************************************************************
; Set-up ATD, make single conversion and store the result to a
; memory location.  Configure and start ATD conversion.
; Analog input signal on PAD0.
; Convert: Using single channel, non-continuous mode.
; The result will be located in ADR2H
;************************************************************
CONVERT:
        LDAA  #$80    ; ATD SCAN=0 (Single read), MULT=0, PAD0
        STAA  ATDCTL5 ; write clears flag  (right justify) DJM =1
WAITCNV:    LDAA  ATDSTAT0
        BPL   WAITCNV ; Branch if SCF = 0.

        LDD   ATDDR0  ; Load accumulator D with the 10bit value

        RTS



;************************************************************
; Subroutine COMPARE
;************************************************************
; When the stored ATD value is lower than the permitted value
; then sound the alarm. Else, the alarm stays off.
;
; $03FB = 1019.     Max value = $03FF = 1023.
; (5V) * 1019 / 1023 = 4.98 V  (When value goes over 4.98 V, ALARM)
;************************************************************
COMPARE:
        CPD $4000    ; Lower bound. Compare ACCD to threshold.
        BHI ALARM    ; Branch if ACCD is lower than specific voltage
        RTS

ALARM:
        LDAA  #$80    ; Output at PT0
        STAA  DDRT
        STAA  PTT

        JSR   DELAYz  ; Alarm for 1 sec.
        JSR   DELAYz

        LDAA  #$00
        STAA  DDRT
        STAA  PTT

        JSR   DELAYz  ;

        STD   $0901,X ; Store ATD value in RAM
        INX          ; Increment X register
        INX

        RTS



;************************************************************
; Subroutines: Various Delays
;************************************************************
DELAYz:
        JSR   DELAYx; ~ 0.5 s delay
        JSR   DELAYx;
        JSR   DELAYx;
        JSR   DELAYx;
        JSR   DELAYx;
        RTS

DELAYx:
        JSR   DELAYb   ; ~0.1 s delay.
        JSR   DELAYb
        JSR   DELAYb
        JSR   DELAYb
        RTS
```

```
DELAYb:
        LDAB   #$FF    ; FF = 255.  255 * 100us = 25.5 ms
LOOPb:     JSR   DELAY
        DECB
        BNE   LOOPb
        RTS
DELAY:
        LDAA  #$C8            ; C8 for 100uS delay
LOOP:      DECA
        BNE   LOOP
        RTS
;*******************************************************
; Interrupt Vectors
;*******************************************************
        ORG   $FFFE
        DC.W  Entry          ; Reset Vector
```