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RESEARCH ARTICLE **OJES0401001-460**

DESIGN AND MODELLING OF GROUND PROXIMITY WARNING SYSTEM (GPWS) FOR TRAINING AID

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ABSTRACT

Controlled flight into terrain (CFIT) is the most common type of aircraft crashes in the world of aviation today. Following the sheer volume of terrain collisions, there was an introduction of CFIT classification to enable the grouping into one category of all crashes involving aircrafts colliding with terrains. To avert CFIT accidents, the Ground Proximity Warning System (GPWS) was introduced onboard the aircraft for the flight crew to be aware of the moment the aircraft is approaching a ground terrain via automatic and very distinct acoustic warning. This paper presents a digital display ground proximity warning system as a teaching aid with audio prompt using ultrasonic sensor to produce forward distance from aircraft to obstacle ahead, height, inclination of aircraft in relation to its terrain beneath the aircraft and a digital computer interface for instrument visualization for better performance using graphic user interface (GUI) thereby enabling clearer understanding on GPWS. The Arduino IDE using Arduino sketch and C language were used on the Arduino Uno. The aircraft was integrated with different electronic modules which includes Arduino single board, Ultrasonic sensor, accelerometer and transceiver module, and all these uses the Arduino to read the signal from the sensor, processes and transmit to the base station wirelessly via radio frequency. Simulation results indicates that the responses of the models are a replica of the actual aircraft operations.

Keywords: *Attitude Warning System, Arduino, CFIT, GPS, Flight path, Terrain Awareness Warning System*.

INTRODUCTION

Aircraft's altitude information remains one of the most critical parameters for decision-making in the aviation industry. Information concerning the aircraft and its sub-systems must be observed by the pilot namely emergency information, air traffic control clearances, weather, direction of flight, route, altitude, position, airspeed etc. The foremost root of global fatalities in the aviation industry originates from unintentionally flying an airplane in perfect condition into the water, ground, or man-made obstruction, typically with no erstwhile knowledge by the crew. This form of accident is known as Controlled Flight into Terrain (CFIT) (Blackett, 2021). The circumstances which brought about CFIT accidents from the analysis have identified common situations that tend to handle this accident type as evident from pilots' experiences in controlled flight in terrain (CFIT) occurrences, air traffic control records, and flight data recorders (Fu *et al.*, 2021).

CFIT occurs mostly in the course of the approach and landing stage of a flight. The GPWS was introduced in the air travel industry to monitor airplanes' flight conditions and warns the crew of imminent danger if the condition of the flight points to the likelihood of unintentional contact with the terrain (Durak *et al.* (2018)). It is a terrain alerting and awareness system that provides extra features in addition to terrain display and alerting functions. The flight conditions that the GPWS monitors include the gear positions, flap, airspeed, barometric altitude and rate, and radio altitude and rate (Vivek *et al.* (2016)). Terrain situational awareness is integrated into GPWS because of the present position of the aircraft and the projected flight route or path with a modern ground proximity warning system.

Alert information is provided both aurally and through displays to the flight crew through GPWS. A database of the terrain map will be employed to offer GPWS a way of estimating selected changes or flight routes for imminent high grounds approach. Depending on the position of the airplane, the system display is alive the moment the terrain is within or above 2,000 feet beneath the airplane. Up to 30 minutes before a probable terrain clash, there may be the provision of terrain situational awareness (Ferguson, (2022)). The success in averting improper/early descents also lies in the terrain map database that contains topographical data of almost every existing airport. The flight path and position of the aircraft are determined by GPWS via info from VOR/ILS systems, Radio Altimeter, Air Data System, FMS, and embedded Global Positioning System. The internal terrain database is compared with the aircraft's altitude by the GPWS computer (Kelly *et al.*, (2019)). A warning is generated by the GPWS system if an imminent danger of impact with the terrain is detected thereby permitting the pilot to take suitable measures. The flight route of the airplane is monitored and the audio and display alerts/warnings are generated by the GPWS as soon as the airplane enters very distinct dangerous circumstances (Bapp & Becker, (2018)).

The GPWS can provide seven capability modes when embedded with a massive terrain database and multi-sensor accuracy:

- Excessive rate of descent which offers warnings and alerts for excessive descent in relation to altitude above ground level (AGL);
- Excessive terrain closure rate to avert impact with mountains and hills;
- Descent after takeoff to avert "sinking" after initial climb;
- Terrain clearance to guarantee the aircraft simply stays above ground safely;

- Excessive glide slope to guarantee the aircraft does not approach the runway too low or too high;
- Advisory callouts, for when bank angles become too steep or a decision height set on the radio altimeter or the aircraft descends through predefined altitudes below 2,500 feet AGL; and
- Reactive wind shear.

GPWS uses data from the air data sensors, the FMS, GPS, and other navigational aids to ascertain the vertical and longitudinal position of the aircraft (Miyamoto *et al*. 2020). This information is added to data from the runway/terrain database to showcase the aircraft's terrain elevations. The vertical and horizontal look-ahead is provided by the GPWS. The aircraft can have visuals of at least a quarter of a mile around the aircraft with the horizontal look-ahead. The GPWS can foresee the turn if the aircraft enters into a bank turn and caution against likely CFIT. The GPWS sends visual warnings and aural alerts from a multicolor image to the crewmen. The color "green" on the image signifies that below the aircraft the terrain is safe, the yellow color indicates 60 secs warning alert preceding the projected impact time and it is followed by an aural message of "caution terrain", and the red color shows terrain that the aircraft would collide with within 30 secs and is followed by "terrain, terrain, pull up" aural message (Kelly *et al.*, 2019).

This study aims to develop a digital display ground proximity warning system with an audio prompt and computer interface to visualise the instrument for better performance using a Graphic User Interface (GUI) thereby providing a means of practical simulation and theoretical understanding to students of the Air Force Institute of Technology (AFIT) Nigeria, on how the GPWS operates and prevents CFIT accident to enhance safety. The following goals were set out to be achieved:

- Design the computer-based software GUI (Graphic User Interface) for the GPWS system.
- Interface Arduino with electronic components that will control the whole operations of both the aircraft and the base station.
- Integrate the system into the aircraft to read the signal from the sensors, processes, and transmits to the base station wirelessly via radio frequency.

This paper is organized as follows; Section 1 is the introduction, Section 2 presents the materials and methods that were used for the development of the ground proximity warning system, Section 3 provides implementation, Section 4 provides results and discussions, while Section 5 concludes the study.

MATERIALS AND METHODS

Typically, there are four phases of any microcontroller-based system's design and development. They include:

- Hardware circuit
- Firmware program
- Simulation
- Modelling

Hardware circuit: this has to do with the electrical circuit design and is made up of digital and analog by applying currents ad voltages everywhere in the circuit. The circuit's input and output can be analysed.

Firmware program: a software program (a set of instructions) programmed on a microcontroller. Its function is to make available needed directives on the manner of communication between devices and components.

Simulation: for effective reduction in error risks and time costs involved in building circuit prototypes, the proteus software was deployed in the test running of the firmware and circuit's working operations.

Modelling: this is characteristically the experimental conditions showcasing the outcome and operations of the system attained at the finish of the design.

DESIGN OF POWER SUPPLY UNIT

The power supply of the circuit was designed using a battery first by putting into cognizance the application and the entire circuit's essential consumption.

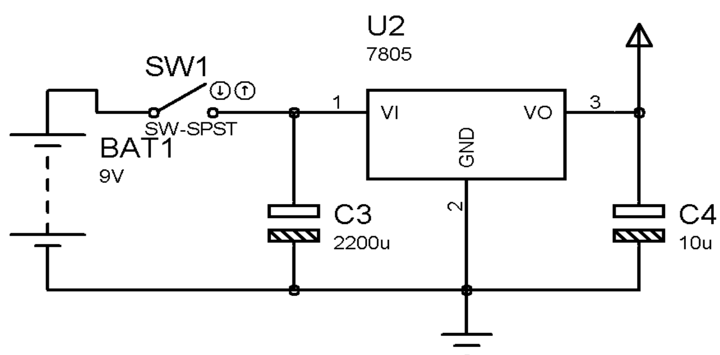


Figure 1: Power supply circuit diagram

Because each IC requires 5mA, the total worst current requirement is around 40mA, therefore a 500mA 9V battery was selected to cope with this. With an emphasis on the ensuing calculation, the filtering capacity was also chosen. Since the maximum load current = 40mA the worst condition of 500mA was used at 0-9V so that's the possible maximum voltage.

Therefore $VDC = 9V$

Secondly, the appropriate value of the capacitance to illuminate the ripples needs to be calculated. This is dependent on the output current and output voltage. The formula below is used to find the appropriate value of the capacitance:

$$C = \frac{I_o}{2\Pi f V_o}$$

Where,

I_o = Load current i.e., 500mA in our design, V_o = Output voltage i.e. in our case 5V, f = Frequency i.e 50Hz.

In our case:

$$C = \frac{500mA}{2\times\Pi\times50\times5} = 3.1847\times10^{-4}$$

This formula can be used to calculate the capacitor value:

$$C = \frac{2+(Rf)}{2(Rf)fR}$$

Where,

R = load resistance, Rf = ripple factor (for a good design it should be less than 10%).

EMBEDDED COMPUTER (MICROCONTROLLER)

The remote station and base station systems are the two embedded computer systems used in this project design in attaining the all-out efficacy of the system. The remote is on the airplane and its parameters are sent to the base station.

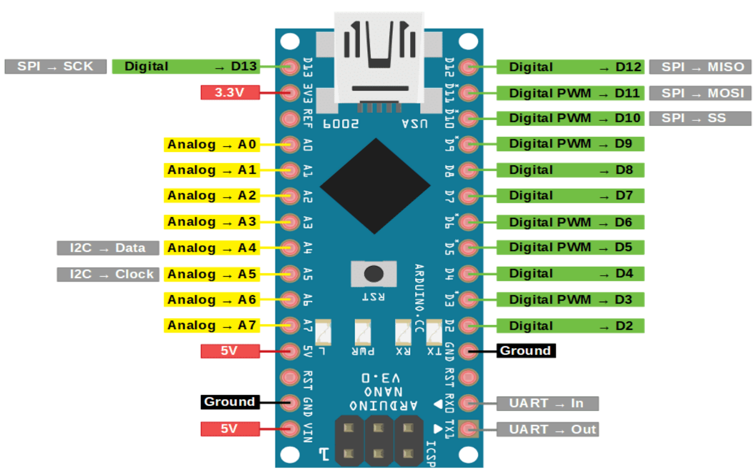


Figure 2: Arduino Nano (Single board)

ULTRASONIC TRANSDUCER INTERFACE WITH ATMEGA328

Ultrasonic receiver and transmitter sensors are rooted in the evaluation of the acoustic waves' properties with frequencies of roughly 40 kHz which is above the audible range of humans. This distance sensor offers an accurate and stable method of measuring distances from 2cm to 450cm. it has an accuracy of roughly 2mm and a focus of less than 15 degrees. It has a transducer that produces ultrasonic sounds and another one listening for echo.

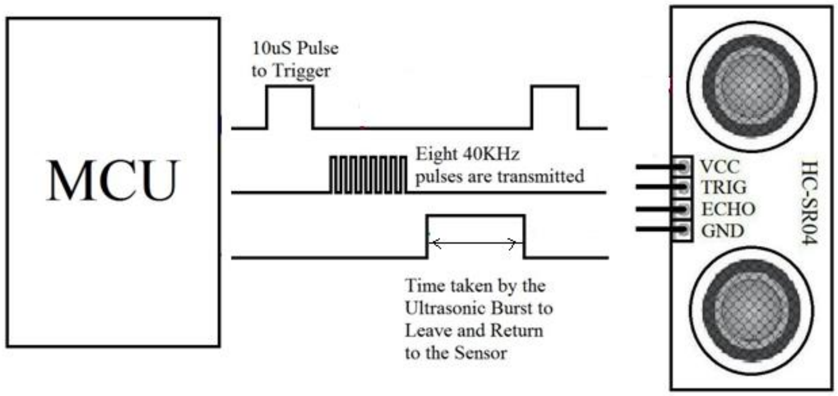


Figure 3: Ultrasonic timing control

The speed of sound is roughly 340 meters per second or around 29.412µs (microseconds) per centimetre. We use the following formula to measure the distance travelled by sound:

$$\text{Distance} = \frac{(time \times speed\ of\ sound)}{2}$$

The ‘2’ in the formula shows the forth and back travel of the sound. The next formula reads the distance as centimetres:

$$\text{Centimetres} = \left(\frac{\frac{(microseconds)}{2}}{29}\right)$$

For instance, assuming it takes the ultrasonic sound 100µs (microseconds) to bounce back, the distance however is ((100 / 2) / 29) centimetres or approximately 1.7 centimetres.

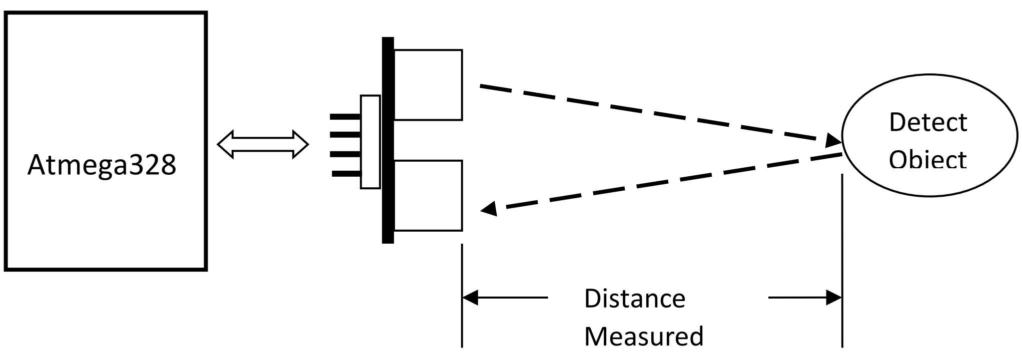


Figure 4: Ultrasonic working principle

The trigger input (Trig) pin is connected to a digital output and the echo (Echo) pin to a digital input on microcontroller whereas the VCC and GND pins modules are connected to a 5V power supply. Wait for a high level on the echo (Echo) pin when the trigger (Trig) pin is pulsed high for a minimum of 10µs (microseconds). The distance travelled by the ultrasonic sound will correspond to the duration that the Echo pin stays high. The faster the response, the nearer to an obstacle your robot is.

LED INDICATOR INTERFACE WITH ATMEGA328

The LED is a two-terminal device that can be described by the current through it and the voltage across it. The configuration of the micro's I/O pin as an output when driven low does not allow current to flow and across the series circuit zero volts appear. However, 5V shows across the series circuit when it was driven high.

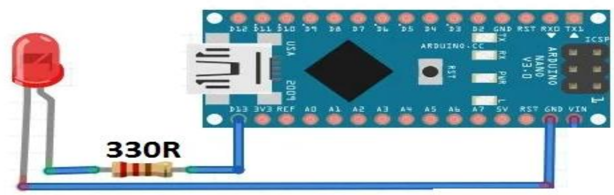


Figure 5: ATmega328p circuit connection with LED

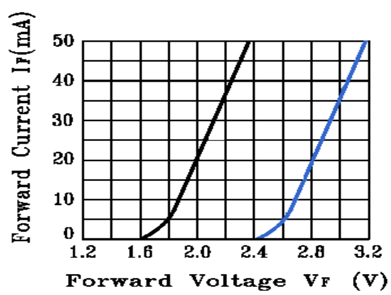


Figure 6: Forward current vs forward voltage.

According to the datasheet ('Forward Voltage, Max.'), 2.0 V is the closest current to the LED's nominal voltage drop at 20 mA and can go as high as 2.6 V. The implication is that the black curve matches a nominal device, a device would still meet the specification of manufacturers if the V-I characteristics were described by the blue curve. Faced with a tight situation and LED drops to 2.6 V, the drop in the resistor is 5 - 2.6 = 1.4 V, and I = 1.4/330 = 4.2 mA would flow.

TRACK ORIENTATION WITH ARDUINO USING ADXL-345 ACCELEROMETER

Both dynamic and static forces of acceleration can be measured with the ADXL345 sensor which is a 3-axis accelerometer. A typical example of static force is the earth's gravitational force while movements, vibrations, and so on cause dynamic forces, thus, the Yaw-Pitch-Roll movement of the aircraft was tracked with it. Acceleration is measured in meters per second squared (m/s^2) but the sensors are typically expressed in gravity or 'g'. An accelerometer placed flat opposite to the gravitational force with its Z-axis pointing upwards, the sensor output of the Z-axis will be 1g. Furthermore, since the force of gravity is perpendicular to the X and Y axis does not affect them, the X and Y outputs will be zero. The Z-axis output will be -1g if the sensor is turned upside down. It shows that gravity can differ from -1g to +1g because of the orientation of the sensor's output.

MINI MP3 PLAYER INTERFACED WITH ARDUINO

The DF-Player Mini MP3 Player interfaced with Arduino is a small module with the speaker receiving simplified output directly. The module can be combined with Arduino or as a separate module with push buttons, a speaker, and an attached battery. With the Arduino Universal Synchronous and Asynchronous Receive Transmit (USART) feature, you have a full-duplex communication with signals transmission and receiving dedicated lines.

Table 1: Interface between the Arduino and the DF-Mini MP3 Player

Arduino Board	DF-Player Mini MP3 Player
TX (Pin1)	RX
RX (Pin0)	TX
VCC (3.3V)	VCC
GND	GND

Each data received or transmitted has the setup of a start bit, parity bit, data bit, and stop bit: 1 start bit, 8 data bits with no parity bit, and 1 stop bit are the most used configuration with Arduino. BAUD RATE which is the unit of measurement for transmission speed is equivalent to the number of bits per second for transmitting and receiving data.

$$BaudRate = \left((systemclockfrequency)/(16(UBRR+1)\right)$$

where:

UBRR is the contents of the UBRRH and UBRRL registers

$$UBRR = \left((systemclockgenerator)/(16*Baudrate)\right) - 1$$

$$UBRR = {}^{fosc}\!/_{16BAUD} - 1$$

Fosc = Microcontroller Crystal Oscillator Speed ($8MH_Z$ = 8000000)

Baud = GSM module Baud rate Communication Speed (9600)

$$UBRR = {}^{8000000}\!/_{16*9600} - 1 = 51$$

The communication speed between the GPS module and MCU was determined with the result of this calculation with 0.005 minimal error and control with ATmega16 C algorithms (ATMEGA Datasheet). The first function initialises the microcontroller; by setting the USART pins (TXD and RXD). The function set the clock speed and also enabled the TXD and RXD.

AUDIO OUTPUT FILTER WITH SPEAKER

The low-pass filter is made up of a wired capacitor and resistor. A high-frequency speaker signal is shunted at low reactance of the capacitor at high frequencies.

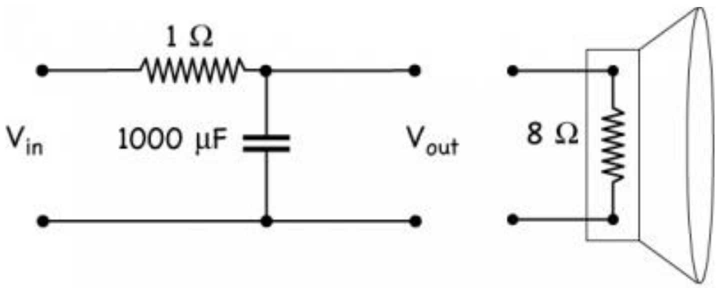


Figure 7: Low-pass audio filter

The circuit again may be seen as a voltage divider since:

$X_C = 1/\omega C$ and $Z = \sqrt{(R^2+X_C^2)}$, $V_{in}/V_{out} = 0.85$

at 100 Hz and 0.16 at 1000 Hz. V_{in} was white noise and V_{out} was shown as a function of frequency up to around 780 Hz. The outcome of adding the 8 Ω speaker load is depicted by the spectrum on the right while the spectrum on the left has no connected speaker.

NRF24L01 INTERFACING WITH ARDUINO UNO

NRF24L01 operates in the 2.4GHz ISM frequency band and is a wireless transceiver. It is expressly designed for ultra-low power applications and is used in wireless data communication with a communication range of up to 100 meters. The configuration and operation can be via SPI Protocol. Data can be transmitted at a rate of up to 2 Mbps. This module has in one place a network of 125 independently working modems as it can use 125 different channels. Each channel can simultaneously communicate with 6 other devices as it has up to 6 addresses. The power supply range is between 1.9V to 3.6V and during transmission mode it takes 12 mA of current which is below a single LED.

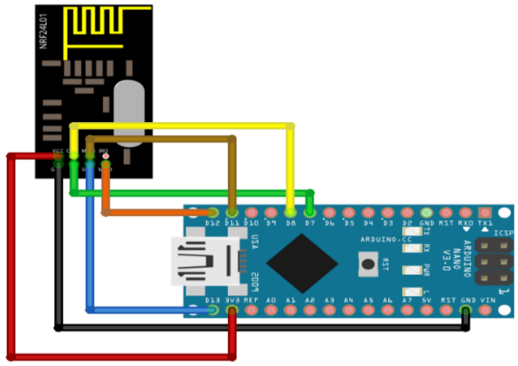


Figure 8: Arduino single board interfaced with nRF24L01

IMPLEMENTATION

The implementation discussed the whole construction and the development of the computer-based software GUI (Graphic User Interface) for the GPWS system and the objective of the project. It explains the various components that were involved and how they were connected. As in all engineering designs, after the paperwork (blueprint i.e., design, calculations, and analysis), the selection of components was made which is the next step, which is based on the availability, reliability, and affordability of components. After components analysis, the preferred values were chosen. They were first tested to make sure that they are in good condition. They were mounted first on a breadboard according to specifications to ascertain their performances.

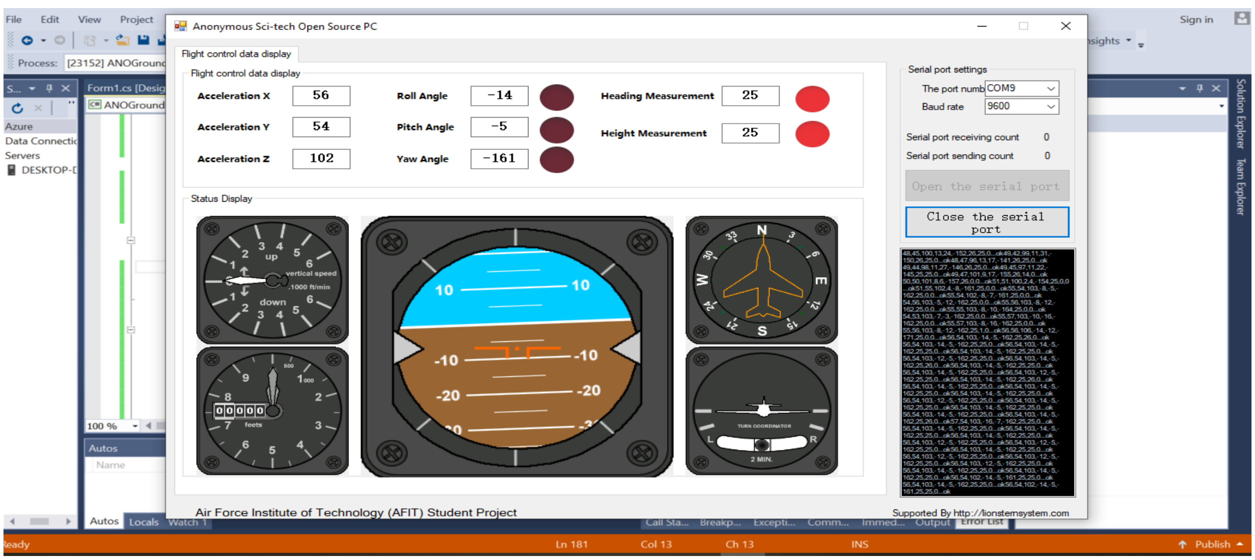


Figure 9: The Monitoring Interface

The Arduino IDE using Arduino Sketch and C language was used on the Arduino Uno to control the whole operations of both the aircraft and the base station.

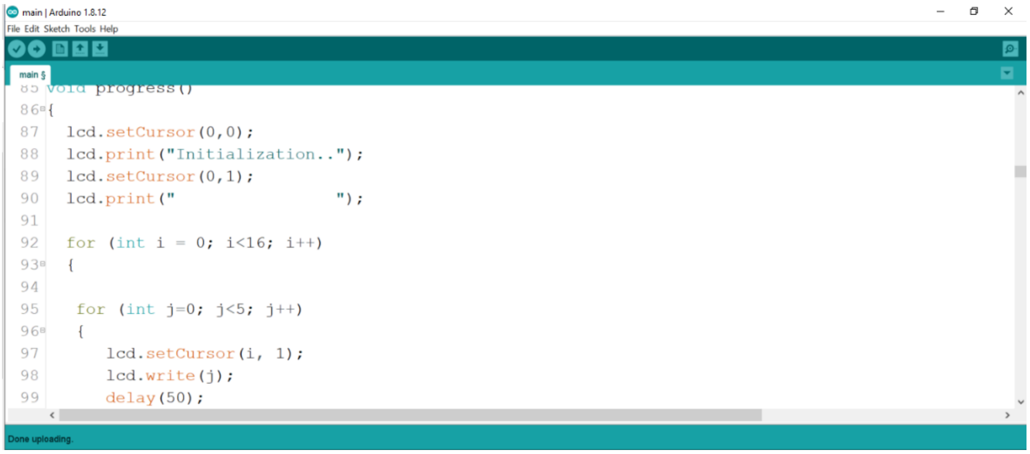


Figure 10: Arduino Development Environment (IDE)

The power supply requirement of the circuit was +5V dc and the power regulator used was LM7805 IC. The power supply components were first connected on a breadboard; the arrangement was powered and tested with a digital multi-meter, which gave the desired voltages of 5V.

The Arduino mounted on the respective pins for connection was checked from IC datasheet. As much as possible, components were placed close to each other to minimize delays in data transfer and circuit complexity and soldered on a Vero board.

(a) (b)

Figure 11: Transfer of the component to Vero Board (a) Base station connected to PC, (b) remote circuit for the aircraft

The power supply, switches and displays were all mounted on board with flexible wires being used for connections

RESULTS AND DISCUSSIONS

The testing employed for this study includes static, dynamic ad operational tests.

Static testing

Static testing is the type of test normally carried out when the circuit is not powered. This is done to ensure that the connections on the board were properly made to avoid damage. This test includes Continuity Test. Continuity test carries out a check on an electronic component to know if it is working properly. All the components were checked individually even after the components were mounted on the breadboard to ensure that they are working properly.

Dynamic testing

This is the type of test normally conducted when the electronic circuits or components are powered and it is also known as signal tests. This form of test is carried out from the power supply with a voltmeter.

Table 2: Dynamic tests carried out

SN	Voltage	Result
1	Power supply was tested from the 9V battery	The voltage was giving 8.7V
2	LM7805 voltage regulator was used to provide 5V as output	After the test, the output was giving the required voltage of 5V
3	The object ahead detection using an Ultrasonic sensor.	Calibrated At 100cm the system performs GPWS notification
4	The tilt position with a three-axis accelerometer	Was tested to obtain the 3 angles and the GPWS works fine
5	16x2 Character LCD was powered.	Using 5V, the contrast was adjusted using a variable connected to PIN3 of the LCD

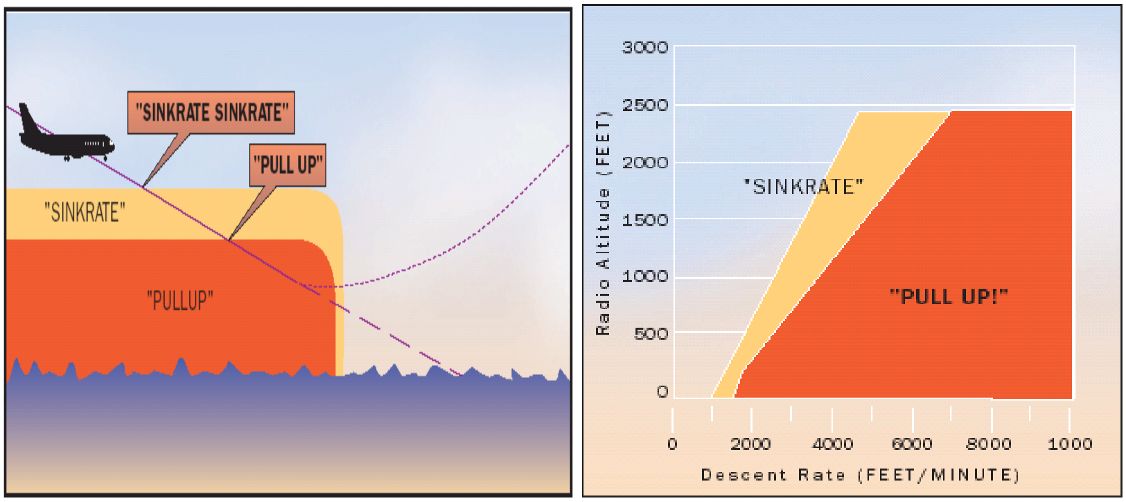
Operational test

Two types of operational tests were carried out the communication between the based station and the aircraft and the GPWS Detection and notification test.

Simulations Result

The performance evaluation of the GPWS device is simulated using Proteus software. The GPWS device was able to accurately and timely send warning signals in all the scenarios stated:

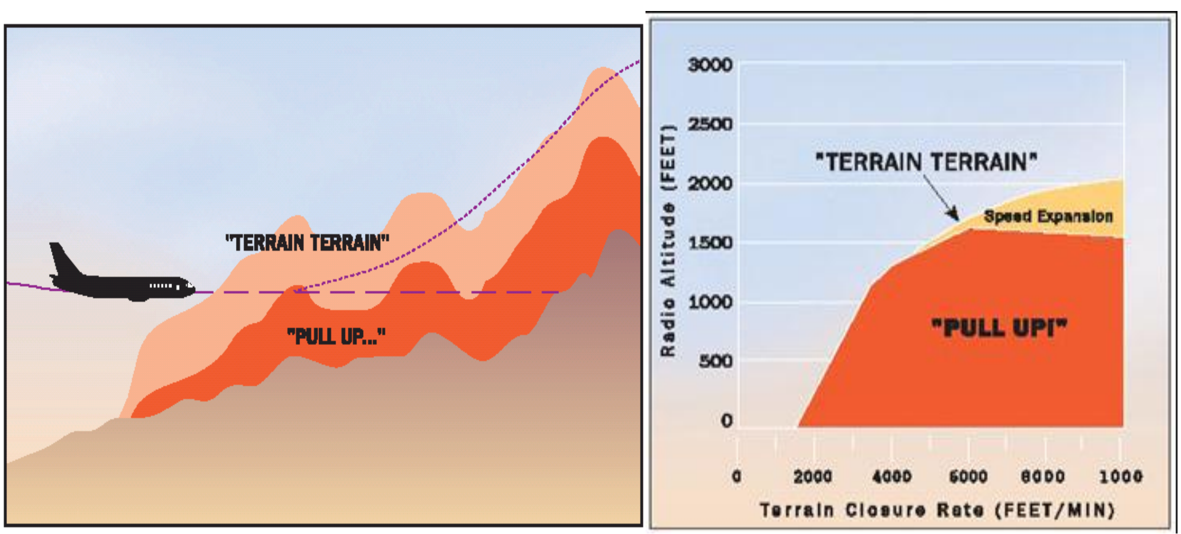
Mode 1 Scenario - Excessive Rate of Descent: This is activated by high rates of descent near the ground "Sink Rate" with the associated warning "Pull Up". Mode 1 is active during all phases of flight**.**



(a) (b)

Figure 12: Simulation result of (a) Excessive descent rate, (b) Excessive descent rate (Jet)

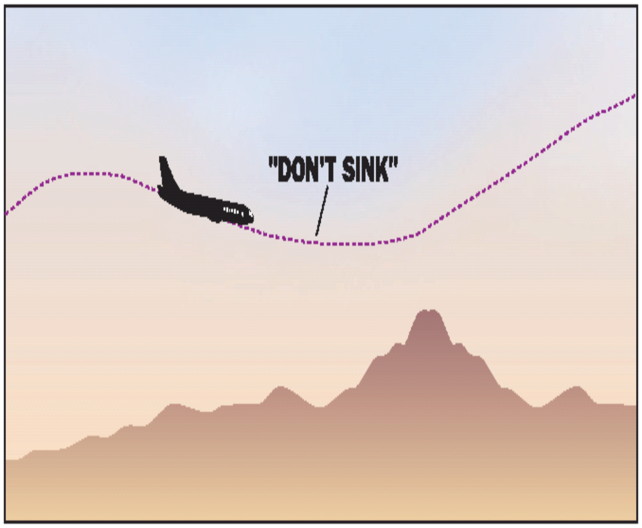
Mode 2 Scenario - Excessive Terrain Closure Rate: Mode 2 takes into account gear and flap configuration. There are two types of Mode 2 alerts: Mode 2A (active during climb, cruise, and initial approach) and Mode 2B (active during approach and 60 secs after takeoff). With landing gear up the warnings are "Terrain", "Terrain" and "Pull Up". With landing gear down, the "Terrain" caution is triggered.

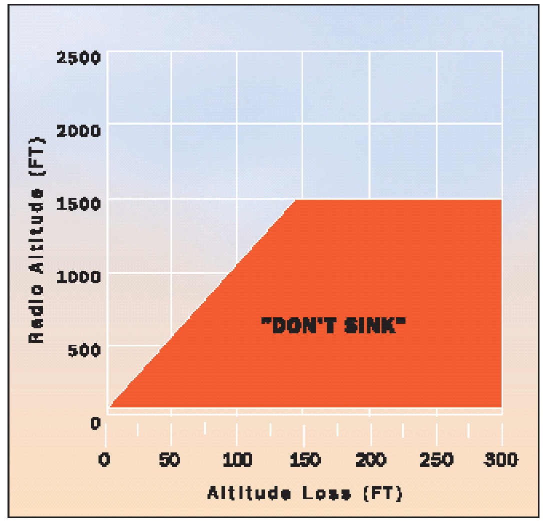


(a) (b)

Figure 13: Simulation result of (a) Terrain closure rate, (b) Terrain closure rate (Jet)

Mode 3 Scenario – Loss of Altitude as a result of a Takeoff or Go-Around: A warning of "Don't Sink, Don't Sink".is activated after takeoff or go-around when there is momentous loss of altitude.





(a) (b)

Figure 14: Simulation result of (a) Altitude loss after takeoff, (b) Altitude loss after takeoff (Jet)

Mode 4 Scenario - Terrain Clearance Not Sufficient (while in landing configuration). Mode 4A and 4B are active during the cruise and approach, and Mode 4C is active during a go-around. Mode 4A triggers "Too Low Terrain, Too Low Gear" when the landing gear is up, Mode 4B triggers "Too Low Terrain, Too Low Flaps" with flaps not in landing configuration (but landing gear down) and Mode 4C triggers with flaps, not in landing configuration OR gear up: "Too Low Terrain".

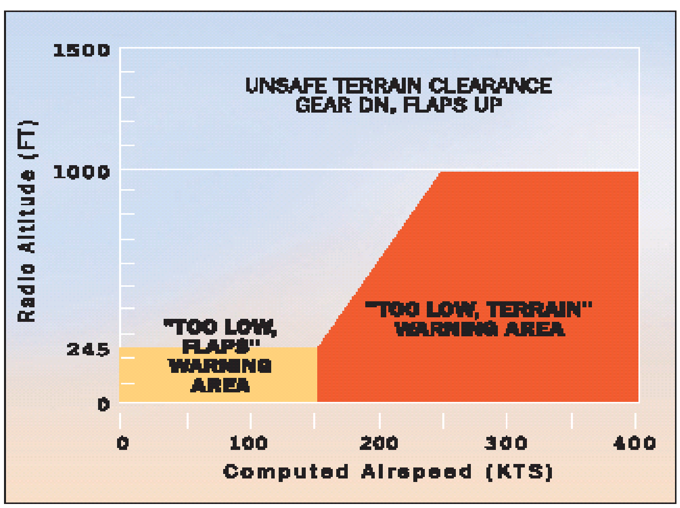


Figure 15: Unsafe terrain clearance

Mode 5 Scenario – Descent Below Glide Slope: For extreme glide slope digression, mode 5 makes available visual and audio alerts once there is a drop by the aircraft on front-course ILS approaches beneath the glide slope beam. Mode 5 triggers 'Glideslope' full volume alerts the moment the airplane is less than 300 feet AGL and it comes with the illumination of GPWS alert lights.

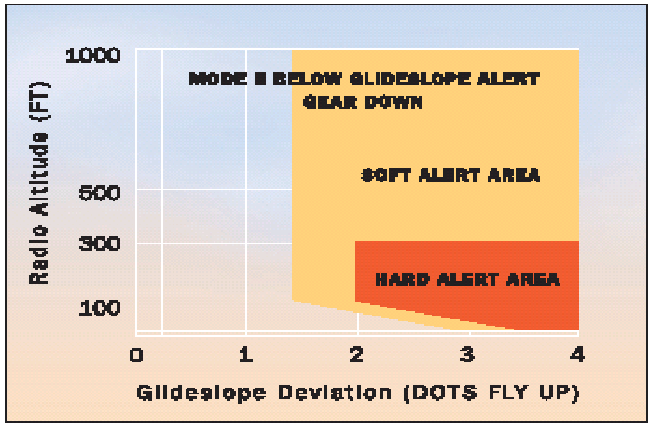


Figure 16: Descent below Glide Slope

Mode 6 Scenario - Altitude callouts; pre-determined altitude callouts are offered by some manufacturers in this mode. A voice message of 'five hundred' is given out the moment the airplane goes below 500 feet above the elevation of the runway. Optional features like bank angle protection can be incorporated into this mode.

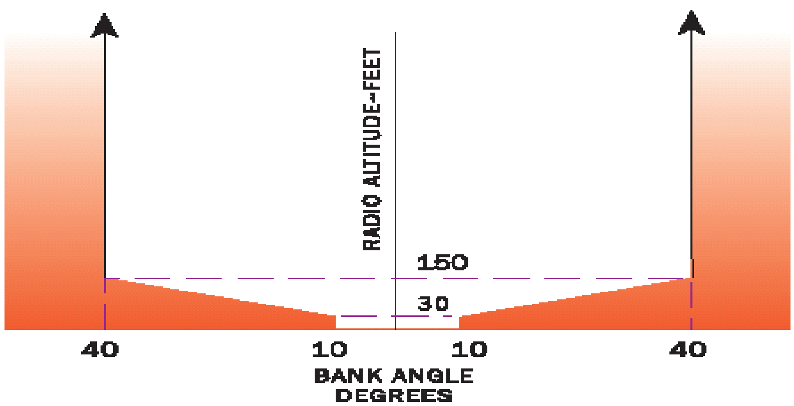


Fig. 17: Advisory callouts

Mode 7 Scenario – Windshear: Windshear is an alteration in the direction and/or speed of the wind towards a small distance and can portend great danger to the airplane since airflow to the wings can come to an abrupt stop thereby making the production of lift impossible. However, a warning system has been embedded in the GPWS capable of alerting the crew members to the wind shear before the entry to the unsafe wind-shear zone by the aircraft.

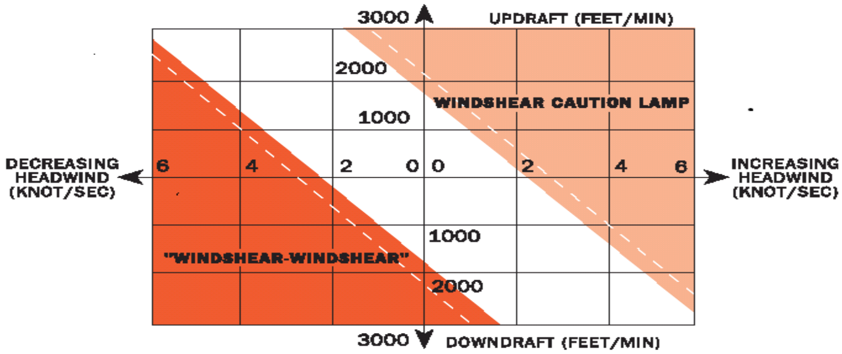


Figure 18: Windshear Alert

CONCLUSIONS

The introduction of GPWS into the air travel industry has vividly decreased the volume of CFIT accidents over the years. Subsequently, flights are made safer, and more than ever before, situational awareness is known by the flight crew. Stakeholders in the aviation industry are obliged to do everything within their power to improve aviation safety. The outcome of the investments in the design and development of the ground proximity warning system has proven the justification for safety enhancements. This work has successfully designed a digital ground proximity warning system with terrain warnings and aural alert systems and has brought about a satisfactory understanding of GPWS' warning systems and their operations and principles. The design and simulation of this GPWS are very useful as a teaching aid to students, it is also useful for researchers, pilots, and technical personnel on aircraft maintenance. It is therefore essential to develop the procedures and equipment that would reduce accident risks to the barest minimum when causes and consequences of other aircraft accident types are studied.

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