An Inexpensive Terrain Awareness and Warning System for Small Aircraft

Kim P. Martin, Dwight D. Egbert, Frederick C. Harris, Jr.
Department of Computer Science and Engineering
University of Nevada
Reno, NV 89557
{kmarti, egbert, Fred.Harris}@cse.unr.edu

Abstract

For pilots the importance of knowing their height (distance above the ground) cannot be minimized. An error in determining height can easily prove fatal.

Commercial and military aircraft usually have radio altimeters to determine their height. These units cost in the thousands of dollars, are a structural part of the aircraft, and require FAA approval. However, radio altimeters are generally not available to private pilots or small aircraft because of their excessive cost.

Important advances have occurred in the last two decades that have made it possible to construct portable devices that can calculate an aircraft's height. These advancements are the Global Positioning System (GPS), powerful microcontrollers, programmable flash memory, and color LCD displays. Using this technology along with publicly available digital elevation data it is possible to build an inexpensive, accurate embedded device that can calculate height and other flight parameters. Such a device is not dependent upon FAA approval and can be used in any aircraft.

Keywords: Embedded System, aircraft

1. Introduction

An accurate means of determining height is necessary, if not mandatory, for many flying conditions. Many commercial and military aircraft fly in conditions that make it impossible for pilots to visually determine their height. The most common solution to this problem has been to use radio altimetry.

Radio altimetry has been in use almost as long as radar has been around. As the name implies radio altimetry uses radio waves to determine an aircraft's height. Radio waves are transmitted towards the ground and the time it takes for the waves to be reflected back to the aircraft is measured. Since the wave speed is known the height of the aircraft can be determined.

Radio altimetry is frequently used by commercial aircraft for approach and landing, for automatic landings when using an autopilot, and is an essential part in ground proximity warning systems (GPWS). In civil aviation applications, radar altimeters generally only give readings up to 2,500' Above Ground Level (AGL).

Today, almost all airliners are equipped with at least one and usually several radio altimeters, as they are essential to autopilot landing capabilities (determining height through other methods such as GPS is not permissible under current legislation).

Knowing an aircraft's height is just one aspect of what is called situational awareness. One recent addition to improve situational awareness involving terrain has been the merging of digital map data with terrain following and forward looking radar systems [1]. This addition along with other improvements in the in-cockpit terrain awareness and warning system has been credited with preventing nineteen Controlled Flight into Terrain (CFIT) incidents in the four years prior to 2001 [2]. The number one cause of passenger and crew member accident fatalities is inadvertently flying an airworthy aircraft into the ground or water [3].

Since radio altimeters and terrain following radars are financially prohibitive for private pilots, a portable embedded device that can determine height from GPS and terrain elevation data can prove useful to pilots.

2. Background

Two companies (AVMAP [4] and Lowrance [5]) offer five portable devices that can determine an aircraft's height. One offering, somewhat typical of all five, is the Geopilot II Plus from AVMAP.

Figure 1: The AVMap Geopilot II Plus.

The suggested retail price is $1299 and some of its features include the following:

- Display colors: 64K
- Disp. resolution: 320x240 pixels
- GPS Receiver: Sirf Star III 20 channels
- Processor: ARM 9 300 MHz
- RAM: 32 MB

This is a powerful embedded device and can execute a sophisticated program with detailed, graphical output. As can be seen in Figure 1, the AVMap Geopilot II Plus presents a sophisticated display that consists of an aeronautical map along with textual output of flying parameters on the right. There is a column of buttons on the right side for user control. This kind of firmware display and layout is typical of all five products.

The large number of inputs, along with the complex displays, implies that these devices are powerful handheld computers. There's nothing intrinsically wrong with that, but is all this complexity necessary when engaging in a moderately dangerous profession such as flying? Does this much information enhance situational awareness or detract from it? This level of complexity might cause enough distraction such that a serious, maybe fatal, error might occur.

3. Terrain Awareness and Warning System Design

The Terrain Awareness and Warning System (TAWS) is conceived as a low-cost embedded device used by pilots to enhance situational flight awareness. In order to completely understand how such a device can help pilots, a quick summary of flight preparation and execution should illuminate the TAWS usefulness.

Prior to any flight pilots prepare a flight plan. This plan consists of such things as origin and destination, flight path, the weather along the flight path, anticipated operating ceiling, flight time, and many other parameters. In the old days (before hand-held digital computers), and still in use today, pilots use aeronautical charts to plot their course over the ground and to determine their height by examining the terrain over the anticipated flight path.

Pilots usually know their origin and destination. They know the operating and service ceiling of their aircraft and have topographical maps on which they map the vector or vectors from their origin to their destination.

The pilot takes his maps and flight plan with him on his flight and visually compares the terrain seen from the aircraft with the topographical data on his maps. Using visual cues seen in the terrain along with navigational information from the aircraft's instruments, the pilot can determine how closely he is staying to his flight plan and makes any corrections necessary in order to stay on course. This is called flying by Visual Flight Reference (VFR). Following a well thought-out and thoroughly prepared flight plan should lead to a successful landing at the desired destination.

The TAWS is meant to supplement and enhance VFR flight by providing the pilot information about his height, heading, groundspeed, and altitude. This additional information increases the pilot's situational awareness and decreases the likelihood of accidents.

Without some type of digital elevation database there can be no Terrain Awareness and Warning System. A digital elevation database can be created manually by reading the elevation and latitude/longitude from maps and entering the data into a data structure. This would require a large amount of man-power and would be highly susceptible to error. Fortunately, this process does not have to happen (except maybe for topographical regions, like the Sierra Nevada Mountains). The Department of Defense (DoD) made public a digital elevation database and only just recently the United States Geological Survey (USGS) has made available some high resolution digital elevation data. The digital database from the DoD has 30 arc-seconds of resolution while the Digital Elevation Models (DEM) from the USGS has a resolution of up to 1 arc-second for many regions in the Western Hemisphere.

Naturally, the highest resolution database that can be used within the hardware constraints is desired. It's possible to get a rough size for the elevation database using a few parameters. If each elevation is a signed short (two bytes), a 1-degree square DEM of 1 arc-second resolution would need at least 24.7 MB (25,920,000 bytes) of storage space! It takes more than 1,000 1-degree cells to cover the coterminous United States. Obviously, this level of resolution cannot be used with the TAWS.

The Department of Defense Digital Terrain Elevation Data (DTED) that is available to the public has a resolution of 30 arc-seconds for each 1-degree square cell. Using the same parameters that we used for the USGD DEM, a 1-degree square DEM of 30 arc-seconds of resolution would need 27.2 KB (28800 bytes) of storage space. The amount of storage space required for the entire United States would be 29.4 MB. This fits within the 32 MB of onboard flash memory selected for the firmware (this is not a coincidence).

4. Digital Elevation Database

The digital elevation data used in this project was derived from the Shuttle Radar Topography Mission (SRTM) of February 2000 [6]. This mission produced Digital Terrain Elevation Data (DTED) at three different levels of detail. The three levels of detail are DTED Level 0, Level 1, and Level 2. Each DTED Level is called a class, and each class consists of several file types. Since the DTED Level 2 (1 arc-second of resolution) and Level 1 (3 arc-seconds of resolution) classes are still classified and are not publicly available, only the Level 0 class (30 arc-seconds of resolution) will be covered (since it also forms the basis of the TAWS) henceforth.

The DTED Level 0 class consists of six file types;

1. onc.dir
2. <xxx>.dt0
3. <xxx>.avg
4. <xxx>.min
5. <xxx>.max
6. dmed.

Each <xxx>.dt0 file contains the elevation data for a one-degree cell (one degree of latitude and one degree of longitude) along with some ASCII Header Data information. Each .dt0 file has 3428 bytes of ASCII Header Data and 30734 bytes of binary elevation data.

For example, the file w120_n39.dt0 has the elevation data for the one degree cell whose southwest corner is at 120 West Longitude and 39 North Latitude and the northeast corner is at 119 West Longitude, 40 North Latitude.

Using the file previously mentioned (w120_n39.dt0), the elevation data for 120.00.00 West Longitude is stored first; the elevation data for 119.59.30 is stored next; and so on to the final meridian of 119.00.00 West Longitude. The elevation data on each meridian starts at 39.00.00 North Latitude and extends to 40.00.00 North Latitude.

It's important that the digital elevation data is accurate. One way to check the accuracy is to compare the elevation data with topographical maps. Certainly this can be done for certain specific areas for specific reasons. But to check all 1071 DTED Level 0 .dt0 files in this manner is no different than creating a digital elevation database by hand!

Various methods have been used to validate and enhance the elevation data from the SRTM [6], [7], [8]. Another way to check the data is to look at it visually. This can be done by using the free version of Global Mapper [9]. This can only detect gross errors, but it is better than nothing.

Figure 2 shows a screenshot of Global Mapper after opening the DTED Level 0 digital elevation data file "w120_n39.dt0". This 1-degree cell contains the elevation data for the area around Lake Tahoe, Reno-Sparks, and Pyramid Lake. Notice the height value in the status bar (1339 meters – 4392 feet) while the mouse is in the Reno airport location. For anyone who has lived in the Reno-Sparks area for sometime, the display is reminiscent of local area maps. The eastern half of Lake Tahoe can be seen in the lower left and the southern half of Pyramid Lake can be seen at the top. With very little work an observer can determine the location of Reno-Sparks and can even find Rattlesnake Mountain!

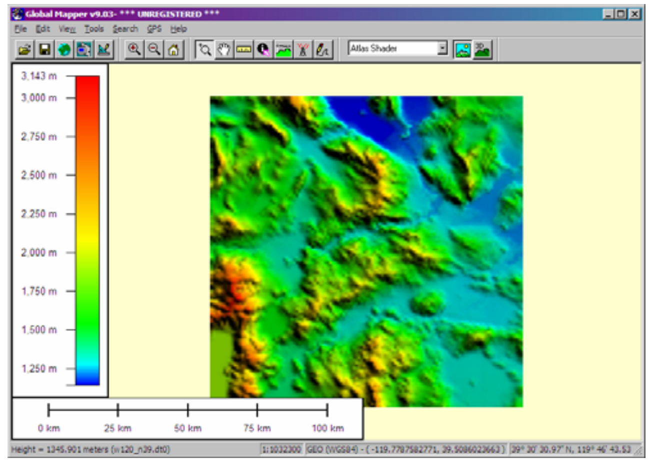

Figure 2: The 1-degree cell covering the Reno-Sparks area.

Using Global Mapper to visually validate the digital elevation data is possible as long as the observer is familiar with the area under examination. We have lived in the Reno-Sparks area for many years so we are familiar with maps of the area. Close examination of the DTED .dt0 file with Global Mapper seems to correlate closely with local area maps.

We have seen hundreds, if not thousands, of maps of the United States during my lifetime. Therefore, if Global Mapper can open all 1071 files that comprise the coterminous United States, we can at least look for obvious errors in elevation. But there is a small problem. The unregistered free version of Global Mapper is crippled. It can only open four datasets simultaneously. That means it is only possible to view four 1-degree cells simultaneously.

Upon first thought the four dataset limitation of the unregistered Global Mapper appears to make a visual confirmation of the data somewhat problematical. However, the DTED specifications for Level 0 .dt0 files suggest that the cell size is not limited to 1-degree squares. In fact the specifications seem to allow for any size of cell as long as the coordinates define a rectangular array. For example, it doesn't violate the DTED Level 0 specifications to define a cell that is 1-degree wide longitudinally while it is 40 degrees tall latitudinally. Nor does it violate the specifications to define a cell that is as wide and as tall as the coterminous United States. So perhaps it's possible to combine the 1-degree cells in a manner such that a single large DTED Level 0 cell contains all the elevation data for the entire United States.

There are a large number of ways to build a rectangular cell the size of the US from individual 1-degree cells, but these cells should be combined in a fashion that allows the results of the merging to be examined. The way chosen in this project was to first combine the cells vertically in 1-degree strips. Starting with the southernmost cell in an arbitrary meridian, it and the cell immediately north of it are merged. Subsequently, this merged cell is merged with its northerly neighbor, and so on, until the desired number of cells is merged.

Now that the original Level 0 .dt0 cells have been merged into longitudinal strips of equal range, strips that are adjacent can be merged into wider longitudinal strips. And these wider longitudinally adjacent strips can be merged with one another into still wider longitudinal strips. This process continues until a single Level 0 cell remains that is subsequently, the complete merger of the 1071 original DTED Level 0 cells.

Three applications were written that merged single cells into longitudinal strips, extended strips to the same size, and finally merged these strips into one cell that encompasses the entire United States. Figure 3 shows the result of merging the sixteen westernmost strips of the United States.

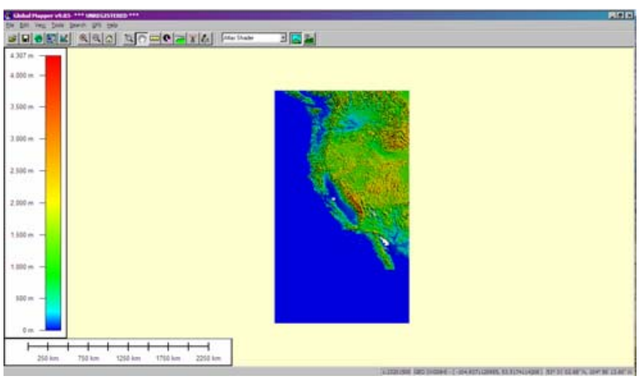

Figure 3: The 16-degree wide cell covering the westernmost United States.

5. Personal Computer Simulation

Now that a proprietary Digital Elevation Database has been created and validated, a simulation of the TAWS can be implemented on a personal computer. This simulation is designed to emulate, as closely as possible, the operation of the TAWS.

Since the TAWS is designed to calculate the height of an aircraft flying above the ground, the simulation must emulate a flying aircraft. A flying aircraft has certain parameters that are determined by sensory input. Since the simulation is designed to emulate flying, these sensors can be simulated by putting them under user control. The sensory inputs now under user control are;

- Altitude
- Heading
- Ground-speed
- Initial Origin (beginning coordinates)

The user interface is designed with the firmware in mind. The color LCD to be used in the TAWS has a resolution of 320x240 pixels and can display 65536 colors. Some very detailed and complex displays can be presented to the pilot. But as was previously mentioned, a simple, uncluttered presentation of important flying data should be shown to the pilot. And there’s nothing better than large, easily readable text. An explanation of the text on the simulator and their functions follows:

Altitude: In the firmware the altitude will be determined by using the barometric altimeter readings as an index into an altitude look-up table. In the simulation this value is under user control.

Height: This is for what the Terrain Awareness and Warning System was designed. This is the height of the aircraft above the ground.

Altimeter: This is the barometric altimeter that is used to determine the aircraft’s altitude. This has no effect in the simulation. As in real aircraft with barometric altimeters, the user can manually adjust the barometer for unusual air pressure situations (thunderstorms, cold fronts, etc.).

Up-Arrow: This increases the barometric pressure of the barometric altimeter.

Down-Arrow: This decreases the barometric pressure of the barometric altimeter.

There are three main menus in the TAWS simulator. The first is **Commands**, the next menu is **Configure**, and the final menu is **Help**. The submenu under **Commands** is **Flying** and **Exit**. The submenu under **Configure** is **Load Data**, **Flight Parameters**, and **Origin**. The submenu under **Help** is **Contents** and **About TAWS**.

There are certain specific steps that need to be followed in order to “fly” the simulator. Prior to “flying”, the user must first load the simulator with elevation data. This is accomplished by choosing **Configure>Load Data…** from the **Configure** menu.

An open file dialog appears in which the user can load a Level 0 .dt0 file. For purposes of this simulation, the 1-degree cell for the Reno-Sparks area is loaded. By no means is the simulator limited to opening cells of that size. The maximum size of Level 0 cell that the simulator can open is 50 MB. This size is hard-coded. It was set as this size so that the simulator can open the Level 0 .dt0 cell for the entire United States.

Certain features of the terrain around the Reno-Sparks area makes initial testing of the Terrain Awareness and Warning System easier and less complex. One feature responsible for this is Lake Tahoe. As can be seen in Figure 2 the southwest corner of this cell is almost centered on the Lake. This makes it possible to start the simulator from a location wherein the tester is guaranteed a large flat area above which to fly. This allows for easier testing of the Look-Ahead Height function.

There is also the large flat area that is Pyramid Lake. This is another place in which to test. It's just as flat as Lake Tahoe, but is somewhat lower. This small elevation difference makes it possible to change testing parameters incrementally.

After the user has loaded an elevation data file, the flying parameters must be initialized. These parameters are the Heading, Altitude, and Airspeed.

This is accomplished by choosing **Configure**>**Flight Parameters…** from the **Configure** menu. As can be seen in Figure 4 the user has set a heading of 45 degrees, an altitude of 10,000 feet, and a ground-speed of 70 mph.

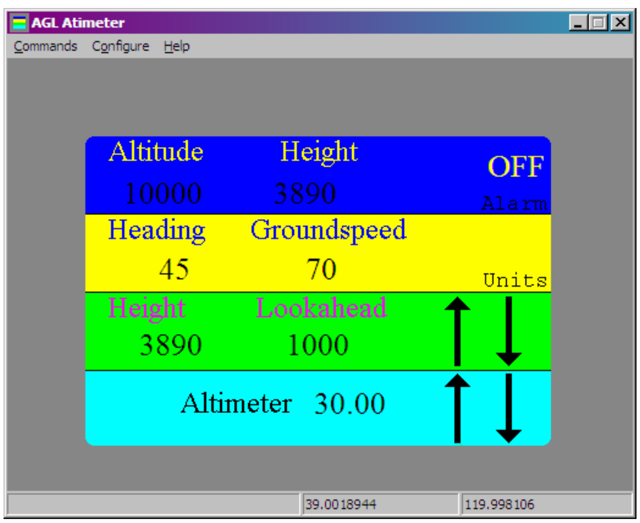

Figure 4: The simulator is "flying" over Lake Tahoe in a north-easterly direction.

After the user has configured the Flight Parameters, the Aircraft Origin has to be set. This is done by selecting **Configure**>**Origin…** from the **Configure** menu.

Now that all the parameters have been set by the user, the final remaining step is to command the simulator to "fly". This is done by choosing the **Commands>Fly** from the Commands menu. Once this has been done the simulator begins flying. What this means is that ten times a second the simulator updates the aircraft position and calculates the Height and Look-a-Head Height. Figure 4 shows the simulator immediately following this command. Since the altitude was set at 10,000 feet and the aircraft origin was set over Lake Tahoe, it's no surprise to see the Height and Look-a-Head Height at 3890 feet.

Lake Tahoe is over 12 miles wide. So it will take some time before the simulated aircraft reaches the north-eastern shore. And 5000 feet before we reach the shore, the Look-Ahead Height will start to increase. Surely enough, after about 2 minutes, the Look-Ahead Height has decreased to 3860 feet, while the Height has stayed at 3890 feet.

If the simulator is flown north of Lake Tahoe near Mount Rose in a northerly direction, with the Altitude set at 10,000 feet, the Height and Look-Ahead Height are precariously low. In fact, if the Alarm is ON and the Height is below 500 feet an alarm will sound to warn the pilot.

The user can "fly" the simulator by using the arrow keys on the keyboard. The arrow keys control the altitude of the "aircraft". The up-arrow will increase the altitude, while the down-arrow will decrease it. The left-arrow and right-arrow keys control the Heading. With these four controls at the user's disposal, it's possible to "fly" anywhere in the elevation database.

6. The Hardware

The firmware and materials were chosen with the goal of market sales in mind. An off-the-shelf case with dimensions of 4.5" x 3.5" x 1.25" (width x height x depth) and no holes for input and/or power control was selected because of its ubiquity and low cost. It has a battery compartment, a rectangular opening on one side for an LCD, and mounting tabs for the circuit boards. Using this case requires a touch panel for user input and control.

The central processing unit is the PIC 18F4550 microcontroller in the 44-pin TQFP package. There is 32 KB (16,384 instruction words – two bytes per instruction) of code space and 32 MB of flash memory available. Originally, it was 16 MB before some trivial size analysis of the required database necessitated a doubling of this size. This microcontroller has a USB module with burned-in code for USB communications. That gives the developer the possibility of downloading new programs and elevation data for this PIC chip from any USB connection.

Along with the previously mentioned hardware, there is a small speaker for the audio alarm, a GPS module for latitude and longitude coordinates, LEDs for a backlight, and an aneroid barometer to determine the altitude. As of the writing of this paper, the hardware (Figure 5) has been assembled and firmware programming has commenced.

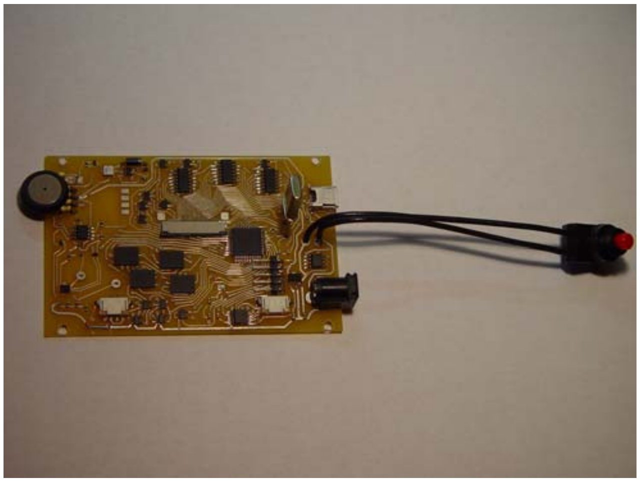

Figure 5: The hardware has been assembled and is ready for firmware programming.

7. Conclusion

Preliminary testing of the Terrain Awareness and Warning System Simulator was satisfactory. There were no obvious errors. It displays the height of a simulated aircraft as it travels over the terrain. It also displays what would be the height of the aircraft on its path anywhere from 0 to 10,000 feet in front of it.

Some of the elevation data is guaranteed to only be accurate within a range of 30 or more meters! As a pilot I would want the Terrain Awareness and Warning System to have almost no error while taking-off or landing. There are sub-accuracy sections in the DTED Level 0 specifications that are not currently used. The sub-accuracy regions will be implemented to improve the height calculations around airports and other important geographical locations.

Also, much could be done to enhance the TAWS. One possibility is to design a graphical display similar to some of the current product offerings. Figure 6 shows a possible future display for the TAWS.

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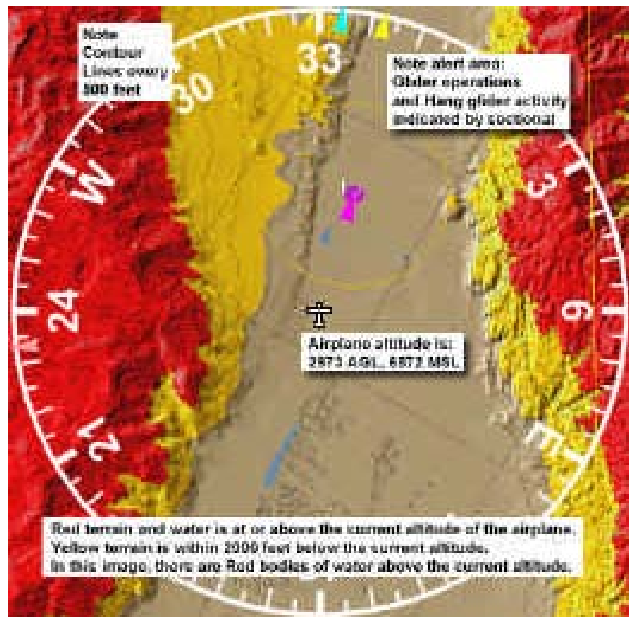

Figure 6: A possible future graphical interface.