METHOD AND SYSTEM FOR THE NAVIGATION AND CONTROL OF VEHICLES AT AN AIRPORT AND IN THE SURROUNDING AIRSPACE

Inventors: Harold R. Pilley, Ringe, NH (US); Lois V. Wortley, Leominster, MA (US)

Correspondence Address:
Harold R. Pilley
P.O. Box 439
Berkeley Heights, NJ 07922 (US)

Assignee: H. Robert Pilley

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ABSTRACT

A navigation and airport control and management method and system for aircraft and surface vehicles. The system incorporates the use of differential GPS to provide increased accuracy and robustness for aircraft and vehicles using GPS as the primary terminal area navigation system. An antenna is precisely located and identified with GPS compatible coordinate references. GPS signals are received with the antenna and supplied to a differential GPS base station. The base station calculates pseudorange and delta range corrections for each tracked satellite. Calculated differential corrections are then broadcast to vehicles in the local area using a radio transmitter. Vehicles receive the broadcast differential corrections and calculate differentially corrected position, velocity and time (PVT) information. This information is used on aboard the vehicle for navigational or automatic dependent surveillance purposes. At an airport control and management system ADS broadcasts are received and used for control purposes.

The construction of precise digital maps compatible with GPS is used for vehicle onboard navigation and for air traffic control situation display purposes. The digital maps include airport features such as runways, taxiways, gate areas, geographical features nearby the airport and other pieces of useful in formation.
TOUCH AND GO TRAJECTORY SHOWING WAYPOINTS EVERY 20 SECONDS (BOXES)

LAT VS LON TRAJECTORY SHOWING WAYPOINTS (BOXES) EVERY 20 SECONDS

FIG. 12

ALTITUDE VS TIME

FIG. 13
ECEF TOUCH AND GO TRAJECTORY SHOWING WAYPOINTS EVERY 20 SECONDS

FIG. 14

ECEF PLAN VIEW OF TRAJECTORY AND WAYPOINTS EVERY 20 SECONDS

FIG. 15
FIG. 22

FIG. 23
WGS-84 KNOWN ANTENNA LOCATION ECEF (X,Y,Z)

FUNCTIONS PERFORMED IN COMPUTER

- RECEIVE SUBFRAME DATA
- DETERMINE SATELLITE POSITIONS
- USE KNOWN POSITION TO FIND DISTANCE TO SATELLITE (SV-DIST)
- GENERATE PR CORRECTION (SV-DIST) - MEAS. PR
- OUTPUT PR CORRECTION
- RECEIVE DGPS POSITION COMPARE TO KNOWN POSITION
- REFIN P cep RECTION TO MINIMIZE ERROR IN POSITION
  MODIFY PR CORRECTION
- OUTPUT PR CORRECTION

FUNCTIONS PERFORMED IN COMPUTER

- TRACK SATELLITES
- OUTPUT SUBFRAME DATA
- CALCULATE PR AND DR
- RECEIVE DIFF. DGPS CORRECTIONS
- APPLY PR AND DR CORRECTIONS
- SOLVE FOR USER POSITION
- OUTPUT POSITION TO COMPUTER

FIG. 31
FIG. 32
FIG. 33
TOUCH SCREEN LAYOUT

FIGURE 34
METHOD AND SYSTEM FOR THE NAVIGATION AND CONTROL OF VEHICLES AT AN AIRPORT AND IN THE SURROUNDING AIRSPACE


BACKGROUND

[0002] 1. Field of the Invention

[0003] The use of GNSS in the airport environment plays an important role in the navigation and control of vehicles comprised of aircraft and surface equipment. To meet the accuracy and integrity of demanding aircraft navigation and control applications, differential GNSS is used. Differential GNSS reference receivers located at precise GNSS surveyed locations provide differential corrections over an RF datalink to differential GNSS capable receivers located aboard vehicles. Two Federal Aviation Administration programs build on this demonstrated technique of the applicant, specifically the Wide Area Augmentation System and the Local Area Augmentation System. Supporting the navigation function, descriptive digital maps indicative of airport surrounding terrain and airport physical features are used in the vehicles for navigation and by air traffic controllers for the control of airport operations. In uncontrolled airports without controllers the pilot and vehicle operators control their movement independently using differential GNSS navigation.

[0004] 2. Description of Prior Art

[0005] Today’s airport terminal operations are complex and varied from airport to airport. Airports today are, in many cases, the limiting factor in aviation system capacity. Each airport has a unique set of capacity limiting factors which may include; limited tarmac, runways, suitable approaches, navigational or/and Air Traffic Control (ATC) facilities.

[0006] Furthermore, operational requirements in the terminal area involve all facets of aviation, communication, navigation and surveillance. The satisfaction of these requirements with technological/procedural solutions should be based upon three underlying principles; improved safety, improved capacity and cost effectiveness.

[0007] Today airport air traffic control procedures and general airport aviation operations are based on procedures from the 1950’s. These air traffic control procedures were initially developed to separate aircraft while in the air. The initial separation surveillance system was a radar system consisting of a rotating radar antenna. The antenna rotated typically about once every 4.8 seconds while transmitting a signal, another receiving antenna picks up a reflected signal from a target. The surveillance system then calculated a range (based on transit time) and an azimuth angle based on the physical orientation of the antenna. The 2-dimensional position was then usually plotted on a display with other detected targets, objects and clutter. Radar today relies on faster rotating antennas or electronically scanned antennas to provide more frequent updates and higher resolution. To further enhance the performance of the target returns, provide altitude information and an identifier, a transponder is used on the aircraft. The transponder is the key element in radar surveillance systems, since without it no identification and no altitude information is provided to the air traffic control system.

[0008] Surveillance data from multiple surveillance systems (radars) is then discretely mosaiced or “filed” into a semi-continuous system. Controllers today separate traffic visually by the rule of “green in between” the target tracks. This is a highly manual method for separation of aircraft, placing stress on the controllers and limits any true automation assistance for the controller.

[0009] In the high density and high precision airport environment numerous single function airport systems have been developed over the years to support air traffic control and pilot needs. Precise landing navigation is currently provided by the Instrument Landing System (ILS), while airside navigation is provided by VOR/DME, ILS and NDB’s, Airport air traffic controller surveillance is provided thorough visual means, airport surface detection radar (ASDE), secondary surveillance radar, parallel runway monitoring radar and in some cases primary radar. Each of these systems is single function, local in nature and operation and provides accuracy which is a function of distance to the object being tracked. Merging these navigation and surveillance systems into a 4-dimensional seamless airport environment is technically difficult and expensive. MIT Lincoln Laboratories is attempting to provide an improved radar based Air Traffic Control environment and has received three U.S. Pat. Nos. 5,374,932, 5,519,618 and 5,570,955 reflecting those efforts. These patents relate to improvements of the current localized surveillance and navigation airport environment without the use of GNSS compatible seamless techniques as described herein by Pilley.

[0010] These localized systems have served the aviation system well for nearly 50 years and numerous mishaps have been prevented over this period through their use. With the advent of new multi-function technologies superior performance is available at a fraction of the cost of today’s current single function systems. The technologies of Global Navigation Satellite Systems, digital communication and low cost commercial computers can support seamless 4-dimen-
sional airport operations at smaller airports unable to justify the heavy financial investment in today's single function navigation and surveillance systems.

The FAA, NASA, the Defense Department and private industry are active utilizing elements of the applicants methods and systems demonstrated over a decade ago. Specific United States Programs involving this technology are:

- FAA Capstone
- FAA Ohio River Valley Project
- FAA Safe Flight 21
- NASA Runway Incursion Protection System (RIPS)

Others are also demonstrating and developing similar systems in prior years included: Haken Lans (GP&C) of Sweden is demonstrating the use of Differential GPS with Self Organizing Time Division Multiple Access datalink communications. The invention of Haken Lans is described in World Intellectual Property Organization document # 93/01576. The invention of Fraughton describes an airborne system for collision avoidance in U.S. Pat. No. 5,153,836. The inventions of Lams and Fraughton fail to provide the seamless 4 dimensional GNSS compatible operational and processing environment of Pilley and fail to include the digital map of Pilley.

After the demonstrations of the applicant it became clear that this technology had great application in airport operations. After a decade the industry is accepting the concepts, deploying systems and equippping vehicles.

BACKGROUND OF THE INVENTION

The inventor having been involved with the FAA's Advanced Automation System became aware that airport program segments were not getting the attention they deserved, nor were advanced technologies being investigated. The inventor set out to demonstrate that new technologies could be used to support seamless airport navigation and surveillance. The multi-year efforts of the inventors are summarized in the book titled:

GPS BASED AIRPORT OPERATIONS, Requirements, Analysis, Algorithms US copyright # TX U.S. Pat. No. 3,926,573, (Library of Congress # 94-69078), (ISBN 0-9645508-0-5). This book provides much of the background for this patent application. In addition to the book the following publications and professional papers have been published by the inventor in efforts of due diligence to promote this life saving technology.

PUBLICATIONS:

- GPS WORLD Magazine, 10-91, Article, “GPS, Aviation and Airports the Integrated Solution”.
- Presentation Seattle, Washington, May 9, 1995, International Civil Aviation Organization of the United Nations, Advanced Surface Movement Guidance and Control (SMGCS) meeting, Presentation and demonstration “GPS based SMGCS”.
- As the list of presentations and publications shows the inventors have been active in getting the government and the aviation community to accept this life saving cost effective airport technology.
- The United States alone currently contains some 17,000 airports, heliports and seaports. Presently only the largest of these can justify the investment in dedicated navigation and surveillance systems while the vast majority of smaller airports have neither. Clearly, a new approach is required to satisfy aviation user, airport operator, airline and ATC needs.
- It would therefore be an advance in the art to provide a cost effective Airport Control and Management System which would provide navigation, surveillance, collision prediction, zone/runway incursion and automated airport lighting control based on the Global Navigation Satellite System (GNSS) as the primary position and velocity sensor on board participating vehicles. It would be still a further advance of the art if this system were capable of performing the navigation, surveillance, collision prediction, lighting control and zone/runway incursion both on board the aircraft/vehicles and at a remote ATC, or other monitoring site.
- With the advent of new technologies such as the Global Positioning System, communication and computer
technology, the application of new technologies to the management of our airports can provide improved efficiency, enhanced safety and lead to greater profitability for our aviation industry and airport operators.

[0038] On Aug. 12, 1993, Deering System Design Consultants, Inc. (DSDC) of Deering, N.H., successfully demonstrated their Airport Control & Management System (AC&M) to the Federal Aviation Administration (FAA). After many years of development efforts, the methods and processes described herein were demonstrated to Mike Harrison of the FAA’s Runway Incursion Office, officials from the FAA’s Satellite Program Office, the FAA New England Regional Office, the Volpe National Transportation System Center, the New Hampshire Department of Transportation, the Office of U.S. Senator Judd Gregg and the Office of U.S. Representative Dick Swett. This was the first time such concepts were reduced to a working demonstrable system. The inventor has taken an active stance to promote the technology in a public manner and, as such, may have informed others to key elements of this application. The inventor has promoted this technology. The inventor’s airports philosophy has been described in general terms to the aviation industry since it was felt industry and government awareness was necessary. The intent of this Continuation application to identify and protect through letters of Patent techniques, methods and improvements to the demonstrated system.

[0039] With these and other objects in view, as will be apparent to those skilled in the art, the improved airport control and management invention stated herein is unique, novel and promotes the public well being.

SUMMARY OF THE INVENTION

[0040] This invention most generally is a system and a method for the control of surface and airborne traffic within a defined space envelope. GNSS-based, or GPS based data is used to define and create a 3-dimensional map, define locations, to compute trajectories, speeds, velocities, static and dynamic regions and spaces or volumes (zones) including zones identified as forbidden zones. Databases are also created, which are compatible with the GNSS data. Some of these databases may contain, vehicle information such as type and shape, static zones including zones specific to vehicle type which are forbidden to the type of vehicle, notice to airmen (notams) characterized by the information or GNSS data. The GNSS data in combination with the databases is used, for example, by air traffic control, to control and manage the flow of traffic approaching and departing the airport and the control of the flow of surface vehicles and taxiing aircraft. All or a selected group of vehicles may have GNSS receivers. Additionally, all or a selected group may have bi-directional digital data and voice communications between vehicles and also with air traffic control. All of the data is made compatible for display on a screen or selected screens for use and observation including screens located on selected vehicles and aircraft. Vehicle/ aircraft data may be compatibly superimposed with the 3-dimensional map data and the combination of data displayed or displayable may be manipulated to provide selected viewing. The selected viewing may be in the form of choice of the line of observation, the viewing may be by layers based upon the data and the objective for the use of the data.

[0041] It is, therefore, an object of this invention to provide the following:

[0042] 1.) A 4-D process logic flow which provides a “seamless” airport environment on the ground and in the air anywhere in the world with a common 3-D coordinate reference and time

[0043] 2.) An Airport Control and Management Method and System which utilizes GNSS, 3-D maps, precise waypoint navigation based on the ECEF reference frame, a digital full duplex communication link and a comprehensive array of processing logic methods implemented in developed operational software

[0044] 3.) An Airport Control and Management Method and System where a vehicle based 4-D navigational computer and ATC computer utilize the same coordinate reference and precise time standard.

[0045] 4.) A database management method compatible with 3-D waypoint storage and presentation in 3-D digital maps.

[0046] 5.) An automated method utilizing the precise 3-D airport map for the definition and creation of airport routes and travel ways.

[0047] 6.) A 4-D process logic flow which provides precise vehicle waypoint navigation in the air and on the ground. This process allows for monitoring of on or off course conditions for vehicles and aircraft operating within the airport space envelope on board the vehicle.

[0048] 7.) A 4-D process logic flow which provides precise ATC waypoint navigation mirroring of actual vehicles in the air and on the ground at ATC. This process allows for monitoring of on or off course conditions for vehicles and aircraft operating within the airport space envelope at the ATC computer

[0049] 8.) A 4-D process logic flow performed on board the vehicle which provides for precise collision prediction based on 3-dimensional zones

[0050] 9.) A 4-D process logic flow performed at the ATC computer which provides for precise collision prediction based on 3-dimensional zones

[0051] 10.) A collision detection management method which utilizes the application of false alarm reducing methods

[0052] 11.) An ATC process logic flow which detects 3-D runway incursions. The process logic then generates message alerts and controls airport lights

[0053] 12.) An ATC zone management method which utilizes the application of false alarm reducing methods

[0054] 13.) A vehicle process logic flow which detects 3-D runway incursions. The process logic then generates message alerts and sounds tones within the vehicle or aircraft

[0055] 14.) A vehicle zone management method which utilizes the application of false alarm reducing methods

[0056] 15.) A 4-D ATC process logic flow which manages ground and air “Clearances” with precise waypoint navigation aboard the vehicle and at the ATC computer.
[0057] 16.) A 4-D ATC process logic flow which manages ground and air “Clearances” incorporating an integrated system of controlling airport lights.

[0058] 17.) A 4-D vehicle process logic flow which manages ground and air “Clearances” with an integrated system of waypoint navigation.

[0059] 18.) A method of management for 3-D spatial constructs called zones

[0060] 19.) A method of management for 3-D graphical constructs called zones

[0061] 20.) A method of management for the automated generation of a zones database at any airport

[0062] 21.) A database management method for the storage of zones data. Zones database management methods are used aboard the vehicle and at ATC.

[0063] 22.) A operational management method where the ATC computer provides navigational instructions to vehicles and aircraft. The instructions result in a travel path with clear paths defined being displayed in an airport map.

[0064] 23.) A operational management method where the ATC computer provides navigational instructions to vehicles and aircraft. The instructions result in waypoints being entered into a 4-D navigation computer.

[0065] 24.) A datalink message content which supports the above management methods and processes.

[0066] 25.) A redundant system architecture which satisfies life critical airport operations.

[0067] 26.) Methods for navigation within the airport environment using map displays, controller clearances and automation techniques in the cockpit at ATC.

[0068] 27.) An integrated airport controller automation interface which supports GNSS compatible processing.

[0069] 28.) A method for managing GNSS travel path information, clearances and conformance monitoring using broadcast GNSS trajectory information and automatic dependent surveillance.

[0070] More specifically, the elements mentioned above form the process framework of the invention stated herein.

BRIEF DESCRIPTION OF DRAWINGS

[0071] The invention may be best understood by reference to one of its structural forms, as illustrated by the accompanying drawings, in which:

[0072] FIG. 1 depicts the high-level Airport Control and Management processing elements and flow.

[0073] FIG. 2 represents an example of a cylindrical static zone in a 3-D ALP. This zone could be graphically displayed in a layer of the ALP.

[0074] FIG. 3 represents an example of a static zone around a construction area of the airport and is used in zone incursion processing in the vehicles and at the ATC Processor.

[0075] FIG. 4 represents an example of a dynamic zone which travels with a moving vehicle, in this case the zone represents the minimum safe clearance spacing which would be used in zone based collision detection processing in the vehicles and at the ATC processor.

[0076] FIG. 5 represents an example of a route zone which is defined by navigational waypoints and is used for on/off course processing and is used in the vehicles and at the ATC Processor.

[0077] FIG. 6 represents an example of a 3-D ATC zone, used to segregate tracked vehicles to particular ATC stations.

[0078] FIG. 7 illustrates the construction of a 3-D runway zone.

[0079] FIG. 8 shows a map display with surface waypoints and travel path.

[0080] FIG. 9 shows a map display with departure waypoints and travel path.

[0081] FIG. 10 illustrates the 4-D collision detection mechanism employed in the Airport Control and Management System.

[0082] FIG. 11 depicts a waypoint processing diagram showing the earth and ECEF coordinate system, expanded view of airport waypoints, further expanded view of previous and next waypoint geometry with present position, the cross hair display presentation used in the developed GPS navigator.

[0083] FIG. 12 graphs latitude, Longitude plot of a missed approach followed by a touch and go with waypoints indicated about every 20 seconds.

[0084] FIG. 13 graphs altitude vs. time for missed approach followed by touch and go, waypoints are indicated about every 20 seconds.

[0085] FIG. 14 graphs ECEF X and Y presentation of missed approach followed by a touch and go with waypoints indicated about every 20 seconds.

[0086] FIG. 15 graphs ECEF Z vs. time of missed approach followed by touch and go, with waypoints about every 20 seconds.

[0087] FIG. 16 shows a block diagram of on/off course processing.

[0088] FIG. 17 shows a missed approach followed by a touch and go GPS trajectory displayed in a 3-D airport map.

[0089] FIG. 18 shows an ECEF navigation screen with navigational window insert and 3-D digital map elements.

[0090] FIG. 19 shows the area navigation display with range rings, course and bearing radial lines, and altitude to true course indicators.

[0091] FIG. 20 depicts the GPS sliding cross hair landing display indicating too low (go up) and too far right (turn left).

[0092] FIG. 21 illustrates the GPS approach cone with digital map elements showing current position with respect to true course line.

[0093] FIG. 22 depicts the demonstration system airport communications diagram showing processor, DGPS base station, radio elements and message flows.
FIG. 23 depicts the demonstration system AC&M hardware block diagram showing various elements of the system.

FIG. 24 depicts the demonstration system aircraft hardware block diagram.

FIG. 25 depicts the demonstration system vehicle #1 hardware block diagram.

FIG. 26 depicts the demonstration system vehicle #2 hardware block diagram.

FIG. 27 shows the navigator display compass rose area navigator and cross hair sliding precision approach display in combination with waypoint information, position, velocity, range to the waypoint, cross track error, speed, heading and distance to true course.

FIG. 28 depicts the airport system single controller station, non redundant design.

FIG. 29 depicts the airport system redundant single controller station.

FIG. 30 depicts the airport system redundant dual controller station.

FIG. 31 depicts the map temporal differential correction system diagram.

FIG. 32 depicts the differential GPS system diagram.

FIG. 33 depicts the closed loop differential GPS system diagram.

FIG. 34 depicts the computer human interface using a touch screen.

FIG. 35 depicts Control Facility and Selected Aircraft elements with RF datalink message flow and Controller Display inputs and actions related to an off course condition.

FIG. 36 identifies Computer Functionality of the AC&M Processor and Graphic Processor. Bold elements represent functions necessary for supporting the controller—computer human interface for sending travel paths to an aircraft, displaying position of an aircraft on a display, performing automated conformance monitoring, detecting an off course condition, displaying an alert and ultimately sending a new travel path to the aircraft.

FIG. 37 contains selected text from the Specification indicative of the automated computer detected off course means using conformance monitoring (mirrored navigation at the AC&M station) and associated controller actions to attempt to bring off course aircraft back on course.

DESCRIPTION OF PREFERRED EMBODIMENT

AC&M Processing Overview

The primary Airport Control and Management (AC&M) functions of the invention utilize a Cartesian ECEF X, Y, Z coordinate frame compatible with GNSS. FIG. 1 provides additional detail for the operational elements of the AC&M processing. The GNSS signals broadcast by the vehicles 8 are processed by the Real Time Communication Handler 3 and sent to AC&M Operational Control 1. The Operational Control 1 uses the GNSS data to perform the following processing functions: position projections, coordinate conversions, zone detection, collision prediction, runway incursion detection, layer filter, alarm control, and lighting control. If waypoints have been issued to the vehicle 8, mirrored waypoint navigation is also performed by the AC&M processing. The Operational Control 1 interfaces directly to the Graphical Control 2. Graphics messages, including GNSS data and coded information pertaining to zone incursions, possible collision conditions, or off course conditions detected by the AC&M Processing, are passed to the Graphical Control 2. The Graphical Control 2 interprets this data and updates the display presentation accordingly.

The Operational Control 1 function also receives inputs from the Controller/Operator Interface 6. The Controller/Operator Interface uses the data received by Controller/Operator Inputs 7 to compose ATC commands which are sent to the Operational Control 1 function for processing. Commands affecting the presentation on the computer display screen are sent by the Operational Control 1 function to the Graphical Control 2. ATC commands composed by the Controller/Operator Interface 6 processing that do not require further AC&M processing are forwarded directly to the Graphical Control 2 to update the display screen. Both the Operational Control 1 function and Graphical Control 2 processing have access to the Monumentation, Aircraft/Vehicle, Static Zones, Waypoints, Airport Map, ATIS Interface and Airport Status and other low level data bases 9 to process and manipulate the presentation of map and vehicle data on a computer display screen.

More specifically, each vehicle 8 supports the capability to transmit a minimum of an identifier, the GNSS referenced position of one or more antennas, velocity, optional acceleration and time reports. Since this data is broadcast, it is accessible to the airport control tower, other aircraft and vehicles in the local area, and various airline monitoring or emergency command centers which may perform similar processing functions. ATC commands, processed by the Controller/Operator Interface 6 and Operational Control 1 function are passed to the Real Time Communication Handler 3 for transmission to the aircraft/vehicle(s) 8. Upon receipt of ATC messages, the vehicle(s) 8 return an acknowledgment message which is received by the Real Time communication Handler 3 and passed to the Operational Control 1 function. Differential GNSS corrections are generated by the Differential GPS Processor 4 and passed to the Real Time Communication Handler 3 for broadcast to the vehicles. The Real Time Communication Handler 8 performs the following functions at a minimum:

a. Initialize ATC computer communication lines
b. Initialize radio equipment
c. Establish communication links
d. Receive vehicle identifier, positions, velocity, time and other information
e. Receive information from ATC Processor to transmit to vehicle(s)
f. Receive ATC acknowledgment messages from vehicle(s)
[0118] g. Transmit information to all vehicles or to selected vehicles by controlling frequency and/or identifier tags.

[0119] h. Monitor errors or new information being transmitted.

[0120] i. Receive and broadcast differential correction data.

[0121] The AC&M techniques and methods described herein provide for GNSS compatible 4-Dimensional Airport Control and Management.

The 3-D Digital Airport Layout Plan

[0122] The combination of ECEF navigation combined with NAD 83 (Lat, Lon, MSL and State Plane) and WGS 84 (X,Y,Z) based 3-D airport features are necessary in constructing an airport layout plan (ALP). The Airport Control and Management System (AC&M) requires that navigation and Automatic dependent Surveillance (ADS) information used in collision detection processing share the same coordinate frame. The processing methods described herein, require very accurate and properly monumented airport layout plans. Physical features surrounding the airport may be surveyed in a local coordinate frame and, as such, require accurate transformation into the airport map/processing coordinate frame. For these reasons, the use of multi-monumented coordinate references is mandatory for such map construction and survey. Clearly, highly accurate 3-D maps are required when using precise GNSS based navigation, collision avoidance and overall Airport Control and Management for life critical airport applications.

[0123] The 3-D ALP database and display presentation support the concept of zones. The display of zone information is managed using the Map Layer Filter. Zones are two and three dimensional shapes which are used to provide spatial cueing for a number of design constructs. Static zones may be defined around obstacles which may pose a hazard to navigation such as transmission towers, tall buildings, and terrain features. Zones may also be keyed to the airport’s NOTAMS, identifying areas of the airport which have restricted usage. Dynamic zones are capable of movement. For example, a dynamic zone may be constructed around moving vehicles or hazardous weather areas. A route zone is a 3-D zone formed along a travel path such as a glide slope. Zone processing techniques are also applied to the management of travel clearances and for the detection of runway incursions. Zones may also be associated with each aircraft or surface vehicle to provide collision prediction information.

Operational Projections

[0124] AC&M projection processing utilizes received GNSS ADS messages from a datalink. The complete received message is then checked for errors using CRC error detection techniques or an error correcting code. The message contains the following information, or a subset thereof, but not limited to: PVT ADS DATA.

<table>
<thead>
<tr>
<th>PVT ADS DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID#</td>
</tr>
<tr>
<td>VEHICLE TYPE</td>
</tr>
<tr>
<td>CURRENT POSITION:</td>
</tr>
<tr>
<td>X = ECEF X Position (M)</td>
</tr>
<tr>
<td>Y = ECEF Y Position (M)</td>
</tr>
<tr>
<td>Z = ECEF Z Position (M)</td>
</tr>
<tr>
<td>X2 = ECEF X2 Position (M)</td>
</tr>
<tr>
<td>Y2 = ECEF Y2 Position (M)</td>
</tr>
<tr>
<td>Z2 = ECEF Z2 Position (M)</td>
</tr>
<tr>
<td>X3 = ECEF X3 Position (M)</td>
</tr>
<tr>
<td>Y3 = ECEF Y3 Position (M)</td>
</tr>
<tr>
<td>Z3 = ECEF Z3 Position (M)</td>
</tr>
<tr>
<td>V = ECEF X Velocity (M/S)</td>
</tr>
<tr>
<td>VY = ECEF Y Velocity (M/S)</td>
</tr>
<tr>
<td>VZ = ECEF Z Velocity (M/S)</td>
</tr>
<tr>
<td>AX = ECEF X Acceleration (MS2)</td>
</tr>
<tr>
<td>AY = ECEF Y Acceleration (MS2)</td>
</tr>
<tr>
<td>AZ = ECEF Z Acceleration (MS2)</td>
</tr>
<tr>
<td>TIME</td>
</tr>
</tbody>
</table>

TOTAL CHARACTERS/MESSAGE: 80 Characters

* OPTIONAL FIELD, FOR DETERMINING VEHICLES ATTITUDE IN 3-D DIGITAL MAP DATA BASE
# OPTIONAL ACCELERATION FIELD

[0125] A database is constructed using the ADS message reports. The AC&M processing converts the position and velocity information to the appropriate coordinate frame (if necessary, speed in knots and a true north heading). Simple first and second order time projections based upon position, velocity and acceleration computations are used. The ability to smooth and average the velocity information is also possible using time weighted averages.

ECEF Position Projection Technique

[0126]

\[
\text{PROJECTED } X = X + (VX(t)) + (AX(t)^2)/2 \\
\text{PROJECTED } Y = Y + (VY(t)) + (AY(t)^2)/2 \\
\text{PROJECTED } Z = Z + (VZ(t)) + (AZ(t)^2)/2 
\]

[0127] This set of simple projection relationships is used in the collision prediction and zone incursion processing methods.

Zone Database

[0128] Zone areas may be defined in the initial map data base construction or may be added to the map database using a 2-D or 3-D data entry capability. The data entry device may be used to construct a zone using a digital map in the following manner:

[0129] Using the displayed map, the data entry device is used to enter the coordinates of a shape around the area to be designated as a zone. (An example may be a construction area closed to aircraft traffic listed in the current NOTAMS.)

[0130] The corners of the polygon are saved along with a zone type code after the last corner is entered. Circles and spheres are noted by the center point and...
a radius, cylinders are noted as a circle and additional height qualifying information. Other shapes are defined and entered in a similar fashion.

[0131] The zone is stored as a list of X, Y, Z coordinates. Lines connecting the points form a geometric shape corresponding to the physical zone in the selected color, line type and style in the proper layer of the base map.

[0132] Zone information may then be used by collision detection and boundary detection software contained in the AC&M system. This processing software is explained later in this specification.

[0133] FIG. 2 depicts a 3-D cylindrical static zone around a hypothetical utility pole. This zone 10 is added into the airport map 11, while the specific coordinates (center point of base 12, radius of circular base 13, and the height 14) are saved to the zone file list in a convenient coordinate frame. Below is an example of a zone which is stored in the zone database.

<table>
<thead>
<tr>
<th>IDENTIFIER</th>
<th>PARAMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility pole</td>
<td>Type of Zone</td>
</tr>
<tr>
<td>Center of base</td>
<td>X, Y, Z</td>
</tr>
<tr>
<td>Radius of base</td>
<td>R</td>
</tr>
<tr>
<td>Height of the cylinder</td>
<td>H</td>
</tr>
</tbody>
</table>

[0134] The 3-D digital map 11 is then updated using a series of graphic instructions to draw the zone 10 into the map with specific graphic characteristics such as line type, line color, area fill and other characteristics.

[0135] A database of zone information containing zones in surface coordinates such as X & Y state plane coordinates and mean sea level, ECEF referenced X, Y, Z and others are accessible to the AC&M Processing. The database may consist of, but is not limited to the following type of zones.

<table>
<thead>
<tr>
<th>OBJECT OF THE ZONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSMISSION TOWERS</td>
</tr>
<tr>
<td>AIRPORT CONSTRUCTION AREAS</td>
</tr>
<tr>
<td>CLOSED AREAS OF AIRPORT MOUNTAINS</td>
</tr>
<tr>
<td>AREAS OFF TAXIWAY AND RUNWAY</td>
</tr>
<tr>
<td>RESTRICTED AIRSPACE</td>
</tr>
<tr>
<td>INVISIBLE BOUNDARIES BETWEEN AIR TRAFFIC CONTROLLER AREAS</td>
</tr>
<tr>
<td>APPROACH ENVELOPE</td>
</tr>
<tr>
<td>DEPARTURE ENVELOPE</td>
</tr>
<tr>
<td>AREAS SURROUNDING THE AIRPORT MOVING ZONES AROUND AIRCRAFT/VEHICLES</td>
</tr>
</tbody>
</table>

[0136] The zone information is retrieved from a zone database. As the AC&M Processor receives current ADS reports, information on each position report is checked for zone incursion. Further processing utilizes velocity and acceleration information to determine projected position and potential collision hazards. If a current position or projected position enters a zone area or presents a collision hazard an alert is generated.

[0137] A zone is any shape which forms a 2-D or 3-D figure such as but not limited to a convex polygon (2-D or 3-D), or a circular (2-D), spherical (3-D), cylindrical (3-D) or conical shape represented as a mathematical formula or as a series of coordinate points. Zones are stored in numerous ways based upon the type of zone. The coordinate system of the map and the units of measure greatly affect the manner in which zones are constructed, stored and processed.

[0138] The invention described herein utilizes four primary types of 2-D and 3-D zones in the Airport Control and Management System.

Four Primary Zone Types

[0139] The first type zone is a static zone as shown in FIG. 3. Static zones represent static non-moving objects, such as radio towers, construction areas, or forbidden areas off limits to particular vehicles. The zone 15 shown in the FIG. 3 represents a closed area of the airport which is under construction. The zone 15 is a 3-D zone with a height of 100 Meters 16, since it is desired not to have aircraft flying low over the construction site, but high altitude passes over the zone are permitted. An example of a permitted flyover path 17 and a forbidden fly through path 18 are shown in the figure. The flythrough will produce a zone incursion, while the flyover will not.

[0140] A second zone type is shown in FIG. 4 and represents a dynamic zone 19 which moves with a moving vehicle or aircraft. Dynamic zones may be sized and shaped for rough check purposes or may be used to describe the minimum safe clearance distance. The dynamic zone is capable of changing size and shape as a function of velocity and or phase of flight and characterized by vehicle or aircraft type.

[0141] The third type zone is shown in FIG. 5 and is a route zone 20. Route zones are described though the use of travel waypoints 21 and 22. The waypoints 21 and 22 define the center line of a travel path, the zone has a specified allowable travel radius X1, Y1 at Waypoint 121 and X2, Y2 at Waypoint 222 for the determination of on or off course processing. For simplicity X1 may equal X2 and Y1 may equal Y2. On course 23 operations result in travel which is within the zone, while off course 24 operations result in travel which is outside the zone and result in an off course warning.

[0142] The fourth type zone(s) shown in FIG. 6 is a 3-D zone which is dynamic and used to sort ATC traffic by. This type zone is used to segregate information to various types of controller/operator positions, i.e. ground control, clearance delivery, Crash Fire and Rescue and others. Travel within a particular zone automatically defines which ATC position or station the traffic is managed by. For example travel within zone 125 is directed to ATC ground station, while travel within zone 226 is directed to ATC Clearance Delivery position. The ATC zone concept allows for automatic handoff from one controllers position to the other as well as providing overall database the management automation.

[0143] The construct of zones is very important to the overall operation of the described invention herein. Further examples of zone processing methods and zone definition is provided below.
EXAMPLE 1

[0144] A cylindrical zone on the airport surface constructed using the state plane coordinate system would be represented as the following:

| Center point of circle | CXsp value, CYsp value |
| Elev (MSL) | Elev = constant, or may be a range |
| Circle radius | CR value |

[0145] The detection of a zone incursion (meaning that the position is within the 2-D circle) is described below.

<table>
<thead>
<tr>
<th>Convert position to State Plane coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current or projected position</td>
</tr>
<tr>
<td>Subtract circle center</td>
</tr>
<tr>
<td>from current position</td>
</tr>
<tr>
<td>Determine distance from circle center</td>
</tr>
<tr>
<td>Test if position is in circle</td>
</tr>
<tr>
<td>If true continue</td>
</tr>
<tr>
<td>Test if position is within altitude range</td>
</tr>
</tbody>
</table>

[0146] If the above conditions are met, the position is in the 3-D cylindrical zone. It can be seen that the basic methods used here are applicable to other grid or coordinate systems based on linear distances.

EXAMPLE #2

[0147] A cylindrical zone on the airport surface (normal with the airport surface) constructed using the Earth Centered Earth Fixed coordinate system is stored using three axis (X, Y, Z).

<table>
<thead>
<tr>
<th>Convert current position to ECEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center point of circle</td>
</tr>
<tr>
<td>Circle radius</td>
</tr>
<tr>
<td>Determine distance from current or projected position to center of circle</td>
</tr>
<tr>
<td>Determine paraxial distance to circle center point from current position</td>
</tr>
<tr>
<td>Test position to see if it is in sphere of radius R</td>
</tr>
<tr>
<td>Determine the vector between the center of the circle and the center of mass of the earth</td>
</tr>
<tr>
<td>Calculate the magnitude</td>
</tr>
<tr>
<td>Determine the vector between the center of mass of the earth and the current or projected position</td>
</tr>
<tr>
<td>Calculate the magnitude</td>
</tr>
<tr>
<td>Determine the difference between the two vectors, if result = 0 then in the 2-D zone, if the result is &lt;0 then position is below, if &gt;0 then position is above the zone</td>
</tr>
</tbody>
</table>

[0148] The final two tests use an approximation which greatly simplifies the processing overhead associated with zone incursion detection. The assumption assumes that over the surface area of an airport, the vector between the center of mass of the earth circular zone center and the vector from the current position to the center of the circle are coincident. That is, the angle between the two vectors is negligible.

[0149] The second assumption based on the first approximation is that, rather than perform complex coordinate reference transformations for zone shapes not parallel with the earth's surface, projections normal to the surface of the earth will be used. Zones which are not parallel with the earth's surface are handled in a manner similar to that applied to on or off course waypoint processing using rotation about a point or center line.

[0150] EXAMPLE #3

[0151] A zone which is shaped like a polygon is initially defined as a series of points. The points may be entered using a data entry device and a software program with respect to the digital map or they may be part of the base digital map. The points are then ordered in a manner which facilitates processing of polygon zone incursion. The following examples indicate how a (4-sided) polygon is stored and how an airport surface zone incursion is performed using both the state plane coordinates and Earth Centered Earth Fixed X, Y, Z coordinates.

<table>
<thead>
<tr>
<th>Convert Position to SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xsp, Ysp, Zsp</td>
</tr>
<tr>
<td>State Plane Zone Vertices</td>
</tr>
<tr>
<td>Order in a clockwise direction</td>
</tr>
<tr>
<td>Height of 3-D zone</td>
</tr>
<tr>
<td>Determine min &amp; max values for X &amp; Y</td>
</tr>
<tr>
<td>Perform rough check of current position or projected position</td>
</tr>
<tr>
<td>If both true then continue with zone checking</td>
</tr>
</tbody>
</table>

Calculate the slope of the line between points 1 & 2

M = \frac{(Y2sp - Y1sp)(X2sp - X1sp)}{(Y2sp - Y1sp)(X2sp - X1sp) = M}

Calculate the slope of the line from the present position normal to the line between points 1 & 2

Ysp = M * Xsp - LN
and position
Determine the intersection of both lines
\[ \text{intXsp} = \frac{(LN - L)(M - M_{\text{nor}})}{(M_{\text{nor}} - \text{intXsp})} \]
\[ \text{intYsp} = M_{\text{nor}} \times \text{intXsp} + \text{Y}_{\text{sp}} \]
\[ \text{Xsp} = \text{intXsp} \times \text{DXsp} \]
\[ \text{Ysp} = \text{intYsp} \times \text{DYsp} \]

Check the sign of \( \text{DXsp} \) and \( \text{DYsp} \).

If the zone vertices are entered in a counter clockwise direction the sign of \( \text{DXsp} \) and \( \text{DYsp} \) are swapped.

If point is on the proper side of all (4) lines of polygon then in 2-D zone.

Note: If the zone vertices are entered in a counter clockwise direction the sign of \( \text{DXsp} \) and \( \text{DYsp} \) are swapped.

Test if position is Min Elev <= Elev <= Max Elev within altitude range.

(\( a \) 3-D polygon zone)

---

**EXAMPLE #4**

**[0152]** A further example is provided in the definition of a 3-D runway zone using LCEF X,Y,Z. A list of runway corners is constructed using the 3-D map and a data entry device and an automated software tool. The runway zone is shown in FIG. 7.

**[0153]** The horizontal outline the runway 27 by selecting the four corners \( C_1, C_2, C_3, C_4 \) in a clockwise direction 28, starting anywhere on the closed convex polygon formed by the runway 27.

**[0154]** Define the thickness of the zone (height above the runway) 29.

**[0155]** The 4 corner 3-D coordinates and min and max altitudes are obtained through the use of a program using the ALP, then conversion are performed if necessary to convert from ALP coordinates to ECEF X, Y, Z values.

\[
\begin{align*}
\text{C1} &= X_1, Y_1, Z_1 \\
\text{C2} &= X_2, Y_2, Z_2 \\
\text{C3} &= X_3, Y_3, Z_3 \\
\text{C4} &= X_4, Y_4, Z_4 \\
\text{MINALT} &= \sqrt{X_{\text{MIN}}^2 + Y_{\text{MIN}}^2 + Z_{\text{MIN}}^2} \\
\text{MAXALT} &= \sqrt{X_{\text{MAX}}^2 + Y_{\text{MAX}}^2 + Z_{\text{MAX}}^2} \\
\text{HEIGHT} &= \text{MAXALT} - \text{MINALT}
\end{align*}
\]

**[0156]** Define the (4) planes formed by the vectors originating at the center of mass of the earth and terminating at the respective four runway corners. Represent the 4 planes by the vector cross product as indicated below:

\[
\begin{align*}
\text{XP1} &= C_1 \times C_2 \\
\text{XP2} &= C_2 \times C_3 \\
\text{XP3} &= C_3 \times C_4 \\
\text{XP4} &= C_4 \times C_1
\end{align*}
\]

**[0157]** Store the vector cross products in the polygon zones database, where the number of stored vector cross products equals the number of sides of the convex polygon.

**[0158]** Determine if the present position or projected position is within the zone (PP=position to be checked).

\[
\text{PP}\text{-FX1, FY1, FZ1}
\]

**[0159]** Determine the scalar Dot product between the current position and the previously calculated Cross Products.

\[
\begin{align*}
\text{DP1} &= \text{PP} \times \text{XP1} \\
\text{DP2} &= \text{PP} \times \text{XP2} \\
\text{DP3} &= \text{PP} \times \text{XP3} \\
\text{DP4} &= \text{PP} \times \text{XP4}
\end{align*}
\]

**[0160]** If the products are negative then PP is within the volume defined by intersection planes, if it is positive then outside the volume defined by the intersecting planes.

**[0161]** Note: The signs reverse if one proceeds around the zone in a counter clockwise direction during the definition process.

**[0162]** Determine if PP is within the height confines of the zone.

**[0163]** Determine the magnitude of the PP vector, for an origin at center of mass of the earth.

\[
\text{PPM} = \sqrt{(\text{PX1})^2 + (\text{PY1})^2 + (\text{PZ1})^2}
\]

**[0164]** Compare PPM=PP magnitude to minimum altitude of zone and maximum altitude of zone.

\[
\text{MINALT} = \text{PPM} = \text{MAXALT}
\]

**[0165]** If the above relationship is true then in the zone.

**[0166]** If false then outside of the zone.

**[0167]** An alternate method of determining if the present position PP is within a zone which is not normal to the earth's surface is determined using a method similar to that above, except that all N sides of the zone are represented as normal cross products, the corresponding Dot products are calculated and their total products inspected for sign. Based upon the sign of the product PP is either out of or inside of the zone.

**[0168]** An example of actual Zone and Runway Incursion software code is contained shown below. The actual code includes interfaces to light control, clearance status, tones and other ATC functions.

**[0169]** Since the extension to polygons of \( N \) sides based upon the previous concepts are easily understood, the derivation has been omitted for the sake of brevity.
In summary, two mathematical methods are identified for detecting zone incursions into convex polygons, one based on the equation and slope of the lines, the other is based on vector cross and dot product operators.

The concept of zones, regardless as to whether they are referenced to surface coordinates, local grid systems or ECEF coordinates, provide a powerful analytical method for use in the Airport Control and Management System.

Zone Based Clearances

The airport control and management system manages overall taxi, departure and arrival clearances in a unique and novel manner through the use of zone processing. A departure ground taxi clearance is issued to the selected vehicle. The waypoints and travel path are drawn into the map aboard the selected vehicle. The vehicle(s) then use the presented taxi information to proceed to the final waypoint. AC&M processing uses this clearance information to mask runway zone incursions along the travel path. Since runway incursions are masked only for the selected vehicle and for zones traversed no runway incursion alert actions or warning lights are produced when following the proper course. Should the position represent movement outside of the established corridor, an alert is issued signifying an off course condition exist for that vehicle. Upon the vehicle exit from a particular “cleared” zone, the mask is reset for that zone. Once the last waypoint is reached the clearance is removed and the zone mask is reset. The description below details how such clearances are managed.

Surface Departure Clearance Management Method

1. The operator or controller wishes to issue a surface departure clearance to a specific vehicle.
2. Through the use of a data entry device such as a touch screen or keyboard or mouse, issue waypoints command is selected for surface departure waypoints.
3. The operator is asked to select a specific vehicle from a list of available aircraft and vehicles.
4. The vehicle data window then displays a scrollable list of available aircraft contained in a database which are capable of performing operations of departure clearance.
5. The operator then selects the specific vehicle using a data entry device such as a touch screen or other data entry device.
6. A list is then displayed in a scrollable graphical window of available departure travel paths for the selected vehicle.
7. The operator then selects from this list using a data entry device such as a touch screen or other data entry device.
8. Upon selection of a particular departure path the waypoints and travel path are drawn into a 3-D ALP. The purpose of presentation is to show the controller or operator the actual path selected.
9. The controller or operator is then asked to confirm the selected path. Is the selected path correct? Using a data entry device such as a touch screen or other data entry device a selection is made.
10. If the selected path was not correct, then the command is terminated and no further action is taken.
11. If the selection was correct the following steps are taken automatically:
   a. AC&M processing sends to the selected vehicle using a radio duplex datalink, the clearance, 4-D waypoint and travel path information.
   b. The selected vehicle upon receipt of the ATC command replies with an acknowledgment. The acknowledgment is sent over the full duplex radio datalink to the AC&M processing.
   c. Should the AC&M processing not receive the acknowledgment in a specified amount of time from the selected vehicle, a re-transmission occurs up to a maximum of N re-transmissions.
   d. The vehicle upon receiving the ATC command then “loads” the 4-D navigator with the 4-D waypoint information. A map display contained in the vehicle then draws into the 3-D ALP the departure travel path as shown in FIG. 8. This figure shows travel path as 30 in the digital ALP 31 while actual waypoints are shown as (14) spheres 32.

Departure Clearance Management Method

1. The operator or controller wishes to issue a departure clearance to a specific aircraft.
2. Through the use of a data entry device such as a touch screen or keyboard or mouse, issue waypoints command is selected for departure waypoints.
3. The operator is asked to select a specific vehicle from a list of available aircraft.
4. The vehicle data window then displays a scrollable list of available aircraft contained in a database which are capable of performing operations of departure clearance.
5. The operator then selects the specific vehicle using a data entry device such as a touch screen or other data entry device.
6. A list is then displayed in a scrollable graphical window of available departure travel paths for the selected vehicle.
7. The operator then selects from this list using a data entry device such as a touch screen or other data entry device.
8. Upon selection of a particular departure path the waypoints and travel path are drawn into a 3-D ALP. The purpose of presentation is to show the controller or operator the actual path selected.
9. The controller or operator is then asked to confirm the selected path. Is the selected path correct? Using a data entry device such as a touch screen or other data entry device a selection is made.
10. If the selected path was not correct, then the command is terminated and no further action is taken.
11. If the selection was correct the following steps are taken automatically.
a. AC&M processing sends to the selected vehicle using a radio duplex datalink, the clearance, 4-D waypoint and travel path information

b. The selected vehicle upon receipt of the ATC command replies with an acknowledgment. The acknowledgment is sent over the full duplex radio datalink to the AC&M processing

c. Should the AC&M processing not receive the acknowledgment in a specified amount of time from the selected vehicle, a re-transmission occurs up to a maximum of N re-transmissions

d. The vehicle upon receiving the ATC command then “loads” the 4-D navigator with the 4-D waypoint information. A map display contained in the vehicle then draws into the 3-D ALP the departure travel path as shown in FIG. 9. This figure shows travel path as 34 in the digital ALP 35 while actual waypoints are shown as (5) spheres 36.

12. Upon AC&M receiving the acknowledgment, the following is performed:

a. The zone mask is updated indicating that the selected vehicle has a clearance to occupy runway(s) and taxiway(s) along the travel path. This mask suppresses zone runway incursion logic for this vehicle.

b. The zone based lighting control processing then activates the appropriate set of airport lights for the issued clearance in this case Take Off Lights

13. The vehicle now has active navigation information and may start to move, sending out ADS message broadcasts over the datalink to other vehicles and the AC&M system

14. The selected vehicle ADS messages are received at the AC&M system and at other vehicles.

15. AC&M processing using information contained in the ADS message performs mirrored navigational processing, as outlined in a latter section.

16. Zone incursion checking is performed for every received ADS message using position projection techniques for zones contained in the zones database

17. Should a zone incursion be detected, the zone mask is used to determine if the incurred zone is one which the vehicle is allowed to be in. If the zone is not in the zone mask then a warning is issued. Should the zone be that of a Runway, a Runway Incursion Alert is Issued and the appropriate airport lights are activated.

18. The ADS position is used to determine when the vehicle leaves a zone. When the vehicle leaves the zone, the clearance mask is updated indicated travel though a particular zone is complete. When this occurs the following steps are initiated by the AC&M:

a. The zones mask is updated

b. Airport light status is updated

19. The vehicle continues to travel towards the final waypoint

20. At the final waypoint the navigator and the map display are purged of active waypoint information, meaning the vehicle is where it is expected to be. New waypoints may be issued at any time with a waypoints command function.

AC&M zones based clearance function as presented here provides a unique and automated method for the controlling and managing airport surface and air clearances.

Collision Detection

Collision detection is performed through the zones management process. The basic steps for collision detection and avoidance are shown below in a general form. FIG. 10 shows graphically what the following text describes.

1. Vehicle Position, Velocity and Time (PVT) information are received for all tracked vehicles. The following processing is performed for each and every ADS vehicle report

2. PVT information is converted to the appropriate coordinate system if necessary and stored in the database

3. A rough check zone 38 and 39 is established based on the current velocity for each vehicle in the database

4. Every vehicle’s rough check radius is compared with every other vehicle in the database. This is done simply by subtracting the current position of vehicle V from the position of vehicle V+1 in the database to determine the separation distance between each vehicle and every other vehicle in the database. This is performed in the ECEF coordinate frame.

5. For each pair of vehicles in the database that are within the sum of the two respective rough check radii values; continue further checking since a possible collision condition exists, if not within the sum of the rough check radii do no further processing until the next ADS message is received

6. For each set of vehicles which have intersecting rough check radii project the position ahead by an increment of Time (t) using the received vehicle velocity and optionally acceleration information. Projected positions at time=t1 are shown by two circles 40 and 41 the minimum safe clearance separation for the fuel truck R1 and aircraft R2 respectively.

7. Determine the new separation distance between all vehicles which initially required further checking. Compare this distance to the sum of minimum safe clearance distances R1 and R2 for those vehicles at the new incremented time. The minimum safe clearance distances R1 and R2 are contained in a database and is a function of vehicle velocity and type. Should the separation distance 42 between them be less than the sum of the minimal safe clearance distances R1+R2, then generate alert warning condition. Record the collision time values for each set of vehicles checked. If no minimum safe clearance distance is violated then continue checking the next set of vehicles.
in a similar fashion. When all vehicle pairs are checked then return to the start of the vehicle database.

8. Increment the projection time value (T+) seconds and repeat step 7 if separation was greater than the sum of the minimal safe separation distance R1+R2. Continue to increment the time value to a maximum preset value, until the maximum projection time is reached, then process next pair of vehicles in a similar fashion, until the last vehicle is reached at that time start the process over. If minimum safe clearance (R1+R2) was violated compare the time of intersection to the previous time of intersection. If the previous intersection time is less than the new intersection time the vehicles are moving apart, no collision warning generated. In the event that the vehicles are moving together, meaning the intersection times are getting smaller, determine if a course change is expected based upon the current waypoints issued, and if the course change will eliminate the collision condition. If a course change is not expected or if the course change will not alleviate the collision situation then generate alert. If the projection time T is less than the maximum projection time for warning alerts, generate a warning. If the projection time T is greater than the maximum projection time for a warning alert and less than the maximum projection time for a watch alert, generate a watch alert. If the projection time T is greater than the maximum projection time for a watch alert generate no watch alert.

9. The warning condition generates a message on the ALERT display identifying which vehicles are in a collision warning state. It also elevates the layer identifier code for those vehicle(s) to an always displayed (non-maskable) warning layer in which all potentially colliding vehicles are displayed in RED. 10. The watch condition generates a message on the ALERT display identifying which vehicles are in a collision watch state. It also elevates the layer identifier code for that vehicle(s) to an always displayed (non-maskable) watch layer in which all potentially colliding vehicles are displayed in YELLOW.

11. The process continually runs with each new ADS message report.

Collision Processing Software Example

The sample code below performs the above collision processing, without the routine which checks for course changes, to reduce false alarms.

/*-------------------------------------------------------*/
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <graph.h>
#include <math.h>
#include "veh.h"
#include "sio.h"
#include "coord.h"
#include "color.h"

On or Off Course Processing

The AC&M processing performs mirrored navigational processing using the same coordinate references and waypoints as those aboard the vehicles. In this manner the ATC system can quickly detect off course conditions anywhere in the 3-D airport space envelope and effectively perform zone incursion processing aboard the vehicles and at the AC&M.

The AC&M processing software converts the position and velocity information to the appropriate coordinate frame (zone & map compatible) using techniques described previously. Waypoints based upon the precise 3-dimensional map are used for surface and air navigation in the airport space envelope. The capability is provided to store waypoints in a variety of coordinate systems, such as conventional Latitude, Longitude, Mean Sea Level, State Plane Coordinates, ECEF X, Y, Z and others. The navigational waypoint and on course-off course determinations are preferred to be performed in an ECEF X, Y, Z coordinate frame, but this is not mandatory.

The following mathematical example is provided to show how waypoints and trajectories are processed in Latitude, Longitude, Mean Sea Level and in ECEF X, Y, Z. An actual GNSS flight trajectory is used for this mathematical analysis. The flight trajectory has been previously converted to an ECEF X, Y, Z format as have the waypoints using the previously described techniques. FIGS. 11, 12, 13, 14, 15 are used in conjunction with the following description.

FIG. 11 depicts the ECEF waypoint processing used in the AC&M. The ECEF coordinate system 43 is shown as X,Y,Z, the origin of the coordinate system is shown as 0,0,0. The coordinate system rotates 44 with the earth on its polar axis. The airport 45 is shown as a square patch. An enlarged side view of the airport 46 is shown with (4) waypoints 47. A further enlargement shows the Present Position 48 (PP), the Next Waypoint (PWP) 49. The True Course Line 58 is between the Next Waypoint 49 and Previous Waypoint 50. The vector from the Present Position 48 to the Next Waypoint 49 is vector TNWP 51. The Velocity Vector 52 and the Time Projected Position is shown as a solid black box 53. The Projected Position 53 is used in zone incursion processing. The 3-D distance to the true course is represented by the Cross Track Vector 54 XTRK. The vector normal to the earth surface at the present position and originating at the center of mass of the earth is shown as 55. This vector is assumed to be in the same direction of the vertical axis 56. The lateral axis 57 is perpendicular to the vertical axis and perpendicular to the true course line 58 between the Next Waypoint 49.
and the Previous Waypoint 50. The Navigational Display 59 shows the Present Position 48 with respect to the True Course Line 58.

[0248] The following equations describe the processing performed in the AC&M while FIGS. 12, 13, 14, and 15 represent plots of the actual trajectory information.

Variable Definition

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω</td>
<td>the number of degrees per radian 57.295779513</td>
</tr>
<tr>
<td>α</td>
<td>semi major axis, equatorial radius 6378137 meters</td>
</tr>
<tr>
<td>e</td>
<td>earth’s eccentricity 0.0818182</td>
</tr>
<tr>
<td>TALT</td>
<td>ellipsoidal altitude of trajectory position (meters)</td>
</tr>
<tr>
<td>WALT</td>
<td>ellipsoidal altitude of the waypoint positions (meters)</td>
</tr>
<tr>
<td>R</td>
<td>earth’s radius of curvature at the position or waypoint</td>
</tr>
<tr>
<td>r</td>
<td>2-d equatorial radius (meters)</td>
</tr>
<tr>
<td>h</td>
<td>altitude of Earth with respect to the reference ellipsoid (meters)</td>
</tr>
<tr>
<td>λ</td>
<td>longitude of position in radians</td>
</tr>
<tr>
<td>φ</td>
<td>latitude of position in radians</td>
</tr>
<tr>
<td>ENU</td>
<td>East, North, Up coordinate reference</td>
</tr>
<tr>
<td>XXYZ</td>
<td>East, North, Up vector distance (meters) to waypoint</td>
</tr>
<tr>
<td>VELENU</td>
<td>East, North, Up velocity in (meters/sec)</td>
</tr>
<tr>
<td>DISTENU</td>
<td>East, North, Up scalar distance to waypoint</td>
</tr>
<tr>
<td>VELEMUMAG</td>
<td>East, North, Up Velocity magnitude (scalar) meters/sec</td>
</tr>
<tr>
<td>NBEAR</td>
<td>True North Bearing</td>
</tr>
</tbody>
</table>

T = Time in seconds
p_w = Earth’s radius of curvature at the waypoint
Waypoint indexes through a list of waypoints
Waypoints are indexed as a function of position
P_r = Earth’s radius of curvature at the GNSS position

<table>
<thead>
<tr>
<th>Waypoint</th>
<th>LO_1 = Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAT_1</td>
<td>Latitude</td>
</tr>
<tr>
<td>WALT_w</td>
<td>Waypoint Lon.</td>
</tr>
<tr>
<td>X_w</td>
<td>ECEF X</td>
</tr>
<tr>
<td>L_w</td>
<td>ECEF Y</td>
</tr>
<tr>
<td>Z_w</td>
<td>ECEF Z</td>
</tr>
</tbody>
</table>

[0249] EARTH RADIUS OF CURVATURE DETERMINATION

\[ R_w = \sqrt{\frac{a^2}{1 - e^2 \sin(LAT_w)^2}} \]

[0250] AT WAYPOINT AT GNSS POSITION

\[ X_w = (LAT_w + p_w) \cos(LA_w) \cos(LO_w) \]
\[ Y_w = (LAT_w + p_w) \cos(LA_w) \sin(LO_w) \]
\[ Z_w = (LAT_w + p_w) \sin(LA_w) \]

[0251] CONVERT TRAJECTORY TO ECEF COORDINATES

\[ A_w = (WALT_w + p_w) \cos(WALT_w) \cos(WLO_w) \]
\[ B_w = (WALT_w + p_w) \cos(WALT_w) \sin(WLO_w) \]

[0252] CONVERT WAYPOINTS TO ECEF COORDINATES

\[ C_{w_1} = [WALT_{w_1} + p_{w_1} \cos(WALT_{w_1}) \sin(WLO_{w_1})] \]

[0253] FIND VECTOR FROM PRESENT POSITION TO NEXT WAYPOINT

\[ T = \text{TIME OF TRAJECTORY DATA MATRIX INDEX} \]
\[ \text{TIME INTO TRAJECTORY} = 61 \text{ SECONDS} \]

[0254] CONSTRUCT ECEF WAYPOINT MATRIX Q

\[ Q = [A_0 \ B_0 \ C_0]
    [A_N \ B_N \ C_N]
    [A_{2,N} \ B_{2,N} \ C_{2,N}]
    [A_{3,N} \ B_{3,N} \ C_{3,N}]
    [A_{4,N} \ B_{4,N} \ C_{4,N}]
    [A_{5,N} \ B_{5,N} \ C_{5,N}]
    [A_{6,N} \ B_{6,N} \ C_{6,N}]
    [A_{7,N} \ B_{7,N} \ C_{7,N}] \]
**WAYPOINT SELECTION CRITERIA #2**

POSITION BASED UTILIZES THE CONCEPT OF ZONES, SEE ZONES

\[ G_n := \begin{bmatrix} \frac{T}{N \cdot (n+1)} \\ 1, n+1 \end{bmatrix} \]

**[0257]** WAYPOINT SELECTION CRITERIA #2

POSITION BASED UTILIZES THE CONCEPT OF ZONES, SEE ZONES

\[ G_n := \begin{bmatrix} \frac{T}{N \cdot (n+1)} \\ 1, n+1 \end{bmatrix} \]

**[0258]** DETERMINE VECTOR BETWEEN PREVIOUS AND THE NEXT WAYPOINT

\[ Qa:=(Qa, Qa, Qa) \]

**[0259]** DETERMINE THE MAGNITUDE OF THE DISTANCE TO THE WAYPOINT

\[ \text{DIST} = \sqrt{(TNWP-TNWP)^2 + (TNWP-TNWP)^2 + (TNWP-TNWP)^2} \]

**[0260]** DISTANCE = 825.834796318 METERS

**[0261]** NEXT DETERMINE IF THE SPEED SHOULD REMAIN THE SAME, OR CHANGE

**[0262]** TIME EXPECTED AT NEXT WAYPOINT IS 80 SECONDS INTO TRAJECTORY CURRENT VELOCITY BASED UPON GNSS RECEIVER DETERMINATION

\[ \text{VX} := \frac{TNWP-TNWP}{80 - T} \]

**[0263]** VX = 20.7373916114 M/S X ECEF VELOCITY TO REACH WAYPOINT ON TIME

**[0264]** COMPARE CURRENT X VELOCITY TO REQUIRED X VELOCITY, IF LESS IN VELOCITY, IF GREATER THAN REQUIRED VELOCITY DECREASE VELOCITY

\[ \text{VX} := \frac{TNWP-TNWP}{80 - T} \]

**[0265]** VY = 22.3441807438 M/S Y ECEF VELOCITY TO REACH WAYPOINT ON TIME

**[0266]** COMPARE CURRENT Y VELOCITY TO REQUIRED Y VELOCITY, IF LESS IN VELOCITY, IF GREATER THAN REQUIRED VELOCITY DECREASE VELOCITY

\[ \text{VY} := \frac{TNWP-TNWP}{80 - T} \]

**[0267]** VZ = 30.9823089937 M/S Z ECEF VELOCITY TO REACH WAYPOINT ON TIME

**[0268]** COMPARE CURRENT Z VELOCITY TO REQUIRED Z VELOCITY, IF LESS IN VELOCITY, IF GREATER THAN REQUIRED VELOCITY DECREASE VELOCITY

\[ \text{VZ} := \frac{TNWP-TNWP}{80 - T} \]

**[0269]** VELECEF = 43.4649892964 M/S

**[0270]** VELECEF = (-20.737 22.344 30.982)

**[0271]** DETERMINE THE ON COURSE OFF COURSE NAVIGATIONAL DATA

**[0272]** UNIT VECTOR PERPENDICULAR TO PLANE OF QA AND TNWP

\[ N = \frac{Qa \times TNWP}{|Qa \times TNWP|} \]

**[0273]** UNIT VECTOR PERPENDICULAR TO PLANE OF QA AND NP

\[ U := \frac{NP \times Qa}{|NP \times Qa|} \]

**[0274]** CROSS TRACK ERROR

\[ \text{XTRK} := UN \times TNWP \]

**[0275]** XTRK = 28.5392020973

**[0276]** XTRK = -24.604392

**[0277]** CALCULATE CROSS TRACK VECTOR
UNIT VECTOR FROM PRESENT POSITION TO NEXT WAYPOINT

\[
\mathbf{UTNWP} := \frac{\mathbf{UNWP} - \mathbf{UPP}}{||\mathbf{UNWP} - \mathbf{UPP}||}
\]

UNIT VECTOR OF PRESENT POSITION

\[
\mathbf{UPP} := \frac{p_0 + p_1}{||p_0 + p_1||} = \begin{pmatrix}
0.2341833314 \\
0.6961209083 \\
0.678659129
\end{pmatrix}
\]

UNIT VECTOR OF NEXT WAYPOINT

\[
\mathbf{UNWP} := \frac{\mathbf{NWPT} - \mathbf{UPP}}{||\mathbf{NWPT} - \mathbf{UPP}||}
\]

CHECK AGAINST GREAT CIRCLE TECHNIQUE

GREAT CIRCLE ANGLE \( \beta = \cos(\mathbf{UNWP} \cdot \mathbf{UPP}) \)

\( \beta = 0.0074290102 \) DEGREES

DETERMINE RANGE TO NEXT WAYPOINT FROM PRESENT POSITION \( h = 0 \) SHOULD BE THE SAME AS DIST WHEN ALT IS NEARLY AT ELLIPSOID

\[
R_3 = \frac{||\mathbf{NWPT}|| + ||\mathbf{UPP}||}{2} \\
R_3 = 825.7516989494 \\
R_3 = -0.0836267824
\]

CONVERTING BACK TO LAT, LON AND MSL

\[
\mathbf{ENU} := \begin{pmatrix}
-sin(\lambda) cos(\lambda) \\
sin(\lambda) cos(\lambda) \\
-\sin(\lambda) sin(\lambda)
\end{pmatrix}
\
\mathbf{VELENU} := \mathbf{ENU} \cdot (\mathbf{VELEC})
\]

DISTENU := \( \sqrt{\mathbf{XYZ} \cdot \mathbf{XYZ}} \) M/S

\[
\mathbf{VELENAG} := \sqrt{\mathbf{VELENAG}^2 + \mathbf{VELENAG}^2 + \mathbf{VELENAG}^2}
\]

THE ECEF ANALYSIS COMPARES TO GREAT CIRCLE ANALYSIS VERY CLOSELY

CONVERTING BACK TO LAT, LON & EL

\[
\lambda := \arctan\left( \frac{p_1}{p_0} \right) \\
\phi := \arctan\left( \frac{p_1}{\sqrt{\mathbf{PP}^2}} \right) \\
\lambda \cdot \Omega = -71.40645 \\
\phi \cdot \Omega = 42.90375339
\]

EDIT: 4/13/2005

-continued

[0286] CONVERT TO ENU COORDINATES

[0287] FIND ENU VECTOR FROM PRESENT POSITION TO NEXT WAYPOINT

[0288] EAST DISTANCE

[0289] NORTH DISTANCE

[0290] UP DISTANCE

[0291] EAST VEL.

[0292] NORTH VEL.

[0293] UP VEL.

[0294] DIST = 825.8347966318 M/S

[0295] VELENAG = 43.4644892872 M/S

[0296] THE ECEF APPROACH AND THE ENU APPROACH PRODUCE THE SAME RESULTS SO IT IS POSSIBLE TO USE EITHER COORDINATE REFERENCE TO CONTROL THE NECESSARY SPEED TOWARDS WAYPOINT

[0297] FIND TRUE NORTH BEARING ANGLE TO NEXT WAYPOINT USING TANGENT

\[
\mathbf{NBEAR} := \arctan\left( \frac{XYZ_2}{XYZ_0} \right) \\
\mathbf{NBEAR} = -16.758166051 DEGREES
\]
Should the Range to the Waypoint become larger than the previous range of the waypoint a waypoint may not have automatically indexed. This situation could occur if the vehicle did not get close enough to the waypoint to index automatically or an ADS message may have been garbled and the waypoint did not index, due to a lost ADS message. In this case the following analysis is performed:

a) temporarily increment the waypoint index
b) find the vector between the vehicles present position (PP) and the next waypoint (NWP)

Vector to the next waypoint, \( TNWP-NWP(X,Y,Z)-PP(X,Y,Z) \)
c) Determine the current vehicle velocity vector
\( VEL=(X,Y,Z) \)
d) Determine the Dot Product between the Velocity Vector and Vector TNWP
\( \cos \theta=TNWP \cdot VEL \)
e) If \( A \leq \cos \theta = B \) then keep current waypoint index

Where \( A \) and \( B \) are between 0 and 1 and represent an adjustable value based on the allowable vehicle velocity angular deviation from the true course

If \( -1<\cos \theta<0 \) then return to previous waypoint index and generate wrong way alert. The above technique can be expanded to include curved approach, using cubic splines to smooth the transitions between waypoints. A curved trajectory requires changes to the above set of equations. Using the technique of cubic splines, one can calculate three cubic equations which describe smooth (continuous first and second derivatives) curves through the three dimensional ECEF way points. The four dimensional capability is possible when the set of cubic equations is converted into a set of parametric equations in time. The table below depicts an ECEF waypoint matrix which is used in cubic spline determinations.

Typical Waypoint ECEF Matrix

The AC&M processing utilizes the combination of precise ECEF X, Y, Z navigation and waypoints. Waypoints may be stored in a data file for a particular runway approach, taxi path or departure path. Waypoints may be entered manually, through the use of a data entry device. A list of waypoints describing a flight and or taxi trajectory is then assigned to a particular vehicle. To further supplement waypoint processing expected arrival time may be added to each waypoint as well as velocity ranges for each phase of flight. In this manner, 4 dimensional airport control and management is provided utilizing a GNSS based system. Mathematical processing is used in conjunction with precise waypoints to define flight trajectories. The mathematics typically uses cylindrical shapes but is not limited to cylinders, cones may also be used, and are defined between adjacent waypoints. Typical on or off course processing is outlined below and is shown in FIG. 16.

EXAMPLE 1

Missed Waypoint, with off Course Condition

a) Construct the True course line between the previous waypoint 61 and the next waypoint 62
b) Determine the shortest distance (cross track error 64) from the current position 63 to the line 60 between the previous waypoint 61 and next waypoint 62
c) Determine the magnitude of cross track error
d) Compare the magnitude of the cross track error to a predefined limit for total off course error shown as 65 in the figure.
e) Construct an mathematical cylindrical zone centered on the line between the previous 61 and next waypoint 62 with radius equal to the off course threshold 65.
f) If the magnitude of the cross track error 64 is greater than the off course threshold 65 then raise flag and generate alert (off course).
g) Determine the necessary velocity to reach next waypoint on schedule, as shown previously
h) Is necessary velocity within preset limits or guidelines?
i) Check actual current velocity against preset limits and necessary velocity, If above preset limits, raise flag and issue alert to slow down. If below preset limits, raise flag and issue alert to speed up
j) Automatically index to the following waypoint 66 when the position is within the index waypoint circle 67
k) Should wrong way be detected (positions 68 and 69), index ahead to the next to waypoint pair 66 and 62 and check direction of travel 71 (Velocity) against the line 72 between the waypoints 66 and 62, if the direction of travel is within a preset angular range 70 (A to B degrees) and not off course. If the check is true meaning not off course and headed towards next waypoint then index permanently to waypoint set 66 and 62, no alert generated
l) In the event that an off course condition and wrong way occur (position 69) a message is formatted which updates the layer filter for the target which is off course, an alert is generated, the waypoints are returned to the initial settings and action is taken to bring vehicle back on course possibly using a set of new waypoints
m) In the event of a velocity check which indicates that the speed up or slow down velocity is outside of an approved range, generate a warning the speed for vehicle is out of established limits, Preset speed over ground limits are adjusted for current air wind speed.
The controller reviews the situation displayed and if necessary invokes a navigational correction message to be sent to the Real Time Communication Handler, and then broadcast by radio to the aircraft off course or flying at the wrong speed. The controller at this time may change the expected arrival time at the next waypoint if so necessary.

**EXAMPLE 2**

**Missed Waypoint, with on Course Processing**

- Construct the True Course line between the previous waypoint 66 and the next waypoint 72.
- Determine the shortest distance (cross track error 73) from the current position 74 to the line between the previous waypoint 66 and next waypoint 72.
- Determine the magnitude of cross track error.
- Compare the magnitude of the cross track error to a predefined limit for total off course error shown as 75 in the figure.
- Construct an mathematical cylindrical zone centered on the line between the previous waypoint 66 and next waypoint 72 with radius equal to the off course threshold 75.
- If the magnitude of the cross track error 73 is greater than the off course threshold 75 then raise flag and generate alert (off course).
- Determine the necessary velocity to reach next waypoint on schedule, as shown previously.
- Is necessary velocity within preset limits or guidelines?
- Check actual current velocity against preset limits and necessary velocity. If above preset limits, raise flag and issue alert to slow down. If below preset limits, raise flag and issue alert to speed up.
- Automatically index to the following waypoint 76 when the position is within the index waypoint circle 77.
- Should wrong way be detected (position 74), index ahead to the next to waypoint pair 76 and 72 and check direction of travel 78 (Velocity) against the line 80 between the waypoints 76 and 72, if the direction of travel is within a preset angular range 79 (A to B degrees) and not off course. If the check is true meaning not off course and headed towards next waypoint then index permanently to waypoint set 76 and 72, no alert generated.
- In the event of a velocity check which indicates that the speed up or slow down velocity is outside of an approved range, generate a warning the speed for vehicle is out of established limits, Preset speed over ground limits are adjusted for current air wind speed.

**m. The controller reviews the situation displayed and if necessary invokes a navigational correction message to be sent to the Real Time Communication Handler, and then broadcast by radio to the aircraft off course or flying at the wrong speed. The controller at this time may change the expected arrival time at the next waypoint if so necessary.**

**[0335] The AC&M processing performs all on or off course processing determinations and the displays information related to on or off course or late or early arrival conditions.**

**Alert Display Function**

- Within the AC&M system collision alerts, zone, off course and improper speed warnings are handled somewhat differently than normal position updates. When the AC&M processing recognizes a warning condition, the aircraft(s)/vehicle(s) involved are moved to a special ALP layer. The layer filter controls what graphic parameters a particular vehicle or aircraft is displayed with. The change in the layer from the default vehicle layer signifies that the target has been classified as a potential collision, zone intrusion risk, off course condition or improper speed.

**AC&M Control Zones**

- ATC Control Zones are used to sort and manage air and surface traffic within the airport space envelope. The AC&M Control Area is divided into AC&M Control Zones. Typically the outermost airport control zone interfaces with an en route zone. Aircraft within the 3-D AC&M zone transmit their GNSS derived positions via an on-board datalink. The GNSS data is received by the airport AC&M equipment. The AC&M Processing determines the ECEF AC&M Control Zone assignment based on the aircraft’s current position and assigns the aircraft to the map layer associated with that Control Zone. Mathematical computations as defined previously, are used to determine when a vehicle is in a particular control zone.

- As an aircraft enters the AC&M or transitions to another ATC Control Zone, a handoff is performed between the controllers passing and receiving control of that aircraft. Surface traffic is handled in the same manner. With this AC&M scenario, each controller receives all target information but suppresses those layers that are not under his control. In this manner the controller or operator views on those vehicles or aircraft in his respective control zone. Should there be a collision condition across an ATC zone boundary the conflicting vehicles will be displayed in a non-superimposable layer.

- All targets within an AC&M Control Zone would be placed in the appropriate map layer for tracking and display purposes. Layer coding for each tracked target can be used to control graphic display parameters such as line type, color, line width as well as be used as a key into the underlying database for that object.

- Additional AC&M Control Zones may be defined for other surface areas of the airport, such as construction areas, areas limited to specific type of traffic, weight limited areas and others. These areas may be handled through ATC but will most or be controlled by airline or airport maintenance departments. The concept of a zone based AC&M system integrated with 3-D map information provides a valuable management and navigational capability to all vehicles and aircraft within the airport space envelope.
Entering Waypoints

[0341] The AC&M processing defined herein allows the user to enter waypoints using the digital map as a guide. To enter a series of waypoints the controller simply uses the map which may provide plan and side views of the airport space envelope. The cursor is moved to the appropriate point and a selection is made by pressing a key. The position is then stored in a list with other waypoints entered at the same time. The user is then prompted to enter a name for the waypoint list and an optional destination. Lastly, the waypoints converted the appropriate coordinate frame and are then saved to a file or transmitted to a particular vehicle. In this manner the user may add and define waypoints.

Defining Zones

[0342] The user may define zones using the digital map as a guide. To enter a series of zones the controller simply uses the map which may provide plan and side views of the airport space envelope. The cursor is moved to the appropriate point and a selection is made by pressing a key. The position is then stored in a list with other zone definition points. The controller is then prompted to enter a name for the zone (pole, tower, construction area, etc.) and type of zone (circle, sphere, box, cylinder, etc.). Lastly, the zones are converted to the appropriate coordinate frame and saved to a file or transmitted to a particular vehicle. In this manner the user may define additional zones.

[0343] The ability to quickly and accurately define zones is key to the implementation of a zones based AC&M capability.

ADS Message Format Considerations

[0344] The definition and standardization of a 'seamless' aviation system datalink format(s) is critical to the implementation of a GNSS-based aviation system.

Sample ADS Message Format

[0345] Perhaps the most critical issue which must be resolved in the determination of the datalink format, is the selection of the coordinate system and units for the GNSS-derived position and velocity data. Compatibility with digital and paper maps, navigation system and overall mathematical processing efficiency play major roles in the selection of the coordinate reference. Below is a list of criteria which are used in this determination:

    ADS Message Format Criteria Definitions

    WORLD WIDE USE  The coordinate reference system is recognized throughout the world. Scale does not change as a function of where you are on the earth.
    SIMPLE NAVIGATION MATHEMATICS  The coordinate system lends itself to simple vector navigational mathematics.
    COMPATIBLE WITH COMPLEX 4-D CURVED PATH 4-D NAVIGATION FUNCTIONS  The coordinate reference can support curved trajectory mathematics.
    COMPATIBLE WITH  Is compatible with management
    COMPATIBLE WITH SPACE OPERATIONS  The coordinate system is compatible with low earth orbit or space-based operations.
    NAD83 AND WGS84 REF.  The reference system is compatible with NAD83 and WGS84.
    SINGLE ORIGIN  The system has one single point origin.
    LINEAR SYSTEM  The system is a linear coordinate system and does not change scale as a function of location.
    UNITS OF DISTANCE  The coordinate system is based on units of distance rather than angle.
    NO DISCONTINUITIES  The coordinate reference system is continuous world wide.

[0347] The ECEF X, Y, Z Cartesian coordinate system satisfies all of the above criteria. Other systems may be used such as, Universal Transverse Mercator, Latitude, Longitude and Mean Sea Level and other grid systems but additional processing overhead and complexities are involved. A representative ADS message structure is provided below:

SAMPLE AIRPORT ECEF MESSAGE CONTENT

| ID # | 8 Characters |
| VEHICLE TYPE | 4 Characters |
| CURRENT POSITION: | |
| ECEF X Position (M) | 10 Characters |
| ECEF Y Position (M) | 10 Characters |
| ECEF Z Position (M) | 10 Characters |
| ECEF X2 Position (M) | 4 Characters |
| ECEF Y2 Position (M) | 4 Characters |
| ECEF Z2 Position (M) | 4 Characters |
| ECEF X3 Position (M) | 4 Characters |
| ECEF Y3 Position (M) | 4 Characters |
| ECEF Z3 Position (M) | 4 Characters |
| ECEF X Velocity (M/S) | 5 Characters |
| ECEF Y Velocity (M/S) | 5 Characters |
| ECEF Z Velocity (M/S) | 5 Characters |
| NEXT WAYPOINT (WHERE HEADED INFORMATION): | |
| ECEF X | 10 Characters |
| ECEF Y | 10 Characters |
| ECEF Z | 10 Characters |
| TIME | 8 Characters |

[0348] A bit oriented protocol, representing the same type of information, may be used to streamline operations and potential error correction processing. (The asterisks denote optional fields which may be used to determine the attitude of an aircraft.)

[0349] The individual fields of the ADS message are described below:

| 0350 | ID (8 Character Word, Alpha-Numeric) |
| 0351 | The individual fields of the ADS message are described below: |
| 0352 | Type of Vehicle (4 Character Word, Alpha-Numeric) |
The vehicle type is used to identify the A/V's type classification. Numerous type classifications may be defined to categorize and identify various aircraft and surface vehicles.

Current ECEF X,Y,Z Position (10 Characters by 3 Words)

The ECEF X,Y,Z position fields provide the vehicle's position at the time of the ADS transmission in ECEF X,Y,Z coordinates. The position is calculated by the GPS receiver. Based on the system design, these values may or may not be smoothed to compensate for system latencies. The message length of 10 characters provides a sign bit in the most significant digit and 9 digits of positional accuracy. The least significant digit represents 0.1 meter resolution. This provides a maximum ADS distance of 49999999.9 which translates to an altitude of about 3600 KM above the earth's surface, providing sufficient coverage to support low earth orbiting satellites and spacecraft.

Delta Positions (Relative Positions, 4 Characters by 6 Words)

Delta positions are used to represent the positional offset of two other GPS antenna locations. These locations can be used to determine the attitude of the aircraft or its orientation when it is not moving. All delta distances are calculated with respect to the current ECEF position. Straight forward ECEF vector processing may then be used to determine the attitude and orientation of the aircraft with respect to the ECEF coordinate frame. An ECEF-to-local on board coordinate system (ie, North, East, Up) conversion may be performed if necessary. Accurate cross wind information can be determined on the ground and on board the aircraft from delta position information. Delta positions may also be used as 3-D graphical handles for display presentations.

The message length of 4 characters provides a sign bit in the most significant digit and 3 digits of delta position accuracy. The least significant digit represents 0.1 meter resolution.

ECEF X,Y,Z Velocity (5 Characters by 3 Words)

The fields represent the A/V's ECEF X,Y,Z velocity in meters per second. Tenth of a meter/second resolution is required during the ground phase of GPS based movement detection, latency compensation, zone and collision detection processing.

The message length of 5 characters provides a sign bit in the most significant digit and 4 digits of velocity accuracy.

Next Waypoint (10 Characters by 3 Words)

These fields describe where the A/V is currently headed, in terms of the ECEF X,Y,Z coordinates of the next waypoint. This provides intent information which is vital to the collision avoidance functions.

Time (Universal Coordinated Time) 8 Characters

This field identifies the Universal Coordinated Time at the time of the ADS transmission. This time is the GPS derived UTC time (in seconds) plus any latency due to processing delays (optional).

The ADS message format provides a very valuable set of information that simplifies mathematical processing. Since the ECEF cartesian coordinate frame is native to every GPS receiver, no additional GPS burden is incurred. This type of ADS broadcast message information is more than adequate for precision ground and air operations as well as for general ATC/airport control and management functions.

Overview of Candidate ADS Architectures

Many communication technologies are available which can provide ADS capability. Many of the systems already exist in some form today, but may require modification to meet the requirements of ADS in the terminal area. In evaluating datalink candidates, it is important that future airport standards are not compromised by forcing compatibility with the past. Systems should develop independently in a manner designed to achieve the systems' maximum operational benefits. Transitional elements and issues of compatibility with current systems are better handled through the implementation of translators which do not detract from a future system's true potential.

Mode S Interrogation

The Mode S system is in use today and is compatible with today's en route radar and Terminal Radar Approach Control (TRACON)-based air traffic control systems. Current Mode S 1030 MHZ interrogation is performed using Mode S radars which scan at the 4.8 second rate. The scan rate represents the rotational period of the scanning antenna. When a target is interrogated by the radar pulse, the aircraft or vehicle broadcasts its GPS-based information to air traffic control at 1090 MHZ. In this manner, ADS information is received by ATC and by other interrogating sources.

Numerous problems exist with any interrogation technique which has multiple interrogators. For radar systems to provide seamless coverage, surface, parallel runway and airport surveillance radars are required. Aircraft and surface vehicles would require the use of a transponder which broadcasts a response at 1090 MHZ when interrogated at 1030 MHZ. In an environment where multiple interrogations are required, system complexities increase dramatically. Early ATRCBS, Mode A and Mode C systems were troubled with too many unsynchronized interrogation requests. This resulted in cross talk, garble and loss of transmission bandwidth. Further complicating the airport environment is the possibility of reflected signals which interrogate areas of the airport outside the view of the surveillance radar. This clogs the 1090 channel and further complicates surveillance processing. Airborne Mode S transponder operation requires that squitter messages be broadcast when in the air and turned off on the ground. A Mode S squitter is a periodic repetitive broadcast of ADS information. This, by definition, will interfere with airport interrogation broadcasts and essentially create a self jamming system.

Any airport ADS system utilizing a Mode S interrogation capability would require almost a ground up development effort encompassing the myriad of necessary surveillance systems.

Mode S Squitter (GPS Squitter)

Similarly, the Mode S squitter utilizes the Mode S frequencies. A squitter is a randomly timed broadcast which
is rebroadcast periodically. The Mode S squitter broadcasts GPS information at a periodic rate at 1090 MHZ with a bit rate of 1 MBPS. Current thinking requires that the ADS system be compatible with the Traffic Collision Avoidance System (TCAS). The TCAS system currently uses a 56 bit squitter message that must be turned off in the low altitude airport environment since it will interfere with other radar processing activities performed on the ground. Turning TCAS off inside the terminal area (where most midair problems and airport surface collisions occur) defeats the system’s operational benefits where they are needed most. Operationally this is unacceptable.

A modified 112 bit squitter message has been proposed by MIT Lincoln Laboratories. With this approach, the GPS data is squittered twice per second to support ground and low altitude operations. The proposed Mode S squitter operation has distinct advantages over the Mode S interrogation method. Broadcasts are generated from all aircraft and (potentially) surface vehicles. Message collisions are possible, especially when the number of users is increased. If a collision occurs, the current message is lost and one must wait for the next message to be transmitted. At a two hertz transmission rate, this is not a significant problem. Analysis performed by MIT Lincoln Laboratories indicates that an enhanced Mode S squitter has potential to support operations at major airports.

The integration of the Mode S Squitter, as currently defined, is not without risk. This implementation requires a fleet update to convert to the 112 bit fixed format. Procedural issues of the switch-over between the 56 and 112 bit operation remain problematic. Operation in metropole areas such as New York may create operationally dangerous conditions. Airside TCAS and ASR 56 bit transponder responses would be turned off based on phase of flight to be compatible with 112 bit squitter messages used at low altitudes and on the ground. In metropole areas, confusion is almost certain for both the pilot and air traffic controller when systems are turned off and on. Further modifications may be required to ground and vehicular equipment should these issues be a significant problem.

The 112 bit fixed squitter length message, as defined in May 1994, fails to take advantage of precise GNSS velocity information. This is a significant limiting factor in the proposed squitter message format. The current squitter message is designed to be compatible with today’s radar processing software and is not designed to fully capitalize on GNSS and ADS capabilities.

AVPAC Packet Radio (AVPAC)

AVPAC radio is currently in use with services provided by ARINC and may be a viable candidate to provide ADS services. Again, a GPS-based squitter or an interrogator-initiated broadcast is utilized at aeronautical VHF frequencies. Work is underway to adapt AVPAC to support both voice and data transmissions. A Carrier Sense Multiple Access (CSMA) protocol is utilized on multiple VHF frequencies.

Another communication system currently in use by the aviation industry is ACARS. ACARS is a character oriented protocol and currently transmits at 2400 baud. Work is underway to increase the baud rate to support more complex message formats.

VHF/UHF Time Division Multiple Access (TDMA)

An interesting communication scheme currently under test and development in Sweden utilizes TDMA operation. TDMA is similar to communication technologies used by the United States military and others. In this system, each user is assigned a slot in which to broadcast the ADS message. A single or multiple frequency system may be utilized based upon total traffic in the area. Upon entering an airport area, the user equipment listens to all slot traffic. The user equipment then selects an unused broadcast time slot. Precise GPS time is used to determine the precise slot. ADS broadcasts are then transmitted at a periodic rate. Broadcasts typically repeat at one second intervals. Should a collision be detected upon entering a new location, the system then transmits on another clear time slot. Since all time slots are continuously received and monitored, all necessary information for situational awareness and collision avoidance is available.

This system maximizes the efficiency of the broadcast link since, in a steady state environment, no transmission collisions can occur. A time guard band is required to assure that starting and ending transmissions do not overlap. The size of the guard band is a function of GPS time accuracy and propagation delay effects between various users of the system. Another feature of this system is an auto-ranging function to the received broadcasts. This is possible due to the fact that the ADS slot transmissions are defined to occur at precise time intervals. It is then possible, using a GNSS synchronized precise time source, to determine the transit time of the ADS broadcast. By multiplying the speed of light by the transit time, one may calculate the 1-dimensional range to the transmitting object. In reality, a more precise direction, distance and predicted future location is obtainable from the ADS message information itself.

Code Division Multiple Access (CDMA) Spread Spectrum

CDMA spread spectrum ADS broadcasts utilize a transmission format similar to that used in the GPS satellites. PRN codes are utilized to uniquely identify the sending message from other messages. The number of users able to simultaneously utilize an existing channel depends upon the PRN codes used and the resulting cross correlation function between the codes. This implementation is being utilized commercially in wireless computer systems with data rates exceeding 256 KBPS. In a frequency agile environment, this implementation may be able to provide secure ADS services.

Cellular Telephone

Cellular technology is rapidly changing to support the large potential markets of mobile offices and personal communication systems. CCITT and ISDN standards will provide both voice, video and data capability. Cellular communication may be used by surface vehicles and aircraft for full duplex data link operations. ADS broadcast message formats receivable by ATC and other users will require changes to commercially available services. Cellular telephone has the mass market advantage of cost effective large
As the above examples show, a number of datalinks exist or may be modified to provide ADS services. It is not the intent of this specification to rigidly define a particular datalink.

[0389] ADS Operational Considerations

[0390] To fully exploit the ADS concepts presented in this specification, a new set of operational procedures and processing techniques are necessary. The ADS concept will provide the controller and the Aircraft/Vehicle (A/V) operator with the best possible view of the airport environment. With highly accurate 3-D position and velocity information, many new operational capabilities are possible which will provide increased efficiency and safety improvements. The following sections show how precise ADS information is used in seamless airport control and management.

Definition Of Compatible Waypoints

[0391] Waypoints based upon the precise 3-D map and standard surface, approach and departure paths are used for surface and air navigation in the 3-D airport space envelope. Waypoints may be stored in a variety of coordinate systems, such as conventional Latitude, Longitude, Mean Sea Level; State Plane Coordinates; ECEF X, Y, Z; and others. The navigational waypoint and on/off course determinations are preferred to be performed in an ECEF X, Y, Z coordinate frame, but this is not mandatory.

[0392] Waypoints and navigation processing should be defined and designed for compatibility with air and ground operations, including precision approach capability. The same information and processing techniques should be in place on board the A/V’s and at the AC&M. The AC&M performs mirrored navigational processing using the same coordinate references and waypoints as those on board the A/V’s. In this manner, the AC&M system can quickly detect off course and ‘wrong way’ conditions anywhere in the 3-D airport space envelope at the same time these conditions are detected on board the A/V’s.

Waypoint Navigation Mathematics

[0393] The following mathematical example is provided to show how waypoints and trajectories are processed in the ECEF X, Y, Z coordinate reference frame. An actual DGPS flight trajectory is used for this mathematical analysis. The flight trajectory and waypoints have been previously converted to an ECEF X, Y, Z format.

[0394] FIG. 11 presented in the earlier ON Or Off Course Processing section depicts the major ECEF waypoint elements which are used throughout the following navigation mathematical processing example. The following example utilizes an ECEF Waypoint Matrix. In this example, the next waypoint (NWP) is element 5 in the matrix and the previous waypoint (PWP) is element 4. The values for the waypoints are shown in the examples. The range to the waypoint is determined from the current position. The range is compared to the previous range for possible off course or wrong way conditions. If the range is increasing, the waypoint auto-indexing distance may have been exceeded even though the vehicle is on course. In this situation, the waypoint index is temporarily indexed and checking is performed to determine whether the velocity vector is pointing within X degrees of the next waypoint (in this example it is set to +/-90 degrees). Based upon the outcome, a wrong way signal is generated or the waypoints are indexed. The ECEF cross track vector (XTRK) is determined and projected onto the vertical axis, local lateral axis and the plane tangent with the earth’s surface at the current position.

<table>
<thead>
<tr>
<th>CONSTRUCT TRAJECTORY VECTOR OF PRESENT POSITION (PP)</th>
<th>INDEX TO NEXT WAYPOINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP&lt;sup&gt;i&lt;/sup&gt; :=</td>
<td>x&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>y&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>z&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td>i := 1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PRESENT POSITION</th>
<th>WAYPOINT INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP&lt;sup&gt;i&lt;/sup&gt;</td>
<td>wpin := floor&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>wpin := 4432742,69262449</td>
</tr>
<tr>
<td></td>
<td>432846,19931227</td>
</tr>
</tbody>
</table>
-continued

<table>
<thead>
<tr>
<th>ECEF X</th>
<th>ECEF Y</th>
<th>ECEF Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1491356.37337769</td>
<td>-4435583.43802856</td>
<td>4319696.32899831</td>
</tr>
<tr>
<td>1491105.26068276</td>
<td>-4434843.77739539</td>
<td>4320510.1001237</td>
</tr>
<tr>
<td>1491191.23102175</td>
<td>-4434078.22140822</td>
<td>4321279.19552478</td>
</tr>
<tr>
<td>1491403.1231625</td>
<td>-4433316.76294102</td>
<td>4322016.0156733</td>
</tr>
<tr>
<td>1491013.94073778</td>
<td>-4432855.36845753</td>
<td>4322641.89680113</td>
</tr>
<tr>
<td>1490386.0739151</td>
<td>-4432652.82158381</td>
<td>4323015.56283451</td>
</tr>
<tr>
<td>1489735.70705071</td>
<td>-4432541.0263631</td>
<td>4323562.8405113</td>
</tr>
<tr>
<td>1489205.89634819</td>
<td>-4432860.45040046</td>
<td>4322985.40668013</td>
</tr>
<tr>
<td>1488862.17692919</td>
<td>-4433298.26186174</td>
<td>4322564.1174943</td>
</tr>
<tr>
<td>1488577.74086904</td>
<td>-4433715.22689756</td>
<td>4322248.17133335</td>
</tr>
<tr>
<td>1488250.73266894</td>
<td>-4434298.26191826</td>
<td>4321864.00370927</td>
</tr>
</tbody>
</table>

**WAYPOINT MATRIX Q**

**WAYPOINT INDICES**

<table>
<thead>
<tr>
<th>PREVIOUS</th>
<th>NEXT</th>
</tr>
</thead>
<tbody>
<tr>
<td>wp&lt;sub&gt;i&lt;/sub&gt; := wp&lt;sub&gt;i+1&lt;/sub&gt;</td>
<td>wp&lt;sub&gt;i&lt;/sub&gt; := wp&lt;sub&gt;i+1&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

for <i>wp</i> = 4

for <i>wp</i> = 5

**PREVIOUS WAYPOINT**

\[
\text{PWP} = (WP_{wpi0}, WP_{wp1}, WP_{wp2})
\]

\[
\text{PWP}^T = \begin{pmatrix}
1491013.94073778 \\
-4432855.36845753 \\
4322641.89680113
\end{pmatrix}
\]

**NEXT WAYPOINT**

\[
\text{NWP} = (WP_{wpi0}, WP_{wpi1}, WP_{wpi2})
\]

\[
\text{NWP}^T = \begin{pmatrix}
1490386.0739151 \\
-4432652.82158381 \\
4323015.56283451
\end{pmatrix}
\]

**DEFINE VECTOR BETWEEN WAYPOINTS FOR CURRENT TRAJECTORY TIME**

\[
\text{BWP} = \text{NWP}^T - \text{PWP}^T
\]

\[
\text{BWP} = \begin{pmatrix}
-627.8667862699 \\
202.5468731794 \\
373.6660263799
\end{pmatrix}
\]

**DISTANCE BETWEEN THE WAYPOINTS**

\[
|\text{BWP}| = 758.20065722787
\]

**DEFINE VECTOR BETWEEN PRESENT POSITION & NEXT WAYPOINT**

\[
\text{TNWP} := \text{NWP}^T - \text{PWP}^T
\]

\[
\text{TNWP} = \begin{pmatrix}
-312.9576405 \\
89.8710406795 \\
169.36352224
\end{pmatrix}
\]

**DISTANCE TO THE WAYPOINT (RANGE)**

\[
|\text{TNWP}| = 367.019472009
\]

**CHECK RANGE TO SEE IF A WAYPOINT HAS BEEN MISSED**

IF VEHI. N RANGE > PREVIOUS VEHI. N RANGE THEN PERFORM TEST:

**INCREMENT WAYPOINT INDEX**

FIND THE VECTORS LINE BETWEEN THE CURRENT POSITION AND NEXT WAYPOINT

\[
\text{TNWP} = \text{NWP}(X,Y,Z) - \text{PP}(X,Y,Z)
\]

**CALCULATE ECEF CURRENT POSITIONS VELOCITY VECTOR**

\[
\text{VEL} = (VX,VY,VZ)
\]

**CALCULATE DOT PRODUCT BETWEEN THE VELOCITY VECTOR AND TNWP**

\[
\cos \theta = \text{TNWP}(X,Y,Z) \cdot \text{VEL}(VX,VY,VZ)
\]

\[
|\text{TNWP}| = |X \cdot X| + |Y \cdot Y| + |Z \cdot Z|
\]

\[
|\text{VEL}| = |(VX \cdot VX) + (VY \cdot VY) + (VZ \cdot VZ)|
\]

IF 0 < \cos \theta < 1 THEN KEEP CURRENT WAYPT INDEX,
NOTE: VLAT(Z) TERM WILL CANCEL OUT WHEN FINDING UNIT VECTOR
VLAT = (VLATX, VLATY, 1)
VLAT = (0.989509706, 1.30796588671)

DETERMINE THE LOCAL LATERAL AXIS UNIT VECTOR

VLAT := \frac{VLAT}{VT LAT^2 + VLAT^2 + 1} \quad UVLAT^T = \begin{bmatrix} 0.5151248629 \\ 0.6809086804 \\ 0.5205859627 \end{bmatrix}

PERFORM CHECK TO SEE IF UVLAT IS PERPENDICULAR TO UVADJ
UVADJ · UVLAT^T = 5.5511151231 · 10^{-17}
CLOSE ENOUGH TO ZERO
IS PERPENDICULAR

PROJECT THE CROSS TRACK TO THE LATERAL AXIS
LATDIST := VXTR · UVLAT^T
LATDIST = -16.2075944693

VER DIST = -4.2570109135
The sign of the lateral distance (LATDIST) and vertical distance (VER DIST)
determine whether one turns right or left or goes up or down to true course.

[0395] From a simplicity standpoint, the ECEF coordinate frame provides direct GPS compatibility with minimal processing overhead. The system is based upon the ECEF world wide coordinate frame and provides for 4-D gate-to-gate navigation without local coordinate reference complications. Furthermore, it is directly compatible with zone processing functions as described in earlier sections.

[0396] The above techniques can also be expanded to include curved approaches using cubic splines to smooth the transitions between waypoints. A curved trajectory requires changes to the above set of equations. Using cubic splines, one can calculate three cubic equations which describe smooth (continuous first and second derivatives) curves through the 3-D ECEF waypoints. Additional information on the use of splines may be found in mathematical and numerical programming textbooks. Four dimensional capability is possible when the set of cubic equations is converted into a set of parametric equations in time.

Display Graphics and Coordinated References

[0397] Three dimensional display graphics, merged with GPS sensor inputs, provide exciting new tools for airport navigation, control and management. Today’s airport users operate in a 4-dimensional environment as precisely scheduled operations become increasingly important in an expansion-constrained aviation system. The 4-D capability of GPS integrated with precise 3-D airport maps and computer graphics, provide seamless airport safety and capacity enhancements. The merger of these technologies provides precise, real-time, 3-D situational awareness capability to both the A/V operators and the air traffic controller.

[0398] The FIG. 17 shows a missed approach 81 on runway 35 followed by a touch and go 82 on runway 24 at the Manchester Airport. The power of such a situation display 83 presentation for the air traffic controller can be instantly recognized. Upon closer inspection, it becomes increasingly clear that GPS and precise graphical maps can be a valuable asset in air and ground navigation.
For the air traffic controller, 3-D situational awareness displays, supplemented with navigation status information, are sufficient. For the pilot navigating in a 3-D world, a 3-D terrain or airport map superimposed with graphical navigational information would be extremely valuable, particularly in adverse weather conditions.

The FIG. 18 combines the elements of precise ECEF navigational information with a 3-D airport map. The key element in the construction of the map is compatibility with the navigation display, where the selection of map and navigation coordinate frames is of paramount importance. Upon inspection of computer graphical rotation and translational matrices, it becomes clear that, for processing speed and mathematical efficiency, the Cartesian coordinate system is preferred for the map database. A 3-D X,Y,Z digital map presentation provides the most efficient path to 2-D screen coordinates through the use of projection transformations.

The integration of GPS-based navigation information with digital maps suggests that new methods of navigation processing should be considered. In the past, aircraft typically relied on a signal in space for instrument-based navigation. The instrument landing system (ILS) consists of a localized direct signal of azimuth and elevation. The VOR-DME navigation system uses a signal in space which radiates from an antenna located at a particular latitude and longitude. Altitude is derived from pressure altitude. Current, 2-D radar surveillance systems are also based upon a localized coordinate reference, usually to the center of the radar antenna. Again, altitude information is from barometric pressure readings which vary with weather. The integration of local navigation and surveillance systems and 3-D ATC and navigational display presentations requires an excessive number of coordinate conversions, making the process overly difficult and inaccurate.

To minimize navigational and display overhead, a Cartesian X,Y,Z coordinate system is used for the navigation computations, map database and display presentations. Many X,Y,Z map database formats are in use today, but many are generated as a 2-D projection with altitude measured above mean sea level. Two examples of this type of system are Universal Transverse Mercator (UTM) and State Plane Coordinate System (SPCS). Neither one of these systems is continuous around the world, each suffer from discontinuities and scale deformity. Furthermore, neither of these systems is directly compatible with GPS and also requires coordinate conversions. If the map, travel path waypoints, navigational processing, navigational screen graphics and airport control and management functions are in the Cartesian coordinate frame, the overall processing is greatly simplified.

In the graphical navigation display FIG. 18, the perspective is that of a pilot from behind his current GPS position 84. From this vantage point 85, the pilot can view his current position 84 and his planned travel path 86. As the aircraft moves, its precise ECEF X,Y,Z velocity 87 components are used to determine how far back 88 and in what direction the observation is conducted from. This is determined by taking the current ECEF velocity 87, negating it and multiplying it by a programmable time value (step-back time). When applied to the aircraft's current position 84, this results in an observation point 89 which is always looking at the current position 84 and ahead in the direction of travel 87.

Once the observation point 89 is established in the 3-D Cartesian coordinate system, an imaginary mathematical focal plane 90 is established containing the current position 84. The focal plane 90 is orthogonal to the GPS-derived ECEF velocity vector 87. The mathematical focal plane 90 represents the imaginary surface where the navigation 'insert' will be presented. The focal plane is always, by definition, orthogonal to the viewing point 85. The travel path 86 composed of ECEF X,Y,Z waypoints (92-95) is drawn into the 3-dimensional map. The point on the true travel path 86 which is perpendicular to the current position 84 represents the center 96 of the navigational insert screen 91. The orientation of the navigational insert with respect to the horizontal axis is determined by the roll of the aircraft. The roll may be determined through the use of multiple GPS antennas located at known points on the aircraft or may be determined by inertial sensors and then converted to the ECEF coordinate frame. Vector mathematics performed in the ECEF coordinate frame are then used to determine the new rotated coordinates of the navigation screen insert 91. The rotated coordinates are then translated through the use of the graphical translation matrix and drawn into the 3-D map 97.

The final step is the placement of the current position ‘cross-hair’ symbol 84 with respect to travel path 86. The aircraft's GPS position, previous and next waypoints are used to determine the ECEF cross track vector 98. The cross track vector 98 is then broken down into its local vertical 99 and local lateral 100 (horizontal) components. (Local components must be used here since the vertical and lateral vectors change as a function of location on the earth.) The cross-hair symbol 101 is then drawn on to the focal (image) plane 90 surface at the proper offset from the true course position indicated by the center of the navigation screen insert 96. Thus, this display provides precise navigation information (lateral and vertical distance to true course) with respect to true course, provides information on 3-D airport features and shows the planned 3-D travel path. The element of time may also be presented in this display format as an arrow (drawn in the direction of travel) of variable length where the length indicates speed up or slow down information.

The construction of this type of display in other than ECEF coordinates entails substantial coordinate conversion and additional processing. Again, for simplicity and compatibility with proven 3-dimensional graphic techniques, an ECEF Cartesian X,Y,Z coordinate framework is desired.

GPS Navigator Display

Various display formats are used to provide the GPS navigational information to the pilot. The area navigation display shown in FIG. 19 features auto-scaling range 102 rings 103 which provide course, 104 bearing 105 and range distance to the waypoint. The length of the course 104 and bearing lines 105 superimposed on the ring scale 103 are proportional to the distance from the waypoint. The compass orientation of the bearing line 105 provide the course to travel from the current position to the waypoint. The course
line 104 indicates the compass direction of current travel. The display also provides altitude information as a auto-scaling bar chart display 106 with indicated go up or down information.

[0408] In this manner the area navigation display provides the following:

[0409] 1. Range to the waypoint based on length of the line and an autoranging scale
[0410] 2. Compass heading to travel to the waypoint
[0411] 3. Compass heading of current travel
[0412] 4. Autoranging altitude navigation bar graph display

[0413] The GPS landing display is shown in FIG. 20. This display is activated when the first GPS waypoint at the top of the glide slope is reached. The precision landing display is composed of a simple heavy cross 107 which moved about on an X Y graticule cross hair display 108. Textual TURN LEFT/TURN RIGHT and GO UP/GO DOWN messages are presented to the pilot when the aircraft is more than a predetermined amount eg. 10.0 meters off of true course.

[0414] Another display format utilizing a 3-D map is provided in FIG. 21. This display technique provides a 3-D view of the approaching airport as viewed from the aircraft’s position. The techniques described above for the cross hair navigation screen are identical to those used in the 3-D approach presentation. In the 3-D approach presentation, a conical zone 109 is constructed around the line 110 between the landing approach waypoints. The apex of the cone is at the touch down point 111 and the base of the cone is at the top of the glide slope waypoint. This 3-D object is viewed normal to the line between the current and previous waypoint as shown in FIG. 21.

[0415] The cone is sliced at the point on the line (formed by the current and previous waypoint) perpendicular to the present position 112. The resulting cross section then effectively represents the cross hair symbology implemented in the graphical GPS landing display. The current position is then displayed within the conical cross section 113 of the glide slope zone 109. A position not in the center of the display means the aircraft is not on true course. For example, a position report in the upper right of the display cross section means the aircraft is too high and too far to the right. In this case the pilot should turn left and go down. As the aircraft gets closer to the touch down point, the conical cross section scale gets smaller. Once the touchdown waypoint 114 is reached, the display reverts to a plan view of the airport similar to that shown in FIG. 8 which is then used for surface navigation. The graphical nature of this display format is useful in the air and on the ground, but requires very fast graphical and computational performance. The advantage of this system is that it minimizes many of the navigational calculations such as cross track errors, but requires moderate spatial graphical computations and fast display performance.

Waypoint Database Definition Software Example

[0416] Waypoints

[0417] ***********************************************************************************************

US 2004/0225432 A1 Nov. 11, 2004

0418] File Name: way.c
[0419] Description: way.c contains the routines used to enter and save the waypoint data.
[0420] Units: store_wps, calc_navedata,
[0421] #include <stdio.h> /* standard input/output */
[0422] #include <math.h> /* MSC math library */
[0423] #include <string.h> /* MSC string routines */
[0424] #include <graph.h> /* MSC graphics routines */
[0425] #include <stdlib.h> /* MSC standard library routines */
[0426] #include <bios.h> /* MSC bios routines */
[0427] #include “coord.h” /* coordinate definitions */
[0428] #include “sio.h” /* CAD/NAV global declarations */
[0429] #include “veh.h” /* vehicle data */
[0430] #include “lights.h” /* lighting definitions */

AC&M Subsystems

[0431] Communications Processor and Communication Flow
[0432] The processing of data communications within the airport is a key element of any GPS-based airport control and management system. A minimum of three types of messages must be addressed:
[0433] (1) the broadcast of Differential GPS correction messages to the vehicles
[0434] (2) the transmission and receipt of Automatic Dependent Surveillance (ADS) messages
[0435] (3) the transmission of control messages from the AC&M to the vehicle and vice versa.

[0436] A high level block diagram of the Airport Communications System and its interfaces to other major elements of the AC&M subsystem is provided in FIG. 22.

[0437] In this design, all ADS and A/V messages are received by the AC&M Processor 115 and are forwarded to the COMM Processor 116 for re-transmission to the vehicles. The AC&M Processor is also used to compose ATC messages which are also forwarded to the vehicles through the COMM interface or passed to the local Graphics Processor 117 to control the situation display presentation. The COMM processor 116 also transmits the differential correction messages generated by the reference station 118 directly to the vehicles.

[0438] Differential GPS Overview
[0439] Real time differential correction techniques compensate for a number of error sources inherent to GPS.

[0440] The idea is simple in concept and basically incorporates two or more GPS receivers, one acting as a stationary base station 118 and the other(s) acting as roving receiver(s) 119, 120. The differential base station is “anchored” at a known point on the earth’s surface. The base station receives the satellite signals, determines the errors in
the signals and then calculates corrections to remove the errors. The corrections are then broadcast to the roving receivers.

[0441] Real time differential processing provides accuracy of 10.0 meters or better (typically 1.0-5.0 meters for local differential corrections). The corrections broadcast by the base station are accurate over an area of about 1500 km or more. Typical positional degradation is approximately a few millimeters of position error per kilometer of base station and roving receiver separation.

[0442] Through the implementation of local differential GPS techniques, SA errors are reduced significantly while the atmospheric errors are almost completely removed. Ephemeris and clock errors are virtually removed as well.

[0443] Antenna Placement

[0444] A site survey of potential differential base station sites should be performed to determine a suitable location for the GPS antenna. The location should have a clear view of the sky and should not be located near potentially reflective surfaces (within about 300 meters). The antenna site should be away from potentially interfering radiation sources such as radio, television, radar and communications transmitters. After a suitable site is determined, a GPS survey should be conducted to determine the precise location of the GPS antenna—preferably to centimeter level accuracy. This should be performed using survey grade GPS equipment.

[0445] Survey grade GPS equipment makes use of the 19 and 21 centimeter wavelength of the L1 and L2 GPS transmissions. Real time kinematic or post processing GPS surveys may be conducted. Real time kinematic utilizes a base station located at a precise location which broadcasts carrier phase correction and processing data to a radio receiver and processing computer. Code, carrier integral cycles and carrier phase information are used at the survey site to calculate the WGS 84 antenna position. In the post processing survey mode, subframe information, time, code, carrier, and carrier phase data are collected for a period of time. This data is later post processed using precise ephemerides which are available from a network of international GPS sites. The collected information is then post processed with post-fit precise orbital information.

[0446] Base Station Operational Elements

[0447] The precisely surveyed location of the GPS antenna is programmed into the reference station as part of its initial installation and set up procedures. Industry standard reference stations determine pseudo range and delta range based on carrier smoothed measurements for all satellites in view. Since the exact ECEF position of the antenna is known, corrections may be generated for the pseudo range and delta range measurements and precise time can be calculated.

[0448] Naturally occurring errors are, for the most part, slow changing and monotonic over the typical periods of concern. When SA is not invoked, delta range corrections provide a valid method of improving positional accuracy at the roving receivers using less frequent correction broadcasts. With the advent of SA and its random, quick changing non-monotonic characteristics, delta range corrections become somewhat meaningless and may actually degrade the system performance under some conditions.

[0449] As shown previously in FIG. 22 the DGPS correction messages are broadcast by the reference station and received by the roving receivers. The corrections are applied directly to the differential GPS receiver. The DGPS receiver calculates the pseudo range and the delta range measurements for each satellite in the usual manner. Prior to performing the navigation solution, the received pseudo range and delta range corrections are applied to the internal measurements. The receiver then calculates corrected position, velocity and time data.

[0450] Since differential GPS eliminates most GPS errors, it provides significant improvements in system reliability for life critical airport operations. Short term and long term drift of the satellite orbits, clocks and naturally occurring phenomena are compensated for by differential GPS as are other potential GPS satellite failures. Differential GPS is mandatory in the airport environment from a reliability, accuracy and fault compensating perspective.

[0451] As with autonomous GPS receiver operation, multipath is a potential problem. The differential reference station cannot correct for multipath errors at the roving receiver(s). Antenna design and placement considerations, and receiver design characteristics remain the best solutions to date in the minimization of multipath effects.

[0452] ADS Messages

[0453] ADS messages are generated on board each vehicle and broadcast to the AC&M System. The message format is shown below:

[0454] MSG Header, Vehicle ID, Vehicle Type, ECEF X, ECEF Y, ECEF Z, ECEF X VEL., ECEF Y VEL., ECEF Z VEL. <CR><LF>

[0455] On board each vehicle, the GPS-based position and velocity data is converted to Earth Centered Earth Fixed (ECEF) coordinates for use in the navigation and zone processing algorithms if necessary. For simplicity, this format is used in the ADS transmission as well. Upon receipt of an ADS message, the AC&M Processor 115 forwards the message to the COMM Processor 116 then stores the data in the vehicle database. The stored ECEF position and velocity data is used to perform collision prediction, zone incursion, lighting control and navigation processing at the AC&M station.

[0456] ATC Messages

[0457] Air Traffic Control (ATC) messages are composed using the AC&M station. The ATC messages are used locally to control the AC&M graphics display 117 or present current status information to the user. ATC message are also broadcast to the vehicles 119 and 120 through the COMM Processor 116. All ATC messages utilize an explicit acknowledgment message. If an acknowledgment is not received within a defined time interval, the message is automatically retransmitted. The standard format is shown below.

[0458] SATC, MESSAGE TYPE, VEHICLE ID, MESSAGE DATA <CR><LF>

[0459] Error Detection and Correction
In the demonstration prototype system, Cyclical Redundancy Checking (CRC) is performed on all messages, with the exception of the [RTCM-104] differential correction messages generated in the Base Station 118. In this scheme, ADS messages are discarded if an error is detected in the received message. This has not been a significant problem for the prototype system since the next message is received in one (1.0) second. The ATC messages directed to specific vehicles also support CRC error detection. ATC messages are "addressed" to a specific A/V and expect an explicit acknowledgment. Upon receipt of an ATC message, the A/V sends back a valid "message received" acknowledgment. The ATC message is discarded by the A/V if an error is detected. In this case, no message received acknowledgment is generated. If no "message received" acknowledgment is received by the AC&M 115 within a preset time interval, the original message is immediately retransmitted. ATC messages require a corresponding acknowledgment since they may represent critical controller instructions and airport and safety operations could be compromised if the message fails to reach its destination.

The CRC system operated effectively in the demonstration prototype system, but a more robust communication error detection and correction capability may be required for end state deployment. Forward error correction and Viterbi—Trellis techniques provide a cost effective forward error correction capability. These techniques are widely used in commercial modem technology and are available in Application Specific Integrated Circuits (ASIC). Wide spread use of the technology makes it very cost effective for use in future airport communication systems.

AC&M Processor and AC&M Processing Flow

A block diagram of the AC&M Processor is provided in FIG. 23.

The AC&M Processor 121 is based on a 33 MHz 386 processor with a 387 math co-processor. This processor performs the following functions:

- Interfaces to communication digital datalinks
- Receives ADS vehicle broadcasts
- Receives acknowledgment messages from vehicles
- Generates and transmits messages to vehicles
- Performs collision prediction processing for each vehicle
- Monitors zone and runway incursion conditions
- Controls runway intersections and runway clearance lights
- Maintains and controls vehicle, waypoint and zone databases
- Performs navigational processing for on-off course checking
- Performs map layer control and assignment
- Sends vehicle reports and commands to Graphic Processor for situation display
- Provides a touch screen and keyboard command interface

Representative command functions are described in the following section.

Touch Screen

The AC&M touch screen provides an efficient means of command input for interfacing to the airport management system. The touch screen is used to perform the following high level functions:

- Command interface to the Graphics Processor
- Command interface to the AC&M Processor
- Communication interface to properly equipped vehicles and aircraft
- Display of various AC&M data lists
- Display of vehicle status information

The touch screen is organized into four discrete display areas—the Command List, the Message Composition and Response (MC&R) Window, the Alerts Window, and the Vehicle List. The following figure shows the touch screen layout used during the final demonstration. FIG. 34 depicts the touch screen with representative information.

The Command List, as shown on the right in the figure below, is used to provide key high level command functions. When a command is invoked, it is emphasized in the Command List and remains emphasized until the command is canceled or completed.

After command selection, the valid command options are displayed in the large MC&R window to the left. The MC&R window has two major functions—it is used to compose ATC messages and it is used to display information to the operator. During message composition, the MC&R window is used to prompt the operator and provide a series of options relating to the content and destination of the message. The MC&R window also serves as the display presentation medium for list displays such as the Vehicle Data display.

Critical watch and warning messages are presented to the operator in the Alerts window of the touch screen. The Alerts window displays messages generated as a result of a potential collision condition, zone incursion or off course determination.

The Vehicle List provides the operator with a list of the active vehicles. Vehicles may be selected from the list during the message composition activities.

Numerous commands have been implemented to demonstrate the capability of the touch screen data entry device. Representative command functions are described in the following section.

AC&M Command List Touch Screen

The AC&M touch screen provides an efficient means of command input for interfacing to the airport management system. The touch screen is used to perform the following high level functions:

- Command interface to the Graphics Processor
- Command interface to the AC&M Processor
[0494] Communication interface to properly equipped vehicles and aircraft
[0495] Display of various AC&M data lists
[0496] Display of vehicle status information

[0497] The touch screen is organized into four discrete display areas—the Command List, the Message Composition and Response (MC&R) Window, the Alerts Window, and the Vehicle List. The following figure shows the touch screen layout used during the final demonstration. FIG. 34 depicts the touch screen with representative information.

[0498] The Command List, as shown on the right in the figure below, is used to provide key high level command functions. When a command is invoked, it is emphasized in the Command List and remains emphasized until the command is canceled or completed.

[0499] After command selection, the valid command options are displayed in the large MC&R window to the left. The MC&R window has two major functions—it is used to compose AC&M messages and it is used to display information to the operator. During message composition, the MC&R window is used to prompt the operator and provide a series of options relating to the content and destination of the message. The MC&R window also serves as the display presentation medium for list displays such as the Vehicle Data display.

[0500] Critical watch and warning messages are presented to the operator in the Alerts window of the touch screen. The Alerts window displays messages generated as a result of a potential collision condition, zone incursion or off course determination.

[0501] The Vehicle List provides the operator with a list of the active vehicles. Vehicles may be selected from the list during the message composition activities.

[0502] Numerous commands have been implemented to demonstrate the capability of the touch screen data entry device. Representative command functions are described in the following section.

[0503] AC&M Command List

[0504] ARRIVAL WAYPOINTS

[0505] The ARRIVAL WAYPOINTS command is issued to grant a landing clearance to an approaching aircraft and provide it with a set of waypoints for the landing operation. The command is invoked by touching the ARRIVAL WAYPOINT soft function key on the AC&M touch screen.

[0506] Upon invocation, the following steps are followed:

[0507] 1. The ARRIVAL WAYPOINTS soft function key is highlighted.

[0508] 2. The list of valid vehicle ids is displayed in the VEHICLE LIST window. The user is prompted to select one of the vehicles.

[0509] 3. Upon selection of a valid vehicle, a description of each predefined arrival waypoint path is displayed in the MESSAGE COMPOSITION AND RESPONSE (MC&R) window. The user is prompted to select one of the waypoint lists.

[0510] 4. Upon selection of the waypoint list, the corresponding waypoints are drawn into the AC&M's digital map display. The user is then prompted as to whether the waypoints are correct.

[0511] 5. If the user accepts the waypoints, an AC&M message is composed and transmitted to the vehicle.

[0512] The waypoints are automatically loaded into the AC&M’s mirrored navigator. The MC&R window is cleared and a message completed indicator is displayed.

[0513] 6. If the user does not accept the waypoints, the waypoints drawn into the map display are cleared, the MC&R window is cleared and no waypoints are processed.

[0514] DEPARTURE WAYPOINTS

[0515] The DEPARTURE WAYPOINTS command is issued to grant a takeoff clearance to a departing aircraft and provide it with a set of waypoints for the operation. The command is invoked by touching the DEPARTURE WAYPOINT soft function key on the AC&M touch screen.

[0516] Upon invocation, the following steps are followed:

[0517] 1. The DEPARTURE WAYPOINTS soft function key is highlighted.

[0518] 2. The list of valid vehicle ids is displayed in the VEHICLE LIST window. The user is prompted to select one of the vehicles.

[0519] 3. Upon selection of a valid vehicle, a description of each predefined departure waypoint path is displayed in the MESSAGE COMPOSITION AND RESPONSE (MC&R) window. The user is prompted to select one of the waypoint lists.

[0520] 4. Upon selection of the waypoint list, the corresponding waypoints are drawn into the AC&M's digital map display. The user is then prompted as to whether the waypoints are correct.

[0521] 5. If the user accepts the waypoints, an AC&M message is composed and transmitted to the vehicle. The waypoints are automatically loaded into the AC&M’s mirrored navigator. The MC&R window is cleared and a message completed indicator is displayed.

[0522] 6. If the user does not accept the waypoints, the waypoints drawn into the map display are cleared, the MC&R window is cleared and no waypoints are processed.

[0523] SURFACE WAYPOINTS

[0524] The SURFACE WAYPOINTS command is issued to grant a ground clearance to an aircraft or surface vehicle and provide it with a set of waypoints for the operation. The command is invoked by touching the SURFACE WAYPOINT soft function key on the AC&M touch screen.

[0525] Upon invocation, the following steps are followed:

[0526] 1. The SURFACE WAYPOINTS soft function key is highlighted.

[0527] 2. The list of valid vehicle ids is displayed in the VEHICLE LIST window. The user is prompted to select one of the vehicles.
3. Upon selection of a valid vehicle, a description of each predefined surface waypoint path is displayed in the MESSAGE COMPOSITION AND RESPONSE (MC&R) window. The user is prompted to select one of the waypoint lists.

4. Upon selection of the waypoint list, the corresponding waypoints are drawn into the AC&M’s digital map display. The user is then prompted as to whether the waypoints are correct.

5. If the user accepts the waypoints, an ATC message is composed and transmitted to the vehicle. The waypoints are automatically loaded into the AC&M’s mirrored navigator. The MC&R window is cleared and a message completed indicator is displayed.

6. If the user does not accept the waypoints, the waypoints drawn into the map display are cleared, the MC&R window is cleared and no waypoints are processed.

CLEAR PATH WAYPOINTS

The CLEAR PATH WAYPOINTS command is issued to manually end a previously granted clearance and clear any pending waypoints for a specific vehicle. The command is invoked by touching the CLEAR PATH WAYPOINTS soft function key on the AC&M touch screen.

Upon invocation, the following steps are followed:

1. The CLEAR PATH WAYPOINTS soft function key is highlighted.

2. The list of valid vehicle ids is displayed in the VEHICLE LIST window. The user is prompted to select one of the vehicles.

3. Upon selection of a valid vehicle, a clear waypoints command is issued to the vehicle, clearing its remaining waypoints. Similarly, the clearance status and waypoints at the AC&M system are cleared as well.

AIRPORT LIGHTS

The AIRPORT LIGHTS command is issued to manually change the status of a specific set of runway approach, departure or intersection lights. The command is invoked by touching the AIRPORT LIGHTS soft function key on the AC&M touch screen.

Upon invocation, the following steps are followed:

1. The AIRPORT LIGHTS soft function key is highlighted.

2. Each lighting system and its current status (ON or OFF) is displayed in the MC&R window. The user is prompted to select the desired light(s) from the window.

3. Upon selection of a set of lights, the status is toggled and the corresponding lights on the map lighting board are changed accordingly.

VEHICLE FILTER

The VEHICLE FILTER command is issued to enable or suppress the display of a particular type of vehicle by altering the status of its graphic layer. The command is invoked by touching the VEHICLE FILTER soft function key on the AC&M touch screen.

Upon invocation, the following steps are followed:

1. The VEHICLE FILTER soft function key is highlighted.

2. The current vehicle types are displayed in the MC&R window with the current filter status (ON or OFF) as shown:

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited Access Area</td>
<td>ON</td>
</tr>
<tr>
<td>Ground Vehicle</td>
<td>ON</td>
</tr>
<tr>
<td>Emergency/Service Ground</td>
<td>ON</td>
</tr>
<tr>
<td>Aircraft</td>
<td>ON</td>
</tr>
<tr>
<td>Arrival</td>
<td>ON</td>
</tr>
<tr>
<td>Departure</td>
<td>ON</td>
</tr>
<tr>
<td>All Vehicles</td>
<td>ON</td>
</tr>
</tbody>
</table>

3. The user has the capability to suppress and re-enable various vehicle types by selecting it from the MC&R window.

4. Upon selection, the user is prompted to accept the command. If the command is selected, the vehicle type’s status is toggled and the vehicle is either suppressed from the map display or re-displayed if previously suppressed.

Vehicle types which are suppressed are not displayed on the AC&M graphics display unless they are in a collision or zone incursion condition.

5. If NO is selected, the vehicle type’s status remains unchanged.

LAYER FILTER

The LAYER FILTER command is issued to manually change the status of a specific graphic layer. Layers which are masked are no longer displayed. The command is invoked by touching the LAYER FILTER soft function key on the AC&M touch screen.

Upon invocation, the following steps are followed:

1. The LAYER FILTER soft function key is highlighted.

2. The current LAYER types are displayed in the MC&R window with the current filter status (ON or OFF) as shown:

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Rings</td>
<td>ON</td>
</tr>
<tr>
<td>Range Rings, 5 Mile Increments</td>
<td>ON</td>
</tr>
<tr>
<td>Airport Lighting Systems</td>
<td>OFF</td>
</tr>
<tr>
<td>Airport Lighting Systems</td>
<td>OFF</td>
</tr>
<tr>
<td>Trackable Surface Veh (Limited Access)</td>
<td>ON</td>
</tr>
<tr>
<td>Trackable Surface Veh (Full Access)</td>
<td>ON</td>
</tr>
<tr>
<td>Trackable Departure Aircraft</td>
<td>ON</td>
</tr>
<tr>
<td>Trackable Arrival Aircraft</td>
<td>ON</td>
</tr>
<tr>
<td>Arrival Waypoints</td>
<td>OFF</td>
</tr>
<tr>
<td>Departure Waypoints</td>
<td>OFF</td>
</tr>
<tr>
<td>Surface Waypoints</td>
<td>OFF</td>
</tr>
<tr>
<td>Custom Waypoints</td>
<td>OFF</td>
</tr>
<tr>
<td>Airport Surface Zones</td>
<td>OFF</td>
</tr>
<tr>
<td>Weight Limited Zones</td>
<td>OFF</td>
</tr>
<tr>
<td>Restricted Travel Area</td>
<td>OFF</td>
</tr>
</tbody>
</table>
3. The user has the capability to suppress and re-enable various layers by selecting it from the MC&R window.

4. Upon selection, the user is prompted to accept the command. If the command is selected, the layer’s status is toggled and the layer is either suppressed from the map display or re-displayed if previously suppressed.

Vehicle types which are suppressed are not displayed on the AC&M graphics display unless they are in a collision or zone incursion condition. Special category, watch or warning layers are never suppressed.

5. If NO is selected, the layer’s status remains unchanged.

VEHICLE DATA

The VEHICLE DATA command is issued to display status information for a particular vehicle. The vehicle data is displayed in the MC&R window. The command is invoked by touching the VEHICLE DATA soft function key on the AC&M touch screen. Upon invocation, the following steps are followed:

1. The VEHICLE DATA soft function key is highlighted.

2. The list of valid vehicle ids is displayed in the VEHICLE LIST window. The user is prompted to select one of the vehicles.

3. Upon selection of a valid vehicle, data corresponding to that vehicle is displayed in the MC&R window. The data is updated automatically as the vehicle’s ADS messages are received at the AC&M. The data includes the vehicle id, tag, type, minimum safe distance for collision processing, heading and speed. If the vehicle has been assigned waypoints the current waypoint, 3-D range and cross track error are also displayed. The vehicle data remains displayed until another soft function key is invoked.

DISPLAY VIEW

The DISPLAY VIEW command is issued to change the display view presented on the situation display. The command is invoked by touching the DISPLAY VIEW soft function key on the AC&M touch screen.

Upon invocation, the following steps are followed:

1. The DISPLAY VIEW soft function key is highlighted.

2. Upon invocation, the following display view options are displayed in the MC&R window:

| VIEW ID | DESCRIPTION
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>PLAN VIEW 10 MILE RANGE</td>
</tr>
<tr>
<td>01</td>
<td>PLAN VIEW 5 MILE RANGE</td>
</tr>
<tr>
<td>02</td>
<td>PLAN VIEW 1 MILE RANGE</td>
</tr>
<tr>
<td>03</td>
<td>PLAN VIEW .5 MILE RANGE</td>
</tr>
<tr>
<td>04</td>
<td>RUNWAY 35</td>
</tr>
<tr>
<td>05</td>
<td>RUNWAY 17</td>
</tr>
<tr>
<td>06</td>
<td>RUNWAY 24</td>
</tr>
<tr>
<td>07</td>
<td>RUNWAY 06</td>
</tr>
<tr>
<td>08</td>
<td>GATE AREA</td>
</tr>
<tr>
<td>09</td>
<td>FIRE, CRASH AND RESCUE</td>
</tr>
<tr>
<td>10</td>
<td>TERMINAL BUILDING</td>
</tr>
<tr>
<td>11</td>
<td>3D VIEW RUNWAY 35</td>
</tr>
<tr>
<td>12</td>
<td>3D VIEW RUNWAY 17</td>
</tr>
<tr>
<td>13</td>
<td>3D VIEW RUNWAY 24</td>
</tr>
<tr>
<td>14</td>
<td>3D VIEW RUNWAY 06</td>
</tr>
<tr>
<td>15</td>
<td>APPROACH VIEW RUNWAY 35</td>
</tr>
<tr>
<td>16</td>
<td>APPROACH VIEW RUNWAY 17</td>
</tr>
<tr>
<td>17</td>
<td>APPROACH VIEW RUNWAY 24</td>
</tr>
<tr>
<td>18</td>
<td>APPROACH VIEW RUNWAY 06</td>
</tr>
</tbody>
</table>

Airport lighting control techniques are provided as a demonstration mechanism and are not intended to dictate a specific lighting scheme for airports.
Situation Display

A vehicle database is maintained by the AC&M and on board 'fully equipped' vehicles to provide a situational awareness capability to the controller and/or vehicle operator. GPS-based situational awareness requires the integration of a datalink between the aircraft, surface vehicles and the AC&M system. In the demonstration prototype system, the position and velocity information determined on board each vehicle is broadcast over and experimental VHF datalink and received by the AC&M. At the AC&M, the message is assembled into a dynamic vehicle database. As each ADS message is received, the following fields in the vehicle database are updated:

- Vehicle 1
- Vehicle Type
- Position (ECEF X,Y,Z)
- Velocity (ECEF X,Y,Z)

In order to present the vehicle position data graphically, the following information is also maintained in the vehicle database:

- Layer ID
- Vehicle Color

Each vehicle is assigned a map layer based on vehicle type. The digital airport map features numerous object oriented layers which are used to segregate various types of graphical information. By assigning vehicles to specific map layers, spatial filtering may be performed on a layer by layer basis. Color may be assigned by layer or by individual vehicle.

Position reporting functions operating on a moving platform potentially suffer from a positional error introduced by processing time. To compensate for this factor, the precise DGPS derived ECEF velocity components are used to project the position ahead. As each ADS message is received, a latency compensation time projection factor is applied in an ECEF Velocity x Time relationship. The new, projected ECEF position is then considered the current position, is stored in the vehicle database and is used throughout the navigation and collision prediction algorithms.

Once the dynamic vehicle database is constructed, a sequential scanning of the database is performed as new ADS position reports are received. Vehicles outside of the defined range are filtered out. Vehicles within range are displayed in the 3-D airport map. In this manner, graphical situational awareness is provided at the AC&M and on board the vehicles/aircraft.

Collision Prediction Processing

As ADS messages are received, collision prediction processing is performed using the current GPS data and the information stored in the vehicle database. The following database fields are used in the collision prediction processing:

- Collision Time
- Collision Count
- Collision Condition
- Collision Separation
- Radius

A 'rough check' is performed to determine if there are any vehicles in the immediate vicinity of the current vehicle. The current vehicle's position is projected ahead using a defined MAXIMUM_PROJECTION_FACTOR. The vehicle database is sequentially scanned. The position of the first vehicle in the database is projected ahead in the same manner. If the projected positions intersect, further collision checking is performed.

When further collision checking is warranted, the current vehicle's position is projected ahead by incrementing time in one second intervals. At each interval, an imaginary sphere is drawn around the vehicle using a predefined radius based on the vehicle's minimum safe separation. Similarly, the position of the next vehicle in the database is projected ahead. If the two imaginary spheres intersect and the time interval of the intersection is less than or equal to the MINIMUMWARNING_TIME factor, a collision warning condition is generated. If the two imaginary spheres intersect at a time interval greater than the MINIMUM WARNING_TIME but less than the MINIMUM WATCH_TIME, a collision watch condition is generated.

If a collision watch condition is generated, the vehicles in the watch condition are displayed in YELLOW on the AC&M map display. A warning message is displayed to the operator in the Alerts window of the touchscreen. If a warning condition is detected, the vehicle's symbol is displayed in RED on the graphics screen and a warning message is displayed in the Alert window.

During any collision condition, the vehicle's symbol is moved to a dedicated watch or warning map layer. These layers are reserved for critical operations and cannot be suppressed by the user.

The following collision data was generated from actual collision tests and represents two surface vehicles driving towards each other. During this test scenario, the following factors were used:

| MINIMUM_WARNING_TIME | 3 seconds |
| MINIMUM WATCH_TIME | 7 seconds |
| RADIUS, VEHICLE 03 | 7 meters |
| RADIUS, VEHICLE 04 | 7 meters |

Note that a COLLISION WATCH is detected when the distance between the two vehicles is less than the sum of its radii. A COLLISION WARNING is detected when the intersection occurs within the MINIMUM WARNING_TIME of 3 seconds or less. Also note that as soon as the vehicles pass one another and the distance between them begins to increase, no WATCH or WARNING condition is detected.
<table>
<thead>
<tr>
<th>Time (SEC)</th>
<th>VEH-03 DIST</th>
<th>VEH-04 DIST</th>
<th>Collision Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74.9</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>64.7</td>
<td>49.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>54.5</td>
<td>49.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>44.3</td>
<td>39.2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>34.2</td>
<td>29.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>Collision Watch</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8.9</td>
<td>43.4</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>64.1</td>
<td>33.1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>53.7</td>
<td>22.8</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>12.7</td>
<td></td>
<td>Collision Watch</td>
</tr>
<tr>
<td>12</td>
<td>59.1</td>
<td>48.6</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>38.1</td>
<td>27.6</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>17.1</td>
<td>7.0</td>
<td>Collision Watch</td>
</tr>
<tr>
<td>15</td>
<td>53.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>Collision Warning</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>Collision Warning</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>Collision Warning</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>Collision Warning</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>Collision Warning</td>
</tr>
</tbody>
</table>
[0647] VEH=03 DIST=5.9 PROJ TIME=1 SECONDS COLLISION WARNING

[0648] VEH=04 DIST=2.9 PROJ TIME=1 SECONDS COLLISION WARNING

[0649] DIST=5.4, VEHICLE SEPARATION IS INCREASING, STOP PROCESSING . . .

[0650] Zone Incursion Processing

[0651] A 3-D map database and ECEF mathematical processing algorithms support the concept of zones. Zones are three dimensional shapes which are used to provide spatial cueing for a number of constructs unique to DSDC’s demonstration system. Zones may be defined around obstacles which may pose a hazard to navigation, such as transmission towers, tall buildings, and terrain features. Zones may also be keyed to the airport’s NOTAMS, identifying areas of the airport which have restricted usage.

[0652] Zones are represented graphically on the map display and mathematically by DSDC’s zone processing algorithms. Multi-sided zones are stored in a zone database as a series of points. Each zone is assigned a zone id and type. The zone type is used to determine whether a particular zone is off-limits for a specific vehicle type.

[0653] Zone information is maintained in the zone database. A zone incursion status field is also maintained for the vehicle in the vehicle database. If the vehicle is currently inside a zone, this field is used to store the zone’s id. If the vehicle is not inside a zone, this field is zero (0).

[0654] At the A&C&M, zone incursion processing is performed in a manner similar to the collision processing described previously. As each vehicle report is received, it is projected ahead by incrementing time up to a MAX_ZONE_PROJECTION_FACTOR. At each interval, the vehicle’s projected position is compared to each line of the zone as defined by its endpoints. If the vehicle’s position is inside all of the lines comprising the zone and the current projection time is less than the MIN_ZONE_WARNING factor, a zone incursion warning is generated. If the vehicle’s position is inside the zone and the current projection time is less than the MIN_ZONE_WATCH factor but greater than the MIN_ZONE_WARNING factor, a zone incursion watch is generated. As in the collision processing, a zone incursion watch or warning will result in a message displayed to the operator and a change in layer assignments for the affected vehicle.

[0655] A zone incursion condition is automatically cleared when the vehicle exits the zone. All zones are defined as 3-dimensional entities and may be exited laterally or vertically. Heights may be assigned to ‘surface’ zones individually or collectively. The concepts of 3-dimensional zones is critical to an airport environment to prevent passing aircraft from triggering ground-based zones.

[0656] Runway Incursion Processing

[0657] If a zone incursion is detected, a further check is performed to determine if the vehicle is entering or inside a runway zone. For Manchester Airport, five (5) runway zones have been defined:

[0658] RNWY_35_ZONE
[0659] RNWY_17_ZONE
[0660] RNWY_24_ZONE
[0661] RNWY_06_ZONE
[0662] RNWY_INT_ZONE “RUNWAY INTER-SECTION VOLUME”

[0663] An additional field is maintained in the vehicle database to indicate whether a runway incursion state has been detected. As with the zone incursion field, the runway incursion value is set to the id of the zone (i.e., the runway) if an incursion is currently occurring and is set to zero (0) if there is no runway incursion.

[0664] If the vehicle is entering or inside a runway zone and is not cleared for that zone, a runway incursion condition is generated at the A&C&M. As in any zone incursion situation, a watch or warning message is displayed in the A&C&M Alerts window and the vehicle’s symbol is moved to the dedicated watch or warning map layer, changing its color to YELLOW or RED. In addition, the runway incursion results in a status change in the runway’s landing, takeoff and intersection lights forcing the lights to flash on the affected (and related) runway(s). The following table describes the lighting states for runway incursions in each of the five runway zones.

<table>
<thead>
<tr>
<th>ACTIVITY DESCRIPTION</th>
<th>RNWY 35</th>
<th>RNWY 17</th>
<th>RNWY 24</th>
<th>RNWY 06</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCURSION - RNWY 35</td>
<td>FLASH</td>
<td>FLASH</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
</tr>
<tr>
<td>INCURSION ENDS</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
</tr>
<tr>
<td>INCURSION - RNWY 17</td>
<td>FLASH</td>
<td>FLASH</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
</tr>
<tr>
<td>INCURSION ENDS</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
</tr>
<tr>
<td>INCURSION - RNWY 24</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
<td>Flash</td>
<td>Flash</td>
</tr>
<tr>
<td>INCURSION ENDS</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
</tr>
<tr>
<td>INCURSION - RNWY 06</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
<td>FLASH</td>
<td>FLASH</td>
</tr>
<tr>
<td>INCURSION ENDS</td>
<td>NO CHANGE</td>
<td>NO CHANGE</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
</tr>
<tr>
<td>INCURSION - INTERSECTION</td>
<td>FLASH</td>
<td>FLASH</td>
<td>Flash</td>
<td>Flash</td>
</tr>
<tr>
<td>INCURSION ENDS</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
<td>DEFAULT</td>
</tr>
</tbody>
</table>

KEY:
A = APPROACH LIGHTS     FLASH = RED/GREEN DEFAULT = RED
D = DEPARTURE LIGHTS    FLASH = RED/GREEN DEFAULT = RED
I = INTERSECTION LIGHTS  FLASH = RED/OFF DEFAULT = OFF
A runway incursion is automatically terminated when the incurring vehicle exits the runway. When the incursion condition is terminated, the lights on the affected runway return to their default state. As in all zone definitions, runway zones are 3-dimensional entities. Runway zones are assigned a height of approximately 100 meters above the surface of the runway in the prototype demonstration system. Therefore, a runway incursion occurs only when an uncleared vehicle enters the zone at the surface level. Demonstration prototype lighting software is provided below:

Lighting Control Software Example

```c
#include <stdio.h> /* standard input/output */
#include <math.h> /* MSC math library */
#include <string.h> /* MSC string routines */
#include <stdlib.h> /* MSC standard library */

#define LIGHT_ADDR 0x000 /* address of digital I/O board */
#define LANDING_35 0x01
#define LANDING_17 0x02
#define LANDING_24 0x04
#define LANDING_06 0x08
#define TAKEOFF_17 0x10
#define TAKEOFF_06 0x20
#define TAKEOFF_35 0x40
#define TAKEOFF_24 0x80

#define NO_ACTIVITY 0
#define RUNWAY_INCURSION 1
#define LANDING 2
#define TAKEOFF 3
#define SURFACE 5

void store_wps(char wp_id[12], int wp[index]);
extern VEHICLE_DATA veh[MAX_VEH]; /* vehicle database */

FILE *
initialize_lights()

initialize_lights(NO_ACTIVITY,RNWAY_35);
update_lights(NO_ACTIVITY,RNWAY_17);
```
UNIT: update_lights
DESCRIPTION: this routine resets the lights on the specified runway.

update_lights(int activity_type, int rnwy)
{
    switch (rnwy)
    {
        case RNWY_35 : case RNWY_17 :
            switch (activity_type)
            {
                case NO_ACTIVITY :
                    curr_lights = curr_lights & 0xCAC;
                    break;
            }
            break;
        case RNWY_24 :
            case RNWY_06 :
                switch (activity_type)
                {
                    case NO_ACTIVITY :
                        curr_lights = curr_lights & 0x53;
                        break;
                }
                break;
        case RNWY_INT :
            switch (activity_type)
            {
                case NO_ACTIVITY :
                    curr_lights = 0;
                    break;
            }
            break;
    } /* write new light settings to board */
    output(LIGHT__ADOR,curr_lights);
}

UNIT: update_clearance_lights
DESCRIPTION: this routine updates the specified clearance lights for a landing or takeoff operation. The landing/ takeoff light for the specified runway is enabled, then the remaining landing/takeoff lights for both runway ends are disabled.

update_clearance_lights(short curr_clear)
{
    /* based on current clearance, affected runway and the current status of the runway’s lights, update the lights */
    switch (curr_clear)
    {
        case LANDING_35 :
        case LANDING_17 :
        case LANDING_24 :
        case LANDING_06 :
            if (((curr_lights & LANDING_35) == 0)
                curr_lights = curr_lights + LANDING_35;
        case LANDING_35 :
        case LANDING_17 :
        case LANDING_24 :
        case LANDING_06 :
            if (((curr_lights & LANDING_06) == 0)
                curr_lights = curr_lights + LANDING_06;
        case TAKEOFF_35 :
            if (((curr_lights & TAKEOFF_35) == 0)
                curr_lights = curr_lights + TAKEOFF_35;
        break;
    } /* write new light settings to board */
}
case TAKEOFF_17:
    if ((curr_lights & TAKEOFF_17) == 0)
        curr_lights = curr_lights + TAKEOFF_17;
    break;

// Added the comment after the case statement.

UNIT: get_runway_clear
DESCRIPTION: determines the landing or takeoff flag setting
INPUTS: int rw_id - id of runway
        char *msg_type - arrival or takeoff

int get_runway_clear(int rw_id, char *msg_type) {
    int clear_stat; /* clear status */
    if (strlen(msg_type) > 0) {
        switch (rw_id) {
        case RNWY_35:
            if (strcmp(msg_type, "ARR") == 0)
                clear_stat = LANDING_35;
            else
                clear_stat = TAKEOFF_35;
            break;
        case RNWY_17:
            if (strcmp(msg_type, "ARR") == 0)
                clear_stat = LANDING_17;
            else
                clear_stat = TAKEOFF_17;
            break;
        case RNWY_24:
            if (strcmp(msg_type, "ARR") == 0)
                clear_stat = LANDING_24;
            else
                clear_stat = TAKEOFF_24;
            break;
        case RNWY_06:
            if (strcmp(msg_type, "ARR") == 0)
                clear_stat = LANDING_06;
            else
                clear_stat = TAKEOFF_06;
            break;
        default:
            clear_stat = SURFACE;
        }
    return(clear_stat);
}

UNIT: process_clearance
for arrival (landing) waypoints and
ATC,004 veh id, waypoint id
for departure (takeoff) waypoints
INPUTS: char clearance_msg[MAX_STR]

process_clearance(char clearance_msg[MAX_STR]) {
    /* Local variables */
    char wp_id[12]; /* waypoint id */
    char *token; /* character field from ATC msg */
    int rw_id; /* id of runway cleared for operation */
    int veh_index; /* index into veh database for current veh */
    int slen; /* string length */
}
DESCRIPTION: process_clearance parses the clearance or departure message issued by the controller via the touch screen. update_clearance_lights is then called to change the specified light settings.

The message format is: SATC.002,veh id,waypoint id

If the vehicle is entering or inside a runway zone and the vehicle has a clearance, a runway incursion is not detected. A clearance is issued by the AC&M operator using the ARRIVAL WAYPOINTS, DEPARTURE WAYPOINTS or SURFACE WAYPOINTS functions.

When a clearance is issued, a global CURRENT_CLEARANCE flag is updated. The CURRENT_CLEARANCE flag is used to maintain the current airport light settings. A separate clearance status flag is also maintained in the vehicle database for each vehicle. As the vehicle approaches a runway zone, its clearance status flag is read to determine whether a runway incursion condition should be generated. Clearances are terminated automatically when the vehicle reaches the last waypoint. Clearances may also be manually cleared by the AC&M operator through the CLEAR PATH WAYPOINTS function. When the clearances are terminated, the global CURRENT_CLEARANCE flag and individual vehicle clearance flags are updated.

ECEF Waypoint Navigation

After waypoints have been issued to a vehicle or vehicles, the AC&M performs a set of navigation functions, mirroring those performed on board the vehicle using the ADS position reports. A set of waypoints is maintained for each cleared vehicle. The vehicle’s current 3-D range to the waypoint and cross track error is computed for each subsequent ADS report. A determination is made as to whether the vehicle is on or off course is also made. If an off course condition is detected, a warning message is displayed to the operator in the AC&M’s Alerts window.

To support the AC&M’s mirrored navigation processing, the following fields are maintained in the vehicle database:

Waypoint Index
Current Waypoint
Cross Track Error
3D Range to Waypoint
Wrong Way Indicator

The Waypoint Index is the ID of the waypoint list assigned to the vehicle and the Current Waypoint is the waypoint the pilot is navigating towards.

At any time after the assignment of waypoints to the vehicle, the vehicle’s 3-D range to the waypoint, cross-track error, current waypoint, speed and heading information may be displayed in the MC&R window using the VEHICLE DATA function.

Graphics Processor and AC&M Interface

The Graphics Processor (GP) 122 interfaces to the AC&M Processor 121 via a dedicated communication link 123. The GP is currently based on a 66 MHz 486 processor with a VESA Video Local Bus. This processor performs the following functions:

- Receives graphics commands from AC&M
- Interprets graphics commands
- Performs the graphic display functions
- Provides situational awareness capability
- Manages the view and content of the display presentation
- Maintains local map-based waypoint, zone and map layer databases
- Interface with large graphics display hardware

Two types of messages are received by the GP:

1. Vehicle position messages
2. Display commands

Upon receipt of an ADS report, the AC&M Processor converts the vehicle’s ECEF X,Y,Z position to the map’s coordinate system if required and determines the appropriate map layer for the vehicle based on the vehicle’s type and any collision or zone incursion conditions. If the vehicle is moving, the newly formatted message is sent to the GP. Stationary vehicle’s are not redisplayed in the map but remain displayed in their last reported position. The message format is shown below:

```
STRK,vehicle id,map layer,map x, map y, mapz coordinates<CR><LF>
```

Display commands are also generated by the AC&M Processor 121 and sent to the GP 122. Numerous AC&M commands, including ARRIVAL WAYPOINTS, DEPARTURE WAYPOINTS, SURFACE WAYPOINTS, CLEAR PATH WAYPOINTS, DISPLAY VIEW, VEHICLE FILTER and LAYER FILTER affect the display presentation on the GP. An acknowledgment is returned to the AC&M Processor 121 when a display command message is received by the GP 122.

Layer Assignments

The GP 122 supports up to 256 unique layers which are used for the display and segregation of graphic information. The layer assignments are provided below:

<table>
<thead>
<tr>
<th>MAP LAYER ASSIGNMENTS</th>
<th>LAYER #</th>
<th>DESCRIPTION</th>
<th>MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>AIRPORT MAP, RUNWAYS, TAXIWAYS, TRAVEL PATHS</td>
<td>ALWAYS</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>RANGE RINGS</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RANGE RINGS, 5 MILE INCREMENTS</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>6-8</td>
<td>EXPANSION</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>AIRPORT LIGHTING SYSTEMS (RUNWAY 35)</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>AIRPORT LIGHTING SYSTEMS (RUNWAY 24)</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>TRACKED SURFACE VEHICLES (LIMITED ACCESS)</td>
<td>ALWAYS</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>TRACKED SURFACE VEHICLES (FULL ACCESS)</td>
<td>ALWAYS</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>TRACKED DEPARTURE AIRCRAFT</td>
<td>ALWAYS</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>TRACKED ARRIVAL AIRCRAFT</td>
<td>ALWAYS</td>
<td></td>
</tr>
<tr>
<td>15-19</td>
<td>EXPANSION</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>ARRIVAL WAYPOINTS</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>DEPARTURE WAYPOINTS</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>SURFACE WAYPOINTS</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>CUSTOM WAYPOINTS DEFINITION</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>EXPANSION</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>AIRPORT SURFACE ZONES</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>WEIGHT LIMITED ZONES</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>RESTRICTED TRAVEL AREA (WINGSPAN, ETC.)</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>AIRSPACE HAZARD ZONES</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>OPEN CONSTRUCTION ZONES</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>CLOSED CONSTRUCTIONS ZONES</td>
<td>ON DEMAND</td>
<td></td>
</tr>
<tr>
<td>31-60</td>
<td>EXPANSION</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>WATCH LAYER (COLOR = YELLOW)</td>
<td>ALWAYS</td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>WARNING LAYER (COLOR = RED)</td>
<td>ALWAYS</td>
<td></td>
</tr>
</tbody>
</table>
Vehicles

[0697] AC&M System Functional Matrix

[0698] Many of the functions performed at the AC&M Processor are also performed on board the vehicles. Three vehicles, equipped with varying configurations of hardware and software, have been used in a number of prototype demonstrations. The matrix below lists the major functions and the vehicles on which they are performed.

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>AC&amp;M</th>
<th>AIRCRAFT 1</th>
<th>FULL ACCESS VEHICLE</th>
<th>LIMITED ACCESS VEHICLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receive &amp; process DGPS corrections</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Formats and transmits ADS posi &amp; vel. data</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Receives remote ADS messages</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Displays ADS positions in map display</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Performs dynamic collision processing</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Performs zone incursion processing</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Performs runway incursion processing</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Controls airport lights</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Receives ATC commands</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Performs waypoint navigation</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Displays current position in moving map display</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

[0699] Hardware block diagrams for each of the three prototype vehicle types are provided in the figures which follow, starting with the Aircraft System FIG. 24.

[0700] Differential GPS data is provided by a GPS GOLD DGPS receiver 124 and a differential data link 125. GPS position, velocity, and time information is supplied to the dual 486 based processing unit. The first 486 processor, or Navigation (NAV) Processor 126, receives GPS Receiver 124 information and performs the following functions:

[0701] Coordinate conversions from Lat/Lon/MSL to ECEF X, Y, Z
[0702] Position projections
[0703] Zone and runway incursion checking
[0704] Map layer control
[0705] General ECEF waypoint navigation and on/off course processing
[0706] ECEF-based precision landing navigation
[0707] Access to waypoint and zone databases
[0708] Transmission of graphic instructions to second 486 processor 127
[0709] Broadcast of position and velocity data over ADS datalink 128
[0710] Control of communication digital datalinks

[0711] Support for monochrome flat panel display 129

[0712] The second 486 processor, the Aircraft Graphics Processor (AGP) 127, receives graphics instructions from the NAV Processor 126 and performs the following functions:

[0713] Graphics command translations and interpretations
[0714] Graphic display functions
[0715] Display presentation view and content management
[0716] Support for monochrome flat panel display 130

[0717] The functions supported in the aircraft are actually a slightly modified version of those performed by the AC&M Subsystem. The use of common hardware and operational software elements simplified the prototype demonstration development efforts.

[0718] The full access surface vehicle (Vehicle #1) high level block diagram is provided in FIG. 25.

[0719] Again, differential GPS data is provided by a DGPS receiver 131 and a differential data link 132. GPS position, velocity, and time information are supplied to the dual 486 based processing unit. The first 486 processor, the Navigation Processor (NAV) 133, receives GPS information and performs the following functions:

[0720] Coordinate conversions from Lat/Lon/MSL to ECEF X, Y, Z
[0721] Position projections
[0722] Collision prediction processing
[0723] Zone and runway incursion checking
[0724] Layer control
[0725] General ECEF waypoint navigation (optional)
[0726] Access to vehicle, waypoint and zone databases
[0727] Transmission of graphic instructions to second 486 processor 134
[0728] Broadcast of position and velocity data over ADS datalink 135
[0729] Receipt of remote ADS messages from other vehicles
[0730] Control of communication digital datalinks
[0731] Support for flat panel LCD display

[0732] The second 486 processor, the Vehicle Graphics Processor (VGP) 134 receives graphics instructions from the NAV Processor 133 and performs the following functions:

[0733] Graphics command translations and interpretations
[0734] Graphic display functions
[0735] Situational awareness capability
[0736] Display presentation view and content management
The functions supported in the full access surface vehicle are identical to those performed in the aircraft with a couple of additions. The full access vehicle receives remote ADS messages from other vehicles operating within the airport space envelope. This information is used to provide a situational awareness capability on board the vehicle. Full collision detection processing is also implemented.

The limited access surface vehicle (Vehicle #2) is equipped with developed hardware and software as shown in FIG. 26.

Since no graphic display is provided on Vehicle #2, a single 386-based processor 137 is utilized. Again, differential GPS data is provided by an on board DGPS receiver 138 and a differential data link 139. GPS position, velocity, and time information is supplied to the 386 based processing unit 137 which performs the following functions:

- Coordinate conversions from Lat/Lon/MSL to ECEF X, Y, Z
- Zone and runway incursion checking
- Access to zone database
- Sounds audible warning when zone incursion is detected
- Broadcast of position and velocity data over ADS datalink

The functions supported in Vehicle #2 are actually a subset of those supported in the aircraft and Vehicle #1.

Communications

Each vehicle is equipped with a VHF/UHF radio capable of full duplex communications. The radio interfaces to an integrated modem/GPS interface card. The radio modem is used to receive differential corrections, ADS messages, and ATC command messages forwarded by the COMM Processor. Local GPS messages are received by the vehicle’s Navigation (NAV) processor. The GPS position and velocity data is converted to the ECEF coordinate frame, reformatted and transmitted to the AC&M Processor over the same radio.

Navigation Processor and Navigation

Navigation functions are performed on board the vehicle when waypoints are received from the AC&M Processor via the VHF datalink. Two navigation screens are provided, a cross hairs display for airborne applications and a map-based display for ground operations.

Upon receipt of the waypoint message from the AC&M Processor, the waypoint id is extracted and used to identify the predefined waypoint path. The waypoints are automatically loaded into the vehicle’s ECEF navigation system and drawn into the vehicle’s map display. FIG. 27 shows the airborne navigation display produced with the previously listed software routines.

The navigator display format is unique since it provides conventional course, bearing and range information and actual position with respect to the true course. The display portion on the right side of the screen is driven by NEU surface parameters while the display at the left is driven directly by ECEF X, Y, Z parameters. This display format may be used for all phases of flight.

The algorithms for 3-D range to the waypoint, transitioning to the next waypoint, cross track error, on/off course and wrong way determination are identical to those performed at the AC&M Processor.

For ground taxi operations, map-based waypoint navigation was found to be preferable. FIG. 8 shows a waypoint path from the Crash, Fire and Rescue (CFR) Station to the East Terminal Ramp drawn in the on board digital map display.

FIG. 9 depicts the predefined waypoint path for a departure on Runway 35.

Zones Processing

All surface vehicles are capable of performing static zone incursion processing. The zone processing algorithms are identical to those implemented at the AC&M system with the addition of an audible tone generated when an incursion occurs.

Collision Detection Processing

The fully equipped vehicle (FEV) is capable of performing collision prediction processing based on the vehicle’s current position (and velocity) and the remote vehicles’ ADS messages.

As the ADS messages are received, they are parsed and stored in the local vehicle database. Collision processing is performed each second, upon receipt of the FEV’s GPS position and velocity data. After each GPS update, predictions are performed on the FEV’s current position and compared to the projected positions for each vehicle stored in the local database. In the same manner as described for the AC&M Processor, potential collision watch and warning conditions are detected between the FEV and other vehicles. However, collisions between two remote vehicles are not detected. Collisions tests are only performed with respect to the FEV itself and those in its vicinity.

Graphic Processor and Moving Map Display

Both the FEV and the aircraft are capable of displaying their current position with respect to an on board moving map display. As the vehicle’s position approaches the edge of the map display, the map is automatically panned and redrawn with the vehicle centered in the display. When the vehicle is on the airport surface, the map is drawn with a north orientation at a 0.25 mile plan view perspective. When the vehicle is more than one mile from the center of the map, the map is automatically redrawn at a ten (10) mile scale.

Situation Awareness

The FEV is capable of displaying the positions of remote vehicle positions in the on board moving map display. As ADS messages are received from the COMM Processor, the remote vehicles’ positions are checked to see if they would appear on the current display view. If the positions are outside of the current view, they are discarded. Positions within the current view are drawn into the map display.
Layer—Color Control

As at the AC&M processor, the FEV's situational awareness display uses color cues to indicate vehicles in a collision or zone incursion condition. As ADS and GPS messages are received and processed by the on board NAV Processor, graphics messages are formatted and sent to the local Graphics Processor (GP). These graphics messages are identical to those created at the AC&M Processor and include the vehicle id, layer id and map x,y,z position.

Coordinate Conversions Software Example

```
#define GRND_ALT 92 /* indicates ground level, specific to Manchester Airport */

#define DECDEG 1 /* lat/lon decimal degrees */
#define NHSPM 2 /* NH state plane meters */
#define NHSPF 3 /* NH state plane feet */

#define conversion factors for map/decimal degree conversions */

double LRLON; /* lon for lower right corner of map */
double LRLAT; /* lat for lower right corner of map */
double ULLON; /* lon for upper left corner of map */
double ULLAT; /* lat for upper left corner of map */
double LRX; /* map x coordinate—lower right */
```

Over Coming Error Sources

Map Temporal Differential Correction

Map temporal differential corrections are a simple and effective means of reducing error sources in GPS operation for short periods of time when Selective Availability is not active. FIG. 31 depicts the map temporal correction elements.

Map temporal corrections utilize at least one precisely surveyed location in the local area. The surveyed location may be determined from a monument marker or may be determined using a highly accurate digital or paper map. A GPS receiver and (optionally) a processing computer are co-located at the known location with the GPS antenna carefully positioned at the survey point. The receiver/computer remains at the known location for a period of time and, when enough data has been collected, determines pseudo range correction and pseudo range rate factors. These correction factors may then be applied to the differential GPS receiver to determine a corrected position. These factors are used in subsequent position determinations until another map temporal correction is applied.

Map temporal corrections are the simplest form of closed loop differential correction. As the name implies, temporal corrections degrade with time as the receiver moves within the local area. SA significantly reduces the benefits of a temporal differential correction approach. When SA is not active, the short term (30 minute) accuracy of this technique is very good (a meter or two), since all error sources are reduced. One additional limiting factor is that the same satellites must be used during roving operations as those used at the surveyed location. This may be accomplished through software control to ensure a "selected" set of satellites are used for a given GPS session.

Regional Differential Corrections and Differential Overview

Real time differential correction techniques compensate for a number of error sources inherent to GPS. The idea is simple in concept and basically incorporates two or more GPS receivers, one acting as a stationary base station and the other(s) acting as roving receiver(s). The differential base station is "anchored" at a known point on the earth’s surface. The base station receives the satellite signals, determines the errors in the signals and then calculates corrections to remove the errors. The corrections are then broadcast to the roving receivers.

Real time differential processing provides accuracies of 10.0 meters or better (typically 1.0-5.0 meters for local differential corrections). The corrections broadcast by the base station are accurate over an area of about 1500 km or more. Typical positional degradation is approximately a few millimeters of position error per kilometer of base station and roving receiver separation. FIG. 32 shows the basic elements for real time differential GPS (DGPS) operations.

Through the implementation of local differential GPS techniques, SA errors are reduced significantly while the atmospheric errors are almost completely removed. Ephemeris and clock errors are virtually removed as well.

ERROR SOURCES CORRECTED OR REDUCED BY DGPS

| USER RANGE ERRORS (URE) 1 SIGMA MAGNITUDES |
|-----------------------------|-----------------------------|
| SATELLITE CLOCK & NAV.     | 2.7                        |
| EPHEMERIDES & PREDICTION  | 2.7                        |
| ATMOSPHERIC                |                            |
| IONOSPHERIC                | 9.0                        |
| TROPOSPHERIC               | 2.0                        |
| SELECTIVE AVAILABILITY     | 30.0                        |

TOTAL RSS: 31.6

*Tropospheric effects are a local phenomenon and are a function of the altitude difference from the base station to the roving receiver and the local elevation angle of the satellite. To counteract the effects of SA, differential corrections must be generated, transmitted and utilized in the GPS receiver at a rate sufficient to compensate for the rate of change of SA.

Differential GPS can introduce an additional error, if not employed properly. The age of the differential correc-
tion must be monitored at the GPS receiver. As the differential correction ages, the error in the propagated value increases as well. This is particularly true for 'vivulent' strains of SA where the errors introduced slew quickly over very short time intervals.

[0793] Operational Elements

[0794] The precisely surveyed location of the GPS antenna is programmed into the reference station as part of its initial installation and set up procedures. Industry standard reference stations determine pseudo range and delta range based on carrier smoothed measurements for all satellites in view. Since the exact ECEF position of the antenna is known, corrections may be generated for the pseudo range and delta range measurements and precise time can be calculated.

[0795] Naturally occurring errors are, for the most part, slow changing and monotonic over the typical periods of concern. When SA is not invoked, delta range corrections provide a valid method of improving positional accuracy at the roving receivers using less frequent correction broadcasts. With the advent of SA and its random, quick changing non-monotonic characteristics, delta range corrections become somewhat meaningless and may actually degrade the system performance under some conditions.

[0796] As shown previously in FIG. 32, the DGPS correction messages are broadcast by the reference station and received by the roving receivers. The corrections are applied directly to the differential GPS receiver. The DGPS receiver calculates the pseudo range and the delta range measurements for each satellite in the usual manner. Prior to performing the navigation solution, the received pseudo range and delta range corrections are applied to the internal measurements. The receiver then calculates corrected position, velocity and time data. Typical DGPS position and velocity performance is presented in the table below.

<table>
<thead>
<tr>
<th>COMPARISON OF TYPICAL GPS POSITION AND VELOCITY MEASUREMENTS USING COMMERCIAL NAVIGATION TYPE RECEIVERS (ACCURACIES ARE A FUNCTION OF CORRECTION AGE)</th>
<th>WITHOUT DGPS</th>
<th>WITH DGPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE RCVR</td>
<td>CARRIER RCVR</td>
<td>CODE RCVR</td>
</tr>
<tr>
<td>2-D POSITION</td>
<td>&lt;100 M</td>
<td>&lt;40 M</td>
</tr>
<tr>
<td>3-D POSITION</td>
<td>&lt;176 M</td>
<td>&lt;80 M</td>
</tr>
<tr>
<td>VELOCITY (knots)</td>
<td>&lt;10 KN</td>
<td>&lt;5 KN</td>
</tr>
<tr>
<td>TIME (ns)</td>
<td>&lt;500 ns</td>
<td>&lt;100 ns</td>
</tr>
</tbody>
</table>

*The time accuracy is highly dependent upon the type of receiver. Specialized, precise time receivers provide accuracies in the 5 to 25 nanosecond range. Most navigational receivers do not provide this level of time accuracy since it is not required for general navigation.

[0797] Since differential GPS eliminates most GPS errors, it provides significant improvements in system reliability for life critical airport operations. Short term and long term drift of the satellite orbits, clock and naturally occurring phenomenon are compensated for by differential GPS as are other potential GPS satellite failures. Differential GPS is mandatory in the airport environment from a reliability, accuracy and fault compensating perspective.

[0798] As with autonomous GPS receiver operation, multipath is a potential problem. The differential reference station cannot correct for multipath errors at the roving receiver(s). Antenna design and placement considerations, and receiver design characteristics remain the best solutions to date in the minimization of multipath effects.

[0799] DGPS provides the means to eliminate most GPS system errors. The remaining errors are related to receiver design and multipath. Not all GPS receivers and reference stations are created equal, some are distinctly better than others. The selection of the reference station and the roving receivers has a significant effect on the overall system accuracy.

[0800] Compensating for Receiver Error

[0801] Receiver errors are not corrected using an 'open loop' differential correction method as described above. These errors may be reduced when a ‘closed loop’ differential technique is employed. FIG. 33 presents a high level block diagram of a ‘closed loop’ differential system.

[0802] FIG. 33 has additional elements over the standard differential system configuration. A second GPS antenna is installed at a precisely surveyed antenna location and a stationary GPS receiver is co-located with the reference station. This receiver accepts differential correction inputs generated by the reference station. The stationary GPS receiver incorporates the pseudo range corrections in the normal manner and determines DGPS position and velocity. The corrected position and velocity are then compared to the stationary receivers known position and velocity (0,0). The ECEF delta position and velocity data are then used by the reference station processing to further refine the pseudo range and delta range corrections which are broadcast to the roving receivers. Processing software which minimizes the position and velocity errors is used. This technique requires that the roving receivers be identical to the stationary GPS receiver located at the reference station site. That is, the roving receivers must exhibit receiver errors similar to those on the stationary DGPS receiver.

Integrity and Multi-sensor Systems

[0803] The issues of integrity and fault monitoring are a major concerns for any technology considered for the life critical application of air transport and air traffic control. The integration of GPS with other technologies provides a higher
degree of fault detection capability, a potentially improved GPS navigational performance, and the potential of limited navigation support should a catastrophic GPS failure occur aboard the vehicle.

[0804] The integration of GPS with an inertial system can be used to improve the dynamic performance of the navigation solution. Dynamic sensors may provide jerk, acceleration and velocity information to aid in the navigation solution. Sole means inertial navigation may be used in conjunction with GPS. The integration of GPS with inertial systems usually require 12 (or higher) state Kalman filter solutions techniques.

[0805] The concept of Receiver Autonomous Integrity Monitoring (RAIM) is accepted as a potential integrity monitoring system. The RAIM concept requires that the GPS receiver and/or navigation system include the required “smarts” to diagnose its own health using additional satellites, redundant hardware and specialized internal software processing. RAIM standards are currently being developed for industry approval.

[0806] When combined with other sensors such as WAAS, inertial, baro altimeter and internal RAIM processing, GPS will have superior accuracy, fault tolerance and fault detection capability.

Fault Tolerance and High Availability

[0807] Any system which controls life critical operations at an airport must support fault tolerance and high availability. At the same time, the system must be cost effective and support technology insertion. High system availability may be achieved through a custom design process utilizing selected and screened components for high Mean Time Between Failure (MTBF). Alternatively, high availability may be achieved through system redundancy using components of non-custom, commercial-off-the-shelf design. The following paragraphs introduce a few of the concepts which are later utilized in the system design analysis.

[0808] AVAILABILITY: Availability is defined as the probability that a system will operate to specification at any point in time, when supported with a specific level of maintenance and spares.

[0809] MEAN TIME BETWEEN FAILURES (MTBF): The mean time a piece of equipment will remain operational before it is expected to fail.

[0810] RELIABILITY: The inherent probability that a piece of equipment or hardware will remain operational for a period of time (t). It is expressed as follows:

\[ R(t) = e^{-\frac{t}{MTBF}} \]

[0811] TRAVEL TIME: The travel time is measured from the time of failure to the time the repair technician and required spare parts arrive at the failed equipment.

[0812] MEAN TIME TO RECONFIGURE (MTTC): The mean time a system is inoperable as measured from the time of failure to the time of full operation. Typically, reconfiguration time involves bringing on line redundant systems in an effort to provide continued service.

[0813] MEAN TIME TO REPAIR AND CERTIFY (MTTRC): The mean time of the actual repair and recertification activities as measured from the time of arrival of the failed equipment to the time which the equipment is on line, certified and declared operational.

[0814] MEAN TIME TO REPAIR (MTTR): MTTR is the sum of TRAVEL+MTTC+MTTRC.

Available Example

[0815] The following analysis builds upon elements of the system composed of off the shelf components arranged in a redundant configuration. Commercial industrial single board computers are connected with other commercial elements in the manner as shown in the FIGS. 28, 29, 30. This approach provides cost effectiveness, COTS technology insertion, declining COTS life cycle costs and high availability. The analysis starts with no design redundancy FIG. 28, and ends describing a two controller station redundant architecture FIG. 30.

[0816] This example will determine the overall reliability and availability of the architecture shown in FIG. 28. The requirement for system availability for this terminal area system comes from the FAA Advanced Automation Program (AAS). The AAS program defines the system yearly availability to be 0.99995 determined using a 2 hour travel time which is added to any other system down time. The major elements of the airport system shown in FIG. 28.

### KEY OPERATIONAL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVAILABILITY</td>
<td>0.99995</td>
</tr>
<tr>
<td>TRAVEL TIME (HRS)</td>
<td>2.0</td>
</tr>
<tr>
<td>TIME TO AUTO CONFIGURE (HRS)</td>
<td>0.25</td>
</tr>
<tr>
<td>MEAN TIME TO REPAIR AND CERTIFY (HRS)</td>
<td>0.25</td>
</tr>
<tr>
<td>MEAN TIME TO REPAIR (MTR)</td>
<td>2.275</td>
</tr>
</tbody>
</table>

### SPECIFIC COMPONENT PARAMETERS

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINGLE BOARD COMPUTER 142, 143</td>
<td>90000</td>
</tr>
<tr>
<td>SBC RELIABILITY (RSBC)</td>
<td>90000</td>
</tr>
<tr>
<td>Component</td>
<td>MTBF (Hrs)</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Digital Radio Transceiver</td>
<td>75,000</td>
</tr>
<tr>
<td>Touch Screen</td>
<td>100,000</td>
</tr>
<tr>
<td>Low Voltage DC Power Supply</td>
<td>50,000</td>
</tr>
<tr>
<td>Flat Screen Display</td>
<td>75,000</td>
</tr>
<tr>
<td>Raid Reliability</td>
<td>150,000</td>
</tr>
<tr>
<td>Local Area Network</td>
<td>87,600</td>
</tr>
<tr>
<td>Keyboard</td>
<td>75,000</td>
</tr>
<tr>
<td>Differential Base Station</td>
<td>100,000</td>
</tr>
</tbody>
</table>

This particular analysis is for a single controller station, multiple stations could be used simply by duplicating the design elements. The controller must have the following capabilities to perform his airport duties:

1. have full duplex voice and data communications
2. a controlling AC&M display and graphic display
3. a command touch screen capability or keyboard
4. differential GPS for all navigation
5. airport lighting interface (independent bulbs and switches may fail without loss of function)

The minimal set of controller actions require the following hardware and associated software to be operational:

1. radio transceiver (voice and data function)
2. AC&M display, SBC server, and RAID
3. Graphic display, SBC
4. a low voltage power supply
5. a command and control touch screen or a keyboard
6. minimal configuration operational software
7. a LAN assembly
8. a differential GPS base station
9. a airport lighting interface

The hardware elements can be connected in a minimal hardware configuration and the overall availability can be compared to the specified value of 0.99995

Initial Series Reliability

\[ R_{INT} = \frac{R_{SR} \times R_{TXCVR} \times R_{TOUCH} \times R_{LVPS} \times R_{RDIS} \times R_{RAID} \times R_{DIFF} \times R_{LITE} \times R_{KBD}}{R_{SR} + R_{TXCVR} + R_{TOUCH} + R_{LVPS} + R_{RDIS} + R_{RAID} + R_{DIFF} + R_{LITE} + R_{KBD}} \]

\[ R_{INT} = 0.950629 \]

The initial MTBF for the series string is determined below.

\[ MTBF_{INT} = \frac{YR}{R_{INT}} \]

\[ MTBF_{INT} = 8358.5694 \]

Initial availability based upon series minimum configuration is

\[ \frac{MTBF_{INT}}{MTBF_{INT} + MTTR} = 0.999728 \]

As expected availability does not meet the specification, system redundancy will be necessary to achieve the design goal. To meet the required availability a system MTBF of about 45,000 hours will be necessary with a 2.275 hour mean time to repair. A new architecture is shown in FIG. 29.

Airport System, Single Redundant Controller Station

Redundant radio transceivers will be necessary since a single point failure is unacceptable in this component. Parallel radio transceiver reliability is determined below:

\[ R_{TXCVR} = R_{TXCVR} \times R_{TXCVR} \times R_{TXCVR} \times R_{TXCVR} = 0.987848 \]

Redundant LVPSs are required for the same reason.

\[ R_{LVPS} = R_{LVPS} \times R_{LVPS} \times R_{LVPS} = 0.999908 \]

Redundant Local Area Networks are also required, since a single point failure can not be tolerated in communications between the AC&M SBC and Graphic SBC.

\[ R_{LAN} = R_{LAN} \times R_{LAN} \times R_{LAN} = 0.999044 \]

Redundant Differential GPS are also required, since a single point failure can not be tolerated in airport navigation functions.

\[ R_{DIFF} = R_{DIFF} \times R_{DIFF} \times R_{DIFF} = 0.916127 \]

Redundant airport lighting control interfaces are required.

\[ R_{LITE} = R_{LITE} \times R_{LITE} \times R_{LITE} = 0.998314 \]

The keyboard and the touch screen provide the same capability, hence may be treated as a parallel redundant system element. The keyboard/touch screen combination is found below:

\[ R_{TOU} = R_{KBD} \times R_{TOUCH} = 0.990054 \]

An extra display surface will be added to display information. This display capability will be used should a failure occur in an AC&M display or in a graphic situation display. A 2 of 3 display scenario is used for successful mission completion. Should a failure occur auto reconfiguration must occur within the specified time allocation. To determine exactly how the 2 out of 3 display process represents, a probability analysis is performed. The probability is determined from the series elements which make up the display function. One display channel may fail while the two others provide the necessary information. The third display is used to provide non mission critical information when acting as a hot spare.

Series Display Channel Elements

\[ R_{DIS} = R_{DIS} \times R_{DIS} \times R_{DIS} = 0.761448 \]

In the 2 of 3 scenario the possible operating combinations must add to one, meaning the probability of all of the possible operating modes must add to 1. The operating combinations are identified below:

1. all 3 serial display channels are operational
2. one channel is down and the other two are operational
3. two channels are down and only one is operating
4. all channels are down

Unreliability is Defined as:

\[ Q = 1 - R_{DIS} \]

The Probability is Defined Below:

\[ R_{TOTAL} = \frac{3}{2} R_{DIS} \times Q^2 + Q \]

\[ R_{TOTAL} = 1 \text{ All combinations do add to 1} \]

Two of Three Operational Reliability is:

\[ R_{OF3} = R_{DIS} \times R_{DIS} \times Q + Q \]

\[ R_{OF3} = 0.856429 \]

Now the overall system reliability and availability functions may be evaluated.

\[ R_{FINAL} = R_{OF3} \times R_{TXCVR} \times R_{LVPS} \times R_{TOU} \times R_{KBD} \times R_{LAN} \times R_{DIFF} \times R_{LITE} \times R_{FINAL} = 0.82354 \]
From a hardware perspective the system meets requirements. The system software must be able to detect hard and soft failures and must be able to fault isolate the failed device. Parallel hardware redundancy and “smart” software provide the necessary fault monitoring, fault containment and fault identification to the LRU level. Operational software is tailored to the specific application, but the hardware is based upon COTS standards to allow for future technology insertion and cost effective replacement.

Multiple controller stations may be added to support larger airport systems. In this case a slightly different architecture is utilized. Common elements are shared by multiple stations. In the 2 station architecture shown parallel differential GPS base stations, parallel lighting control interfaces, parallel Local Area Networks and parallel transceivers are utilized. Since a redundant capability is provided with multiple controller stations consisting of 2 of 3 scenario increased availability is provided as shown in FIG. 30.

The Reliability of the Two Controller Station is Found Below

\[ R_{STAT} = R_{2OF3-RTOU-KBD-RUNPSP} = 0.848255 \]

The Reliability of the Shared Elements Follows

\[ R_{EXT} = R_{LVPS-P-RCPVRP-RDFPPP-RPTPPLAP} = 0.97057 \]

Reliability of the Two Parallel 2 of 3 Controller Stations is

\[ R_{STAT2} = R_{STAT2} = R_{2OF3-RTOU-KBD-RUNPSP} = 0.976973 \]

Reliability of the Two Controller Station Airport System is

\[ R_{TOT} = R_{STAT2} \cdot R_{EXT} \cdot R_{TOT} = 0.948222 \]

System Total MTBF is

\[ MTBF := \frac{-\ln(R_{TOT})}{-\ln(R_{EXT})} \quad MTBF = 164763.651999 \]

System Availability is

\[ AVAIL := \frac{MTBF}{MTBF + MTTR} \quad AVAIL = 0.999986 \]

Further availability improvements and cost reduction may be realized when configured with multiple controller stations. The 2 of 3 display channel operation may be reduced to 2 single display channels and RAID5 may be eliminated while still meeting availability goals when operating with multiple redundant reconfigurable controller stations.

Airport Layout Plan

The U.S. FAA recommends the development of digitized Airport Layout Plans (ALPs). In an ALP, the existing and proposed land and facilities required in the operation and development of the airport are provided in a scaled drawing. Each ALP should include the following information: airport facilities—runways, taxiways, ramps, service roads, navigation aids, and buildings

- airspace matters—existing and planned approach/missed approach/departure procedures, special use and controlled airspace, control zones and traffic patterns
- obstructions to air and ground navigation
- airport topography
- precise airport monumentation

If designed properly, the ALP should be suitable for use in airport master plan activities, emergency work, maintenance, navigation and ATC.

GPS Compatible Monumentation

Airport ALP generation or mapping activities may use any number of map coordinate systems based on a number of earth datums or ellipsoid references. Standardization of the mapping techniques and references are key in the development of any successful multi-use mapping program. In addition to the selection of a standard reference system, the interface to the local area surrounding the airport must be addressed. Accurate cross referenced monumentation is necessary to allow for a smooth transition between the local coordinate system and the one used in the airport maps or in the navigation system. In the U.S., local State Plane Coordinate Systems (SPCS) form the baseline for most local mapping activities. As such, the ALPs for all U.S. airports should be monumented with reference points to provide for accurate coordinate conversion between World Geodetic Survey of 1984 (WGS 84) Latitude—Longitude, Earth Centered Earth Fixed (ECEF) X, Y, Z and local SPCSS or Universal Transverse Mercator (UTM). GPS and conventional survey techniques are recommended for such monumentation.

The surveyed accuracy of the multi-use airport map is recommended to be better than 0.5 meters for the horizontal and 0.1 meter for elevation. Of particular interest are the Airport Runway Touch Down Marker Reference Points (the precise coordinates of the center of a runway’s touch down marker) and the Airport Runway Reference Points (the precise coordinates along the centerline path of the runway). In addition, the precise locations of all turn outs and turn ins should be identified in the airport map database.

Earth reference systems used in these locations should be ECEF X, Y, Z, North American Datum of 1983 (NAD 83) or WGS 84 latitude, longitude, MSL. These three models are compatible with GPS-based MSL. Should the positions not be in one of these coordinate reference systems, then local airport multi-coordinate reference monumentation should be used to support the required coordinate conversions.
Airport map latitude, longitude projections should be based upon the Transverse Mercator, Lambert Conformal Conic, or Hotine Oblique Mercator. These projections are used in state plane coordinate systems. Additional information on reference systems and projections is available in North American Datum of 1983 (NAD 83), by Charles R. Schwartz.

The Manchester, N.H. (NH) airport map used in numerous test activities was initially in NH State Plane Coordinate System feet. This coordinate system was chosen for compatibility with existing maps and because it represented distances in linear feet rather than in degrees of latitude and longitude. The map was later converted to NH state plane meters and ECEF X,Y,Z representations. Manchester Airport was carefully surveyed and monumentation was performed at multiple sites around the airport. The monumentated points were referenced to the ECEF Cartesian Coordinate System, NAD 83 Latitude, Longitude, and Mean Sea Level (MSL), and the NH State Plane. Coordinate conversions were performed using the monumented points shown below.

MULTI-REFERENCE MONUMENTATION

<table>
<thead>
<tr>
<th>FLAGPOLE</th>
<th>RUNWAY 35 END</th>
</tr>
</thead>
<tbody>
<tr>
<td>MONUMENT SITE #1</td>
<td>MONUMENT SITE #2</td>
</tr>
</tbody>
</table>

NEW HAMPSHIRE STATE PLANE COORDINATES

<table>
<thead>
<tr>
<th>ECEF X, Y, Z COORDINATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAT83 = 42.93325800 N</td>
</tr>
<tr>
<td>LON83 = 71.43299094 W</td>
</tr>
<tr>
<td>MSL = 225.04 FT</td>
</tr>
<tr>
<td>MSL ALT = 68.59 M</td>
</tr>
</tbody>
</table>

NAD83 LLA, LON, MSL

ECEF X = 1488741.9 M  
ECEF Y = -4433764.7 M  
ECEF Z = -4321318.4 M

| GHA83 = -28.24 M  
| GEOID HT = -28.24 M  

| WGS ALT = 40.35 M  

NAD 83 PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimajor axis*</td>
<td>6378137</td>
<td>M</td>
</tr>
<tr>
<td>Angular velocity*</td>
<td>7.292115 x 10^-11</td>
<td>RAD/SEC</td>
</tr>
<tr>
<td>Gravitational constant*</td>
<td>3986005 x 10^7</td>
<td>M^2/SEC^2</td>
</tr>
<tr>
<td>Dynamic form factor</td>
<td>108263 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>Semiminor axis</td>
<td>6356752.314</td>
<td>M</td>
</tr>
<tr>
<td>Eccentricity squared</td>
<td>0.006943802290</td>
<td></td>
</tr>
<tr>
<td>Flattening</td>
<td>0.033528100818</td>
<td></td>
</tr>
<tr>
<td>Polar Radius of Curvature*</td>
<td>6399593.625</td>
<td>M</td>
</tr>
</tbody>
</table>

(*Denotes values which are identical to WGS 84, underline denotes differences between NAD 83 and WGS 84)

NAD 83 is a reference datum for the earth replacing the North American Datum of 1927 (NAD 27). It was developed over many years through international efforts of many people. It was the largest single project ever undertaken by the National Geodetic Survey (NGS), spanning 12 years.

The task involved 1,785,772 survey observations at 266,636 sites in North and Central America, Greenland and the Caribbean Islands. The observations were made with all types of survey and measurement equipment from satellites to tape measures. The ultimate task was to develop an earth model which satisfied a set of 1,785,722 simultaneous equations. The task was performed using a least squares approach and Helmert blocking. The purpose was to update NAD 27, calculate geoid heights at 193,241 control points and the deflections of vertical at the control points.

The NAD 83 reference uses the Geodetic Reference System of 1980 (GRS 80) ellipsoid based on the Naval Surface Warfare Center 92-Z (NSWC 92-Z) doppler measurements. The ellipsoid is positioned to be geocentric and have cartesian coordinate orientation consistent with the definition of Bureau International de l’Heure (BIH) Terrestrial System of 1984.

NAD 83 data sheets contain information to update North American 1927 references. The data sheets contain new information which is relevant for precise surveys and users of GPS equipment. These include: precise latitude and longitude [DDD MM SS.sssss], latitude—longitude shift in seconds of degree from NAD 27 to NAD 83, elevation above the geoid with standard error, geoid height and standard error, state plane and Universal Transverse Mercator (UTM) coordinates. These fundamental corrections and ellipsoid constants are the basic parameters used in many coordinate conversions and navigational programs and form the basis of modern survey measurements. GRS 80 used by NAD 83 has the following fundamental parameters:

NAD 83 PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimajor axis</td>
<td>6378137</td>
<td>M</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>7.292115 x 10^-11</td>
<td>RAD/SEC</td>
</tr>
<tr>
<td>Gravitational constant</td>
<td>3986005 x 10^7</td>
<td>M^2/SEC^2</td>
</tr>
<tr>
<td>Dynamic form factor</td>
<td>108263 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>Semiminor axis</td>
<td>6356752.314</td>
<td>M</td>
</tr>
<tr>
<td>Eccentricity squared</td>
<td>0.006943802290</td>
<td></td>
</tr>
</tbody>
</table>

WGS 84 was developed by the U.S. Department of Defense. The reference system started with the same initial BIH conventions as NAD 83 but, over the development, some parameters changed slightly. The geocentric ECEF system is based on a cartesian coordinate system with its origin at the center of mass of the earth. The system defines the X and Y axis to be in the plane of the equator with the X axis anchored 0.554 arc seconds east of 0 longitude meridian and the Y axis rotated 90 degrees east of the X axis. The Z axis extends through the axis of rotation of the earth. The WGS 84 reference uses the GRS 80 ellipsoid as does NAD 83. WGS 84 includes slight changes to GRS 80 parameters which are identified below:

WGS 84 PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimajor axis</td>
<td>6378137</td>
<td>M</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>7.292115 x 10^-11</td>
<td>RAD/SEC</td>
</tr>
<tr>
<td>Gravitational constant</td>
<td>3986005 x 10^7</td>
<td>M^2/SEC^2</td>
</tr>
<tr>
<td>Dynamic form factor</td>
<td>-434.16685 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>Semiminor axis</td>
<td>6356752.314</td>
<td>M</td>
</tr>
<tr>
<td>Eccentricity squared</td>
<td>0.006943802290</td>
<td></td>
</tr>
</tbody>
</table>

World Geodetic Survey of 1984

WGS 84 was developed by the U.S. Department of Defense. The reference system started with the same initial BIH conventions as NAD 83 but, over the development, some parameters changed slightly. The geocentric ECEF system is based on a cartesian coordinate system with its origin at the center of mass of the earth. The system defines the X and Y axis to be in the plane of the equator with the X axis anchored 0.554 arc seconds east of 0 longitude meridian and the Y axis rotated 90 degrees east of the X axis. The Z axis extends through the axis of rotation of the earth. The WGS 84 reference uses the GRS 80 ellipsoid as does NAD 83. WGS 84 includes slight changes to GRS 80 parameters which are identified below:
Comparison of NAD 83 and WGS 84

The North American Datum of 1983 (NAD 83) and World Geodetic Survey of 1984 (WGS 84) attempt to describe the surface of the earth from two different perspectives. NAD 83 describes the surface of North America using the Geodetic Reference System of 1980 (GRS 80) ellipsoid and over 1.7 million actual measurements. A least squares Helmert blocking analysis was performed by National Geodetic Survey (NGS) on these measurements to determine the best fit solution to the actual measurements. NAD 83 uses monumented reference points across the country to precisely reference various coordinate systems such as the State Plane Coordinate Systems. WGS 84 incorporates positional referencing using GPS and local references. Position determination by GPS incorporates precise Keplerian orbital mechanics and radio positioning technology. Clearly, the two systems are describing the same thing, but the methods of determining a position are different.

Both NAD 83 and WGS 84 are based on BIH conventions. Though both are based on the GRS 80 ellipsoid, small changes have occurred between the two systems during their development. The basic difference in the dynamic form factor was attributed to GRS 80 using the unnormalized form while WGS 84 used a normalized form and rounded to eight significant figures. Since other parameters derived from the dynamic form factor differences usually appear after the eighth decimal place, most experts feel that the computational differences are of no significance.

Computations to determine the latitude and longitude from ECEF X, Y, Z coordinates highlight the small difference in the two reference systems. It has been shown that the maximum error between the two reference systems occurs at a latitude of 45 degrees. (Refer to North American Datum of 1983, Charles R. Schwartz) No error occurs between the two systems in the determination of longitude. The maximum error amounts to 0.000003 seconds of arc which amounts to a latitude shift of 0.0001 meters. For all practical purposes, the computational differences between the two systems are negligible. This is an important point for, if the two earth models differed in basic latitude and longitude computations, serious charting and navigational problems would occur and GPS navigation based on NAD 83 referenced maps would be seriously limited.

Both WGS 84 and NAD 83 have many common points used as local reference points. The differences between the two systems may reach several meters in rare locations, but on the average the systems should be identical. Generally, measurement errors and equipment inaccuracies introduce more error than the differences in the two systems.

For airport mapping and GPS navigation we can assume that errors due to the differences between the NAD 83 and WGS 84 ellipsoid models are negligible. This implies that either system can be used in calculating navigational entities and performing precise mapping with GPS navigation. The monumented New Hampshire points established on NAD 83 near the airport are well within the measurement accuracy of the GPS survey and navigation equipment. The documented offsets between NAD 83 and WGS 84 for New Hampshire are 0.0 meters in the Y direction and ~0.5 meters in the X direction.

Photogrammetry

Photogrammetry techniques incorporating ground reference point(s) are recommended for creating electronic ALP's. Various techniques may be employed to generate digital ALP's including aerial photogrammetry and ground based moving platforms with integrated video cameras and sensors. The collected image data may be post processed to produce a highly accurate 2 or 3-D digital map of the surrounding area.

A digital map of Manchester (NH) Airport was created to support early test activities. The digital map was based on aerial photogrammetry and GPS ground control using postprocessing software. A Wild Heerbrugg aerial camera equipped with forward motion compensation was used to capture the photogrammetry. The 3-D digitalization was performed using a Zeiss stereoscopic digitizing table. During the digitalization process, numerous object oriented map layers were constructed to segregate various types of map information. The resulting 3-D digital map had a relative horizontal accuracy of better than 1.0 meter and a relative vertical accuracy of better than 0.1 meter across the airport.

3-D Graphics Formats

Many digital map formats are in widespread use today. Translators are available to convert from one computer format to another. Maps may be in either raster format (such as those generated by image scanning) or vector format (those developed on CAD and digitizing equipment). The vector format provides a much more robust environment for developers of ATC and map display systems. Vector based drawings are represented by individual vectors which can be controlled and modified individually or collectively. This enables the developer to manage these entities at a high level rather than at the individual pixel level. The vectors may represent specific geographical features (entities) in the map which may be assigned to a particular map layer in a particular user defined color.

Since the map and ATC situation display are in a vector format, a convenient method of graphically identifying and manipulating information is available. The selection of a graphical symbol on the screen through the use of a pointing device can be used to access an entity-related database or initiate an entity-based processing function. With raster-based images, there is no simple way to segregate the various pieces of map or graphic information for high level management.

Raster formats represent a series of individual pixels, each pixel controlled as a function of a series of control bits. Typically a series of three (3) words are used to describe the Red, Green and Blue (RGB) intensity of each pixel. Each pixel of information represents the smallest piece of the image and has no information about the larger graphical entity that it is part of. From a management perspective, this introduces additional complications for even the simplest graphical manipulation tasks such as
Suppressing the display of a series of raster based topographical contour lines in the airport map.

A high level management capability is required for ALP graphic entity control. The current raster-based maps do not provide this functionality, hence additional processing is required each time the map is displayed or modified. For raster-based maps to provide this capability, the pixel elements must be functionally organized in some manner to support the higher level management functions described in this application. For this reason, raster scan map formats are not recommended for ALPs at this time.

Vector formats may be in ASCII or binary and may be constructed using different rules for their generation. The example below uses the AutoCAD™ DXF standard drawing format. (AutoCAD™ is a registered trademark of AUTODESK, Inc.) AutoCAD™ is one of the most popular Computer Aided Design (CAD) software packages in the world today and is typical of vector ALP formats. The DXF map format may be easily converted to almost any CAD drawing format.

The two formats shown above represent the vertical side of a building which is, by AutoCAD™ convention, a 3-D face. Since the two coordinate systems are different, one must appropriately set the respective viewpoint for each display. This is accomplished in the initial ALP DXF configuration declarations. In a similar fashion, the drawing could be converted to other coordinate systems such as Universal Transverse Mercator (UTM) using a DXF coordinate conversion utility program such as TRALINE™ (available from Mentor Software, Thornton, Colo.)

The above example represents just one of the thousands of entities making up an ALP. Many commercial graphical libraries and commercial CAD software products are available today for the construction and use of ALPs and other 3-D graphic entities.

The use of modern digital Computer Aided Design (CAD) techniques is required for the development of electronic map databases. The use of GPS-based, ground referenced photogrammetry with post processing 2 or 3-D digitalization provides a cost effective, highly accurate and automated method of constructing the 2 or 3-D ALP.

An industry or international standard format for the construction and interchange of digital graphical information should be used. Numerous standards are established with readily available software translators for conversions between the various formats. Map file formats may be binary or ASCII characters.

3-D Object Oriented Map Layers

When stored in a digital format, the ALP should be arranged in object oriented map layers. Proper layering of information provides the capability to present only the information that is needed for a particular purpose. For example, navigational maps should not necessarily include all the digital layers of the ALP. A simplified version of the map showing only runways, taxiways, navigational references (landmarks) and gate areas should be used. The use of specific layers of interest provides the following advantages:

- minimizes possible confusion in presenting too much information to the pilot or controller
- decreases reaction times of controller and pilot by only presenting what is needed
- reduces computer memory requirements
- minimizes computer processing requirements
- provides faster display updates (fewer pixels to redraw)

3-D Digital Map Coordinate Systems

In order to integrate GPS navigational data with 2 or 3-D maps, the potential map formats must be evaluated for compatibility and ease of use with the navigational output and coordinate reference system. The table below lists twelve of the most likely combinations.

<table>
<thead>
<tr>
<th>COMBINATIONS OF MAPS, NAVIGATIONAL PARAMETERS AND MATHEMATICAL COORDINATE REFERENCES</th>
<th>#</th>
<th>DIGITAL MAP FORMAT</th>
<th>MATHEMATICAL NAVIGATIONAL LO FORMAT</th>
<th>COORDINATE REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>LAT, LON, MSL</td>
<td>LAT, LON, MSL</td>
<td>LAT, LON, MSL</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>LAT, LON, MSL</td>
<td>LAT, LON, MSL</td>
<td>ECEF</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>LAT, LON, MSL</td>
<td>STATE</td>
<td>ECEF</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>LAT, LON, MSL</td>
<td>ECEF</td>
<td>ECEF</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>STATE</td>
<td>STATE</td>
<td>STATE</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>STATE</td>
<td>STATE</td>
<td>STATE</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>STATE</td>
<td>STATE</td>
<td>STATE</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>STATE</td>
<td>STATE</td>
<td>STATE</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>ECEF</td>
<td>ECEF</td>
<td>ECEF</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>ECEF</td>
<td>ECEF</td>
<td>ECEF</td>
<td></td>
</tr>
</tbody>
</table>
Other permutations are possible for the different combinations of coordinate systems, map references and navigational output formats. Other combinations can be “made to work”, but based on arithmetic precision, map availability and software complexity, the combinations identified with an asterisk satisfy the evaluation criteria most effectively. The table below presents a compliance matrix, where each of the twelve combinations are evaluated against a set of criteria. The criteria used are described in greater detail following the table.

<table>
<thead>
<tr>
<th>COMPLIANCE MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAPPING FORMAT:</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>EXISTING MAP DATA</td>
</tr>
<tr>
<td>RECOGNIZABLE MAP</td>
</tr>
<tr>
<td>CONV. SW EXISTS</td>
</tr>
<tr>
<td>EASY 3D-2D CONV</td>
</tr>
<tr>
<td>MULTI-USE FORMAT</td>
</tr>
<tr>
<td>WORLD WIDE SYSTEM</td>
</tr>
<tr>
<td>LINEAR SYSTEM</td>
</tr>
<tr>
<td>GPS COMPATIBLE</td>
</tr>
<tr>
<td>SEAMLESS SYSTEM</td>
</tr>
<tr>
<td>NAV INPUT-OUTPUT</td>
</tr>
</tbody>
</table>

**TOTAL YES COUNT:**

15 18 13 15 12 14 17 14 13 16 13 11

**CRITERIA DEFINITIONS**

**COMPATIBILITY WITH EXISTING MAP DATA:**

Existing digital map data is available for the airport and surrounding area.

**RECOGNIZABLE MAP:**

A map which is instantly recognizable, one which resembles the surface on which we live. The map should not need to be differentially corrected from the reference geoid.

**CONVERSION SW EXISTS:**

Commercially available software exists to convert from one 3-D map reference system to the other.

**EASY 3D-2D CONVERSION:**

Digital map presentations can be easily converted from 3-D to 2-D by setting the altitude to zero without any additional mathematical conversions in the raw map data or in the 3-D graphical interface.

**MULTI-USE FORMAT:**

The map data is in a standard format which can satisfy multi-use needs such as Master Plans, construction needs, ATC and general navigation.

**WORLD WIDE SYSTEM:**

References in the map are with respect to world wide datums and accepted world wide mapping units.

**LINEAR SYSTEM:**

The axes and units of the map are linear and represent distance.

**GPS COMPATIBLE:**

Mapping units and presentations are directly compatible with existing GPS receiver output formats and calculation references.
SEAMLESS SYSTEM
Maps do not have mathematical/physical discontinuity, the map format must be seamless on a world wide basis. For example UTM maps do not cover polar regions and map edges do not match on 0 degree boundaries when placed together.

NAVIGATIONAL OUTPUT
The final navigational output should be instantly recognizable; i.e. if LAT, LON, MSI output is used, one can instantly visualize a location on the earth, while if ECEF outputs are given it is difficult to visually picture a point in space.

ACCEPTED STANDARD
Navigational format is an accepted standard; i.e. LAT, LON, MSI.

WORLD WIDE USE
The navigational format is usable over the entire world.

GPS COMPATIBLE
Navigational format is compatible with existing GPS receiver outputs.

CHARTS AVAILABLE
Paper and digital charts are available.

COORDINATE REFERENCE
The coordinate reference system is recognized throughout the world.

SIMPLE NAVIGATION MATHEMATICS
The coordinate system lends itself to simple linear navigational mathematics.

NAD83 AND WGS84 REF.

SINGLE ORIGIN
The system has one and only one origin.

LINEAR SYSTEM
The system is a linear coordinate system.

UNITS OF DISTANCE
The coordinate system is based on units of distance rather than angle.

* Suggested combinations 2, 7, 10

[0909] To illustrate the differences between GPS trajectories displayed in maps using different coordinate systems, the following plot examples are provided. FIG. 12 shows a plan view of latitude versus longitude. FIG. 14 shows the same trajectory in ECEF X and Y coordinates. FIG. 13 depicts the MSL Altitude versus Time while FIG. 15 shows the ECEF X values versus Time. Note the distortion between the latitude, longitude, MSL altitude and the ECEF X,Y, and Z coordinates. (The small rectangles on each plot represent waypoints along the trajectory path.)

[0910] Plotting points in the map database requires that the navigational computations provide output which is compatible with the map database coordinates. Combination # 7 in the previous Table includes a map database which is in a State Plane Coordinate System and a navigational output in latitude, longitude and MSI. Additional conversions are required to convert the navigational data to state plane coordinates prior to plotting the points in the map database. A more convenient map, navigational and coordinate reference frame is required.

[0911] ALP Summary and Recommendations

[0912] Future airport maps or modifications to existing maps should make every attempt to utilize recent technological advances in their construction. The following items are guidelines for future map development:

[0913] Precise, 3-D airport maps (ALPs) should be created and maintained for all major and reliever airports.

[0914] ALPs should be constructed to satisfy multiple user requirements.

[0915] Electronic graphical design tools should be used in ALP construction. Computer Aided Design tools should be used wherever possible.

[0916] Standard graphical formats (either ASCII character or industry standard binary file formats) should be used.

[0917] The concept of electronic layers should be used to identify and isolate entities in the map database.

[0918] Airport Reference Points (ARPs) should be located at precisely monumented positions around the airport. ARPs should be referenced to the coordinate systems of interest (such as LAT,LON,MSL, ECEF X,Y,Z and the SPCS).

[0919] At least three (3) ARPs, located within the airport confines in areas which are not likely to be disturbed, are recommended. Where possible, these points should be placed in the far corners of the airport to form a triangle. These points should be surveyed with GPS based survey equipment and monumented physically on the ground and within the digital map database.

[0920] ARPs should be recomputed as necessary to assure accuracy of the navigation and ATC functions. Re-monumentation may be required as a part of airport construction and expansion. Natural phenomena such as plate tectonics, may force re-monumentation of the airport. When ARP positions change more than 0.5 meters horizontally and 0.1 meters vertically, re-monumentation is recommended.
Areas used by aircraft such as runways, taxiways, gate areas and ramps should be surveyed to a horizontal accuracy of 0.5 meters horizontally and elevation to 0.1 meters.

The use of photogrammetry is suggested as an efficient means of creating a digital database of an existing airport.

Earth reference systems used for the various map projections should be the NAD 83 or WGS 84. Older, previously accepted datums which do not correlate with GPS navigation or surveys should be avoided.

ALPs should be compatible with cockpit instrumentation and ATC databases.

GPS calibration areas should be located at all gates or areas where aircraft remain stationary. These areas should be identified in the airport digital map. The purpose of the calibration area is to allow the pilot to check the accuracy of the on board GPS equipment.

Cost effective and highly accurate mapping technology is available to allow for the generation of multi-use maps which should be compatible with a host of platforms and potential uses. The exploitation of these common use maps will enhance master planning, aviation and Air Traffic Control (ATC) capabilities. Maps developed to national standards will provide a cost effective navigational and ATC data base.

Summary, Ramification and Scope

The present invention provides a valuable enhancement to the current airport environment. This enhancement will result in safer air travel and more efficient operation of our currently capacity limited airports. Human blunders in the cockpit and in the control tower have cost hundred of lives in the past. Seamless airport air/ground operations will result in lower air traffic controller and pilot workloads through the use of automation processing. Advanced situational awareness displays showing travel paths, and clearance compatible mirrored navigation automation processing will reduce the likelihood of human blunders in the control tower and in the cockpit resulting in a safer airport environment. The elimination of out dated single function navigation and surveillance systems will result in significant cost savings for the airport authority and the FAA. The cost effective nature of this GNSS based airport control and management system will allow deployment at smaller airports resulting in safer operations and better on time performance throughout the whole aviation system.

It is obvious that minor changes may be made in the form and construction of the invention without departing from the material spirit thereof. It is not, however, desired to confine the invention to the exact form herein shown and described, but is desired to include all such a properly come within the scope claimed.

1. An airport navigation method for a plurality vehicles selected from the group comprising aircraft and surface vehicles, said method comprising

   a. installing a GPS reference antenna at a known physical location, said physical location being GPS referenced;
   b. preparing an airport map that is GPS referenced; said map containing at least one digital representation of features selected from the group comprising runways, taxiways, gate areas, geographical features of the area surrounding the airport, approach paths, departure paths and identified obstructions;
   c. providing said map to a vehicular navigation computer system;
   d. receiving GPS signals at said GPS reference antenna;
   e. providing said received GPS signals to a Differential GPS base station;
   f. calculating with said Differential GPS base station differential corrections;
   g. providing said differential corrections to a radio transmitter;
   h. broadcasting using said radio transmitter, said differential corrections to said vehicle;
   i. receiving using a radio receiver located on said vehicle said broadcast differential corrections;
   j. receiving GNSS signals using a GNSS antenna located on said vehicle and providing said received GNSS signals to a differential GNSS receiver located on said vehicle;
   k. providing said received differential corrections to said differential GPS receiver;
   l. calculating using said differential GPS receiver at least one differentially corrected information element selected from the group comprising 3-dimensional position, 2-dimensional horizontal position, vertical position, 3-dimensional velocity, speed, heading, vertical rate and time;
   m. navigating said vehicle using said differentially corrected information using said vehicular navigation computer system that displays said location of said vehicle on said digital map;

2. An airport control and management method for a plurality vehicles selected from the group comprising aircraft and surface vehicles, said method comprising

   a. installing a GPS reference antenna at a known physical location, said physical location being GPS referenced;
   b. preparing an airport map that is GPS referenced; said map containing at least one digital representation of features selected from the group comprising runways, taxiways, gate areas, geographical features of the area surrounding the airport, topography surrounding the airport, approach paths, departure paths and identified obstructions;
   c. providing said map to an airport control and management computer system;
   d. receiving GPS signals at said GNSS reference antenna;
   e. providing said received GPS signals to a Differential GPS base station;
f. calculating with said Differential GPS base station differential corrections;
g. providing said differential corrections to a radio transmitter;
h. broadcasting using said radio transmitter, said differential corrections to said vehicle;
i. receiving using a radio receiver located on said vehicle said broadcast differential corrections;
j. receiving GPS signals using a GPS antenna located on said vehicle and providing said received GPS signals to a differential GPS receiver located on said vehicle;
k. providing said received differential corrections to said differential GPS receiver;
l. calculating using said differential GPS receiver at least one differentially corrected information element selected from the group comprising 3-dimensional position, 2-dimensional horizontal position, vertical position, 3-dimensional velocity, speed, heading, vertical rate and time;
m. broadcasting differentially corrected position information indicative of said vehicle location using a radio transmitter located on said vehicle;

3. An airport navigation system, the system comprising:
a. a GPS antenna used to receive broadcast signals from GPS satellites, said GPS antenna located at a known location, identified with 3-dimensional GPS compatible coordinates;
b. a differential GPS base station that receives GPS signals from said GPS antenna;
c. means within said differential GPS base station to calculate differential corrections consisting of pseudorange corrections;
d. a radio transmitter connected to said differential GPS base station;
e. means within said differential GPS base station to send pseudorange corrections to said radio transmitter;
f. a radio receiver located on a vehicle selected from the group comprising aircraft and surface equipment;
g. means on said vehicle to receive said pseudorange corrections using said radio receiver and means to provide said pseudorange corrections to an onboard differential GPS receiver;
h. means to calculate a differentially corrected position using said onboard differential GPS receiver and said received pseudorange corrections and

i. means to navigate said vehicle using said differentially corrected GPS position.

* * * * *